

DERIVED CATEGORIES

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Dedicated to Alexander Grothendieck, in Memoriam

ABSTRACT. - - -

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First Part**cmnt:**

The division of the book into “parts” is temporary for the duration of the writing process. The division into “Sections” – such as “0. Introduction” – will be kept in the final version of the book.

cmnt:

Start of course I.
This part is essentially arXiv:1610.09640v1.

0. INTRODUCTION

cmnt:

needs many changes

This book develops the theory of *derived categories*, starting from the foundations, and going all the way to applications in algebra and geometry. The emphasis is on explicit constructions (with examples), as opposed to axiomatics. The most abstract concept we use is probably that of abelian category (which seems indispensable).

A special feature of this book is that most of the theory deals with $\mathbf{D}(A, \mathbf{M})$, the *derived category of DG A -modules in \mathbf{M}* , where A is a DG (differential graded) ring and \mathbf{M} is an abelian category. This covers most important examples that arise in algebra and geometry:

- The derived category $\mathbf{D}(A)$ of DG A -modules, for any DG ring A . This includes ordinary rings.
- The derived category $\mathbf{D}(\mathbf{M})$ for any abelian category \mathbf{M} . This includes $\mathbf{M} = \text{Mod } \mathcal{A}$, the category of sheaves of \mathcal{A} -modules on a ringed space (X, \mathcal{A}) .

Furthermore, we work with *unbounded* derived categories. We prove existence of resolutions (bounded or unbounded) in several contexts.

The first half of the book (Sections 1-11) covers the general theory. This is done in an unorthodox manner, using DG categories as the source of derived categories and triangulated functors. Another departure from the tradition is that we only consider *pretriangulated categories*, thus sparing ourselves the burden of the octahedral axiom. In this part of the book we provide detailed proofs of all statements (except the routine ones, that are left as exercises). A more detailed description of the contents of the first half is in the Synopsis (subsection 0.2 of the Introduction).

The second half of the book (that is not yet written) shall start off with more of the general theory: derived bifunctor, and derived categories in geometry. This is in Sections 13-17).

After that we shall deal with a few specialized topics:

- ▷ Derived Categories in Commutative Algebra.
- ▷ Residues and Duality in Algebraic Geometry.

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▷ Derived Categories in Noncommutative Algebra.

In this last portion of the book we shall leave out some of the proofs (but there are precise external references). Much of the material here is the state of the art, and is not included in any prior textbook.

The book is based on notes for advanced courses given at Ben Gurion University, in the academic years 2011-12 and 2015-16. The main sources for the first part of the book are [RD] and [KaSc1]; but the DG theory component is absent from those earlier texts, and is pretty much our own interpretation of folklore results.

cmnt: Differences from other books; advice to the reader

0.1. A Motivating Discussion: Duality. By way of introduction to the subject of derived categories, let us consider *duality*.

We begin with something elementary: linear algebra. Take a field \mathbb{K} . Given a \mathbb{K} -module M (i.e. a vector space), let

$$D(M) := \text{Hom}_{\mathbb{K}}(M, \mathbb{K}),$$

be the dual module. There is a canonical homomorphism

$$\theta_M : M \rightarrow D(D(M)),$$

namely $\theta_M(m)(\phi) := \phi(m)$ for $m \in M$ and $\phi \in D(M)$. If M is finitely generated then θ_M is an isomorphism (actually this is “if and only if”).

To formalize this situation, let $\text{Mod } \mathbb{K}$ denote the category of \mathbb{K} -modules. Then

$$D : \text{Mod } \mathbb{K} \rightarrow \text{Mod } \mathbb{K}$$

is a contravariant functor, and

$$\theta : \text{Id} \rightarrow D \circ D$$

is a natural transformation. Here Id is the identity functor of $\text{Mod } \mathbb{K}$.

Now let us replace \mathbb{K} by any nonzero commutative ring A . Again we can define a contravariant functor

$$D : \text{Mod } A \rightarrow \text{Mod } A, \quad D(M) := \text{Hom}_A(M, A),$$

and a natural transformation $\theta : \text{Id} \rightarrow D \circ D$. It is easy to see that $\theta_M : M \rightarrow D(D(M))$ is an isomorphism if M is a finitely generated free module. Of course we can't expect reflexivity (i.e. θ_M being an isomorphism) if M is not finitely generated; but what about a finitely generated module that is not free?

In order to understand this better, let us concentrate on the ring $A = \mathbb{Z}$. Since \mathbb{Z} -modules are just abelian groups, the category $\text{Mod } \mathbb{Z}$ is often denoted by Ab . Let Ab_f be the full subcategory of finitely generated abelian groups. Any finitely generated abelian group is of the form $M \cong T \oplus F$, with F free and T finite. (The letters “T” and “F” stand for “torsion” and “free” respectively.) It is important to note that this is *not a canonical isomorphism*. There is a canonical short exact sequence

$$(0.1.1) \quad 0 \rightarrow T \xrightarrow{\phi} M \xrightarrow{\psi} F \rightarrow 0,$$

but the decomposition $M \cong T \oplus F$ comes from *choosing a splitting* $\sigma : F \rightarrow M$ of this sequence.

Exercise 0.1.2. Prove that the exact sequence (0.1.1) is functorial (i.e. natural); namely there are functors $T, F : \mathbf{Ab}_f \rightarrow \mathbf{Ab}_f$, and natural transformations $\phi : T \rightarrow \text{Id}$ and $\psi : \text{Id} \rightarrow F$, such that for any $M \in \mathbf{Ab}_f$, the group $T(M)$ is finite; the group $F(M)$ is free; and the sequence of homomorphisms

$$(0.1.3) \quad 0 \rightarrow T(M) \xrightarrow{\phi_M} M \xrightarrow{\psi_M} F(M) \rightarrow 0$$

is exact.

Next, prove that there does not exist a *functorial decomposition* of a finitely generated abelian group into a free part and a finite part. Namely, there is no natural transformation $\sigma : F \rightarrow \text{Id}$, such that for every M , the homomorphism $\sigma_M : F(M) \rightarrow M$ splits the sequence (0.1.3). (Hint: find a counterexample.)

We know that for a free finitely generated abelian group F there is reflexivity, i.e. $\theta_F : F \rightarrow D(D(F))$ is an isomorphism. But for a finite abelian group T we have

$$D(T) = \text{Hom}_{\mathbb{Z}}(T, \mathbb{Z}) = 0.$$

Thus, for a $M \in \mathbf{Ab}_f$ with nonzero torsion subgroup T , reflexivity fails: $\theta_M : M \rightarrow D(D(M))$ is not an isomorphism.

On the other hand, for an abelian group M we can define another sort of dual:

$$D'(M) := \text{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}).$$

There is a natural transformation $\theta' : \text{Id} \rightarrow D' \circ D'$. For a finite abelian group T the homomorphism $\theta'_T : T \rightarrow D'(D'(T))$ is an isomorphism; this can be seen by decomposing T into cyclic groups, and for a finite cyclic group it is clear. So D' is a duality for finite abelian groups. (We may view the abelian group \mathbb{Q}/\mathbb{Z} as the group of roots of 1 in \mathbb{C} , via the exponential function; and then D' becomes *Pontryagin Duality*.)

But for a finitely generated free abelian group F we get $D'(D'(F)) = \widehat{F}$, the profinite completion of F . So once more this is not a good duality for all finitely generated abelian groups.

We could try to be more clever and “patch” the two dualities D and D' , into something that we will call $D \oplus D'$. This looks pleasing at first – but then we recall that the decomposition $M \cong T \oplus F$ of a finitely generated group is not functorial, so that $D \oplus D'$ can't be a functor.

This is where the *derived category* enters. For any commutative ring A there is the derived category $\mathbf{D}(\text{Mod } A)$. Here is a very quick explanation of it.

Recall that a *complex* of A -modules is a diagram

$$(0.1.4) \quad M = (\dots \rightarrow M^{-1} \xrightarrow{d_M^{-1}} M^0 \xrightarrow{d_M^0} M^1 \rightarrow \dots)$$

in the category $\text{Mod } A$. Namely the M^i are A -modules, and the d_M^i are homomorphisms. The condition is that $d_M^{i+1} \circ d_M^i = 0$. We sometimes write $M = \{M^i\}_{i \in \mathbb{Z}}$. The collection $d_M = \{d_M^i\}_{i \in \mathbb{Z}}$ is called the *differential* (or the coboundary operator) of M .

Given a second complex

$$N = (\dots \rightarrow N^{-1} \xrightarrow{d_N^{-1}} N^0 \xrightarrow{d_N^0} N^1 \rightarrow \dots),$$

a *homomorphism of complexes* $\phi : M \rightarrow N$ is a collection $\phi = \{\phi^i\}_{i \in \mathbb{Z}}$ of homomorphisms $\phi^i : M^i \rightarrow N^i$ in $\text{Mod } A$ satisfying

$$\phi^{i+1} \circ d_M^i = d_N^i \circ \phi^i.$$

The resulting category is denoted by $\mathbf{C}(\text{Mod } A)$.

The i -th *cohomology* of the complex M is

$$H^i(M) := \frac{\text{Ker}(d_M^i)}{\text{Im}(d_M^{i-1})} \in \text{Mod } A.$$

A homomorphism $\phi : M \rightarrow N$ in $\mathbf{C}(\text{Mod } A)$ induces homomorphisms

$$H^i(\phi) : H^i(M) \rightarrow H^i(N)$$

in $\text{Mod } A$. We call ϕ a *quasi-isomorphism* if all the homomorphisms $H^i(\phi)$ are isomorphisms.

The derived category $\mathbf{D}(\text{Mod } A)$ is the localization of $\mathbf{C}(\text{Mod } A)$ with respect to the quasi-isomorphisms. This means that $\mathbf{D}(\text{Mod } A)$ has the same objects as $\mathbf{C}(\text{Mod } A)$. There is a functor

$$Q : \mathbf{C}(\text{Mod } A) \rightarrow \mathbf{D}(\text{Mod } A)$$

that is the identity of objects, and it sends quasi-isomorphisms to isomorphisms. Furthermore, any morphism in $\mathbf{D}(\text{Mod } A)$ can be written as a fraction:

$$Q(\phi) \circ Q(\psi)^{-1},$$

where ϕ is a morphism in $\mathbf{C}(\text{Mod } A)$, and ψ is a quasi-morphism in $\mathbf{C}(\text{Mod } A)$. This is studied in Section 8 of the book.

A single A -module M^0 can be viewed as a complex M concentrated in degree 0:

$$(0.1.5) \quad M = (\cdots \rightarrow 0 \xrightarrow{0} M^0 \xrightarrow{0} 0 \rightarrow \cdots).$$

This turns out to be a fully faithful embedding

$$(0.1.6) \quad \text{Mod } A \rightarrow \mathbf{D}(\text{Mod } A).$$

The essential image of this embedding is the full subcategory of $\mathbf{D}(\text{Mod } A)$ on the complexes M whose cohomology is concentrated in degree 0 (i.e. $H^i(M) = 0$ for all $i \neq 0$). In this way we have *enlarged* the category of A -modules.

Here is a very important kind of quasi-isomorphism. Suppose M is a module and

$$(0.1.7) \quad \cdots \rightarrow P^{-2} \xrightarrow{d_P^{-2}} P^{-1} \xrightarrow{d_P^{-1}} P^0 \xrightarrow{\epsilon} M \rightarrow 0$$

is a free resolution of it. We can view M as a complex concentrated in degree 0, by the embedding (0.1.6). Let P be the complex

$$P = (\cdots \rightarrow P^{-2} \xrightarrow{d_P^{-2}} P^{-1} \xrightarrow{d_P^{-1}} P^0 \rightarrow 0 \rightarrow \cdots),$$

concentrated in nonpositive degrees. Then ϵ becomes a morphism of complexes

$$\epsilon : P \rightarrow M$$

with trivial components in nonzero degrees, and the exactness of the sequence (0.1.7) says that ϵ is actually a quasi-isomorphism. Thus

$$Q(\epsilon) : P \rightarrow M$$

is an isomorphism in $\mathbf{D}(\text{Mod } A)$.

Let us now return to $A = \mathbb{Z}$. The functor $D = \text{Hom}_{\mathbb{Z}}(-, \mathbb{Z})$ from $\text{Mod } \mathbb{Z}$ to itself has a *right derived functor*

$$RD = \text{RHom}_{\mathbb{Z}}(-, \mathbb{Z}),$$

which is a contravariant *triangulated functor*

$$RD : \mathbf{D}(\text{Mod } \mathbb{Z}) \rightarrow \mathbf{D}(\text{Mod } \mathbb{Z}).$$

And there is a natural transformation of triangulated functors

$$\theta : \text{Id} \rightarrow RD \circ RD.$$

Here is the way to calculate the value of the functor RD on a finitely generated abelian group M . Let us choose a free resolution of M like in (0.1.7). To be easy on ourselves, we can take it to be of this form:

$$P = (\cdots \rightarrow 0 \rightarrow P^{-1} \xrightarrow{d_P^{-1}} P^0 \rightarrow 0 \rightarrow \cdots) = (\cdots \rightarrow 0 \rightarrow \mathbb{Z}^{r_1} \xrightarrow{d} \mathbb{Z}^{r_0} \rightarrow 0 \cdots),$$

where $r_0, r_1 \in \mathbb{N}$ and d is a matrix of integers. Because $Q(\epsilon) : P \rightarrow M$ is an isomorphism in $\mathbf{D}(\text{Mod } \mathbb{Z})$, it suffices to calculate $RD(P)$.

It is known that $RD(P) = D(P)$ for bounded complexes of free modules, where $D(P)$ is calculated term by term. Thus

$$RD(P) = D(P) = \text{Hom}_{\mathbb{Z}}(P, \mathbb{Z}) = (\cdots \rightarrow 0 \rightarrow \mathbb{Z}^{r_0} \xrightarrow{d^*} \mathbb{Z}^{r_1} \rightarrow 0 \cdots),$$

a complex concentrated in degrees 0 and 1, with the transpose matrix d^* as its differential.

Because $RD(P) = D(P)$ is itself a bounded complex of free modules, its derived dual is

$$RD(RD(P)) = D(D(P)) = \text{Hom}_{\mathbb{Z}}(\text{Hom}_{\mathbb{Z}}(P, \mathbb{Z}), \mathbb{Z}).$$

The canonical morphism

$$\theta_P : P \rightarrow D(D(P))$$

in $\mathbf{C}(\text{Mod } \mathbb{Z})$ is an isomorphism in this case, because P^0 and P^{-1} are finite rank free modules. Therefore

$$\theta_M : M \rightarrow RD(RD(M))$$

is an isomorphism in $\mathbf{D}(\text{Mod } \mathbb{Z})$. (For a more general statement see Subsection 14.2.) We see that RD is a duality that holds for all finitely generated \mathbb{Z} -modules!

Here is the connection between the derived duality RD and the “classical” dualities D and D' . Take a finitely generated abelian group M , with short exact sequence (0.1.1). There are functorial isomorphisms

$$H^0(RD(M)) \cong \text{Ext}_{\mathbb{Z}}^0(M, \mathbb{Z}) \cong \text{Hom}_{\mathbb{Z}}(M, \mathbb{Z}) \cong D(M)$$

and

$$H^1(RD(M)) \cong \text{Ext}_{\mathbb{Z}}^1(M, \mathbb{Z}) \cong D'(M).$$

The cohomologies $H^i(RD(M))$ vanish for $i \neq 0, 1$.

Note that $D(M) \cong D(F)$ and $D'(M) \cong D'(T)$. We see that if M is neither free nor finite, then $H^0(RD(M))$ and $H^1(RD(M))$ are both nonzero; so that the complex $D(M)$ is not isomorphic to an object of $\text{Mod } \mathbb{Z}$, under the embedding (0.1.6).

This sort of duality holds for *many noetherian commutative rings* A . But the formula for the duality functor

$$RD : \mathbf{D}(\text{Mod } A) \rightarrow \mathbf{D}(\text{Mod } A)$$

is somewhat different – it is

$$RD(M) := \text{RHom}_A(M, R),$$

where $R \in \mathbf{D}(\text{Mod } A)$ is a *dualizing complex*. Such a dualizing complex is unique (up to a degree translation and tensoring with an invertible module).

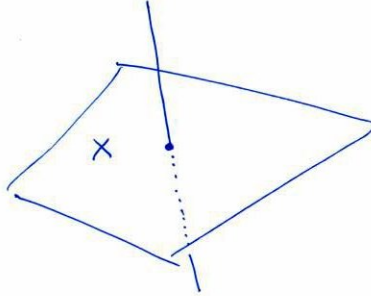


FIGURE 1. An algebraic variety that is connected but not equidimensional, and hence not Cohen-Macaulay.

Interestingly, the structure of the dualizing complex R depends on the geometry of the ring A (i.e. of the affine scheme $\text{Spec } A$). If A is a regular ring (like \mathbb{Z}) then $R = A$ is dualizing. If A is Cohen-Macaulay (and $\text{Spec } A$ is connected) then R is a single A -module. But if A is a more complicated ring, then R must live in several degrees.

Example 0.1.8. Consider the affine algebraic variety $X \subseteq \mathbf{A}_{\mathbb{R}}^3$ which is the union of a plane and a line, with coordinate ring

$$A = \mathbb{R}[t_1, t_2, t_3]/(t_3 \cdot t_1, t_3 \cdot t_2).$$

See figure 1. The dualizing complex R must live in two adjacent degrees; namely there is some i s.t. $H^i(R)$ and $H^{i+1}(R)$ are nonzero.

One can also talk about dualizing complexes over *noncommutative rings*. (This is a favorite topic of mine!)

0.2. Synopsis of the Book. Here is a section-by-section description of the material in the book (the first half only).

Sections 1-2. These sections are pretty much a review of the standard material on categories and functors (especially abelian categories and additive functors) that is needed for the book. A reader who is familiar with this material can skip these sections. We do recommend looking at our notational convention, that are spelled out in Convention 1.2.2.

Section 3. A good understanding of *DG algebra* (“DG” is short for “differential graded”) is essential in our approach to derived categories. We aim to study both the derived category $\mathbf{D}(\mathbf{M})$ of an abelian category \mathbf{M} , and the derived category $\mathbf{D}(A)$ of DG modules over a DG ring A . In order to accomplish this, we introduce a new concept, that combines both these setups: the category $\mathbf{C}(A, \mathbf{M})$ of *DG A-modules in M*. See Subsection 3.7.

Actually, our methods can be expanded to handle the DG category $\mathbf{C}(A, \mathbf{M})$ of DG A -modules in \mathbf{M} , where A is a DG category (rather than a DG ring as above). This includes as a special case ($\mathbf{M} = \mathbf{Ab}$) the category $\mathbf{C}(A)$ of DG A -modules, in

the sense of Keller; see Remark 3.7.7. We have decided to stick to the less general setup $\mathbf{C}(A, \mathbf{M})$ for these reasons:

- (1) The treatment is much more streamlined and intuitive.
- (2) Virtually all DG categories that occur in practice (in algebra and algebraic geometry) are full subcategories of $\mathbf{C}(A, \mathbf{M})$, for suitable A and \mathbf{M} . A noteworthy instance is derived Morita theory for schemes (see Section 19.4), that fits nicely within our framework.

There do not exist (to our knowledge) detailed textbook references for DG algebra (by which we mean DG rings, DG modules, DG categories, DG functors and related constructions). Therefore we have included a lot of basic material in this section. Moreover, we present a new treatment of translations and cones, using the “little t operator”, following our paper [Ye11]. Among other things, we prove (in Theorem 4.1.7) that the translation functor T of $\mathbf{C}(A, \mathbf{M})$ is a DG functor, and $t : \text{Id} \rightarrow T$ is a degree -1 morphisms of DG functors from $\mathbf{C}(A, \mathbf{M})$ to itself.

Section 5. This section consists mostly of new material, some of it implicit in the paper [BoKa] on *pretriangulated DG categories*.

Inside the DG category $\mathbf{C}(A, \mathbf{M})$ there is the *strict category* $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, that has all the objects, but its morphisms are the degree 0 cocycles. Any morphism $\phi : M \rightarrow N$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ gives rise to a *standard triangle*

$$M \xrightarrow{\phi} N \xrightarrow{e_\phi} \text{Cone}(\phi) \xrightarrow{p_\phi} T(M)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

Consider a DG functor

$$(0.2.1) \quad F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N}),$$

where A and B are DG rings, and \mathbf{M} and \mathbf{N} are abelian categories. In Theorem 5.2.3 we show that there is a canonical isomorphism of DG functors

$$(0.2.2) \quad \tau_F : F \circ T \xrightarrow{\sim} T \circ F$$

called the *translation isomorphism*. Then, in Theorem 5.3.7, we prove that F sends standard triangles in the $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ to standard triangles in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$.

We end this section with several examples of DG functors. These examples are prototypes – they can be easily extended to other setups.

Section 6. We start with the theory of *pretriangulated categories* and *triangulated functors*, following mainly [RD]. Because the *octahedral axiom* plays no role in our approach, we exclude it from the discussion, and this is the reason we do not talk about triangulated categories. In Subsection 6.4 we prove that the homotopy category $\mathbf{K}(A, \mathbf{M})$ is pretriangulated.

We conclude this section with Theorem 6.4.15. It says that given a DG functor F as in (0.2.1), with translation isomorphism τ_F from (0.2.2), the T -additive functor

$$(F, \tau_F) : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{K}(B, \mathbf{N})$$

is triangulated. This is possibly a new result (unifying well-known yet disparate examples).

Section 7. In this section we take a close look at *localization of categories*. We give a detailed proof of the theorem on Ore localization (also known as noncommutative localization). We then prove that the localization \mathbf{K}_S of a pretriangulated category \mathbf{K} at a multiplicatively closed set of cohomological origin S is a left and right Ore

localization, the category \mathbf{K}_S is pretriangulated, and the localization functor $Q : \mathbf{K} \rightarrow \mathbf{K}_S$ is triangulated.

Section 8. In the case of the pretriangulated category $\mathbf{K}(A, M)$, and the quasi-isomorphisms $\mathbf{S}(A, M)$ in it, we get the *derived category*

$$\mathbf{D}(A, M) := \mathbf{K}(A, M)_{\mathbf{S}(A, M)},$$

and the triangulated localization functor

$$Q : \mathbf{K}(A, M) \rightarrow \mathbf{D}(A, M).$$

We look at the full subcategories $\mathbf{K}^\star(A, M)$ of $\mathbf{K}(A, M)$ corresponding to boundedness conditions \star , and prove that their localizations with respect to quasi-isomorphisms embed fully faithfully in $\mathbf{D}(A, M)$. We also prove that the obvious functor $M \rightarrow \mathbf{D}(M)$ is fully faithful.

Section 9. In this section we talk about *derived functors*. To make the definitions of the derived functors precise, we introduce some *2-categorical notation* here.

The setting is general: we start from a triangulated functor $F : \mathbf{K} \rightarrow \mathbf{E}$ between pretriangulated categories, and a denominator set of cohomological origin $S \subseteq \mathbf{K}$. A *right derived functor* of F is a pair $(\mathbf{R}F, \eta)$, where $\mathbf{R}F : \mathbf{K}_S \rightarrow \mathbf{E}$ is a triangulated functor, and $\eta : F \rightarrow \mathbf{R}F \circ Q$ is a morphism of triangulated functors. The pair $(\mathbf{R}F, \eta)$ has a universal property, making it unique up to a unique isomorphism. The *left derived functor* $(\mathbf{L}F, \eta)$ is defined similarly.

We provide a general existence theorem for derived functors. For the right derived functor we assume the existence of a pretriangulated category $\mathbf{J} \subseteq \mathbf{K}$ that is “right F -acyclic”. Likewise for the left derived functor. This is the original result from [RD], but our proof is much more detailed.

Section 10. Here we specialize the general existence theorem from Section 9 to the case of the pretriangulated categories $\mathbf{K}^\star(A, M)$, for a DG ring A , and abelian category M and a boundedness condition \star . We define *K-injective DG modules*, and show they can be used to present any right derived functor (if there are enough of them). We also define *K-projective* and *K-flat DG modules*, and explain how they are used.

Section 11. In this section we prove existence of K-injective, K-projective and K-flat resolutions in several important cases of $\mathbf{C}^\star(A, M)$:

- K-projective resolutions in $\mathbf{C}^-(M)$, where M is an abelian category with enough projectives. This is classical (i.e. it is already in [RD]).
- K-projective resolutions in $\mathbf{C}(A)$, where A is any DG ring. This includes $\mathbf{C}(\text{Mod } A)$, the category of unbounded complexes of modules over a ring A .
- K-injective resolutions in $\mathbf{C}^+(M)$, where M is an abelian category with enough injectives. This is classical too.
- K-injective resolutions in $\mathbf{C}(A)$, where A is any DG ring. This includes $\mathbf{C}(\text{Mod } A)$ for any ring A .

Our proofs are explicit, and we use limits of complexes cautiously (since this is known to be a pitfall).

This ends the first half of the book. As mentioned before, the second half is yet to be written.

cmnt: continue synopsis

0.3. Recommended Bibliography.

cmnt: and prerequisites

For further discussion of categories (and the related set theory), functors, and classical homological algebra, see the books [Mac2], [HiSt], [Rot], [GeMa], [KaSc1], [KaSc2], [Ne1], and [We].

Derived categories are treated in [RD] (the original reference), and in the last five books in the previous list. None of these references has emphasis on DG categories as the background out of which derived categories arise; indeed, most of these books do not even mention DG algebra.

Sources for algebraic geometry and modern differential geometry are [Har] and [KaSc1]. For commutative ring theory see the books [Eis], [Mats] and [AlKl]. For noncommutative ring theory see [Row] and [Rot].

Almost everything can be found in the evolving online reference [SP].

0.4. Acknowledgments. I want to thank the participants of the course on derived categories held at Ben Gurion University in Spring 2012, for correcting many of my mistakes (both in real time during the lectures, and afterwards when writing the notes [Ye7]). Thanks also to Joseph Lipman, Pierre Schapira, Amnon Neeman and Charles Weibel for helpful discussions during the preparation of that course. Vincent Beck, Yang Han and Lucas Simon sent me corrections and useful comments on the material in [Ye7].

As already mentioned, this book is being written while I am teaching a four semester course on the subject at Ben Gurion University, spanning the academic years 2015-16 and 2016-17. I wish to thank the participants of this course, and especially Rishi Vyas, Stephan Snigerov, Asaf Yekutieli, S.D. Banerjee and Alberto Voix, who contributed material and corrected numerous mistakes. Stephan also helped me prepare the manuscript for publication. Ben Gurion University is generous enough to permit this ongoing project. Some of this work was supported by the Israel Science Foundation grant no. 253/13.

In the process of writing the book I have also benefitted from the advice of Pierre Schapira, Bernhard Keller, Robin Hartshorne, Rodney Sharp, Manuel Saorin, and the anonymous referees for Cambridge University Press. Special thanks to Thomas Harris of CUP for his invaluable assistance.

1. BASIC FACTS ON CATEGORIES

1.1. Set Theory. In this book we will not try to be precise about issues of set theory. The blanket assumption is that we are given a *Grothendieck universe* \mathbf{U} . This is a “large” infinite set. A *small set*, or a \mathbf{U} -small set, is a set S that is an element of \mathbf{U} . We want all the products $\prod_{i \in I} S_i$ and disjoint unions $\coprod_{i \in I} S_i$, with I and S_i small sets, to be small sets too. (This requirement is not crucial for us, and it is more a matter of convenience. When dealing with higher categories, one usually needs a hierarchy of universes anyhow.) We assume that the axiom of choice holds in \mathbf{U} .

A \mathbf{U} -category is a category \mathbf{C} whose set of objects $\text{Ob}(\mathbf{C})$ is a subset of \mathbf{U} , and for every $C, D \in \text{Ob}(\mathbf{C})$ the set of morphisms $\text{Hom}_{\mathbf{C}}(C, D)$ is small. If $\text{Ob}(\mathbf{C})$ is also small, then \mathbf{C} is called a *small category*. See [SGA 4] or [KaSc2, Section 1.1]. Another approach, involving “sets” vs “classes”, can be found in [Ne1].

We denote by \mathbf{Set} the category of all small sets. So $\text{Ob}(\mathbf{Set}) = \mathbf{U}$, and \mathbf{Set} is a \mathbf{U} -category. A group (or a ring, etc.) is called small if its underlying set is small. We denote by \mathbf{Grp} , \mathbf{Ab} , \mathbf{Ring} and \mathbf{Ring}_c the categories of small groups, small abelian groups, small rings and small commutative rings respectively. For a small ring A we denote by $\mathbf{Mod} A$ the category of all small left A -modules.

By default we work with \mathbf{U} -categories, and from now on \mathbf{U} will remain implicit. The one exception is when we deal with localization of categories, where we shall briefly encounter a set theoretical issue; but for most interesting cases this issue has an easy solution.

1.2. Notation. Let \mathbf{C} be a category. We often write $C \in \mathbf{C}$ as an abbreviation for $C \in \text{Ob}(\mathbf{C})$. For an object C , its identity automorphism is denoted by id_C . The identity functor of \mathbf{C} is denoted by $\text{Id}_{\mathbf{C}}$.

The opposite category of \mathbf{C} is \mathbf{C}^{op} . It has the same objects as \mathbf{C} , but the morphism sets are

$$\text{Hom}_{\mathbf{C}^{\text{op}}}(C_0, C_1) := \text{Hom}_{\mathbf{C}}(C_1, C_0),$$

and composition is reversed. Of course $(\mathbf{C}^{\text{op}})^{\text{op}} = \mathbf{C}$. The identity functor of \mathbf{C} can be viewed as a contravariant functor

$$(1.2.1) \quad \text{Op} : \mathbf{C} \rightarrow \mathbf{C}^{\text{op}}.$$

To be explicit, on objects we take $\text{Op}(C) := C$. As for morphisms, given a morphism $\phi : C_0 \rightarrow C_1$ in \mathbf{C} , we let

$$\text{Op}(\phi) : \text{Op}(C_1) \rightarrow \text{Op}(C_0)$$

be the morphism $\text{Op}(\phi) := \phi$ in \mathbf{C}^{op} . The inverse functor $\mathbf{C}^{\text{op}} \rightarrow \mathbf{C}$ is also denoted by Op . (We could have distinguished between these two functors, say by writing $\text{Op}_{\mathbf{C}}$ and $\text{Op}_{\mathbf{C}^{\text{op}}}$; but this would have been pretty awkward.) Thus $\text{Op} \circ \text{Op} = \text{Id}_{\mathbf{C}}$.

A contravariant functor $F : \mathbf{C} \rightarrow \mathbf{D}$ is the same as a covariant functor $F \circ \text{Op} : \mathbf{C}^{\text{op}} \rightarrow \mathbf{D}$. Since we prefer dealing only with covariant functors, we make the following convention:

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Convention 1.2.2. By default all functors will be covariant, unless explicitly mentioned otherwise.

Contravariant functors will almost always we dealt with by replacing the source category with its opposite.

Rings and modules are important for us, so let us also put forth the next convention.

Convention 1.2.3.

- (1) All rings and ring homomorphisms are unital. The category of rings is denoted by \mathbf{Ring} .
- (2) All modules are left modules by default. For a ring A , we denote by $\mathbf{Mod} A = \mathbf{M}(A)$ the category of (left) A -modules.

Right A -modules are left modules over the opposite ring A^{op} , and this is the way we shall most often deal with them.

We will try to keep the following font and letter conventions:

- $f : C \rightarrow D$ is a morphism between objects in a category.
- $F : C \rightarrow D$ is a functor between categories.
- $\eta : F \rightarrow G$ is morphism of functors (i.e. a natural transformation) between functors $F, G : C \rightarrow D$.
- $f, \phi, \alpha : M \rightarrow N$ are morphisms between objects in an abelian category \mathbf{M} .
- $F : \mathbf{M} \rightarrow \mathbf{N}$ is an additive functor between abelian categories.
- The category of complexes in an abelian category \mathbf{M} is $\mathbf{C}(\mathbf{M})$.
- If \mathbf{M} is a module category, and $M \in \text{Ob}(\mathbf{M})$, then elements of M will be denoted by m, n, m_i, \dots

1.3. Epimorphisms and Monomorphisms. Let \mathbf{C} be a category. Recall that a morphism $f : C \rightarrow D$ in \mathbf{C} is called an *isomorphism* if there is a morphism $g : D \rightarrow C$ such that $f \circ g = \text{id}_D$ and $g \circ f = \text{id}_C$. The morphism g is called the *inverse* of f , it is unique (if it exists), and it is denoted by f^{-1} . An isomorphism is often denoted by this shape of arrow: $f : C \xrightarrow{\cong} D$.

A morphism $f : C \rightarrow D$ in \mathbf{C} is called an *epimorphism* if it has the right cancellation property: for any $g, g' : D \rightarrow E$, $g \circ f = g' \circ f$ implies $g = g'$. An epimorphism is often denoted by this shape of arrow: $f : C \twoheadrightarrow D$.

A morphism $f : C \rightarrow D$ is called a *monomorphism* if it has the left cancellation property: for any $g, g' : E \rightarrow C$, $f \circ g = f \circ g'$ implies $g = g'$. A monomorphism is often denoted by this shape of arrow: $f : C \hookrightarrow D$.

Example 1.3.1. In \mathbf{Set} the monomorphisms are the injections, and the epimorphisms are the surjections. A morphism $f : C \rightarrow D$ in \mathbf{Set} that is both a monomorphism and an epimorphism is an isomorphism. The same holds in the category $\mathbf{Mod} A$ of left modules over a ring A .

This example could be misleading, because the property of being an epimorphism is often not preserved by forgetful functors, as the next exercise shows.

Exercise 1.3.2. Consider the category of rings \mathbf{Ring} . Show that the forgetful functor $\mathbf{Ring} \rightarrow \mathbf{Set}$ respects monomorphisms, but it does not respect epimorphisms. (Hint: show that the inclusion $\mathbb{Z} \rightarrow \mathbb{Q}$ is an epimorphism in \mathbf{Ring} .)

By a *subobject* of an object $C \in \mathbf{C}$ we mean a monomorphism $f : C' \rightarrow C$ in \mathbf{C} . We sometimes write $C' \subseteq C$ in this situation, but this is only notational (and does not mean inclusion of sets). We say that two subobjects $f_0 : C'_0 \rightarrow C$ and $f_1 : C'_1 \rightarrow C$ of C are *isomorphic* if there is an isomorphism $g : C'_0 \xrightarrow{\cong} C'_1$ such that $f_1 \circ g = f_0$.

Likewise, by a *quotient* of C we mean an epimorphism $g : C \rightarrow C''$ in \mathbf{C} . There is an analogous notion of isomorphic quotients.

Exercise 1.3.3. Let \mathbf{C} be a category, and let C be an object of \mathbf{C} .

- (1) Suppose $f_0 : C'_0 \rightarrow C$ and $f_1 : C'_1 \rightarrow C$ are subobjects of C . Show that there is at most one morphism $g : C'_0 \rightarrow C'_1$ such that $f_1 \circ g = f_0$; and if g exists, then it is a monomorphism.
- (2) Show that isomorphism is an equivalence relation on the set of subobjects of C . Show that the set of equivalence classes of subobjects of C is partially ordered by “inclusion”. (Ignore set-theoretical issues.)
- (3) Formulate and prove the analogous statements for quotient objects.

An *initial object* in a category \mathbf{C} is an object $C_0 \in \mathbf{C}$, such that for every object $C \in \mathbf{C}$ there is exactly one morphism $C_0 \rightarrow C$. Thus the set $\text{Hom}_{\mathbf{C}}(C_0, C)$ is a singleton. A *terminal object* in \mathbf{C} is an object $C_\infty \in \mathbf{C}$, such that for every object $C \in \mathbf{C}$ there is exactly one morphism $C \rightarrow C_\infty$.

Definition 1.3.4. A *zero object* in a category \mathbf{C} is an object which is both initial and terminal.

Initial, terminal and zero objects are unique up to unique isomorphisms (but they need not exist).

Example 1.3.5. In Set , \emptyset is an initial object, and any singleton is a terminal object. There is no zero object.

Example 1.3.6. In $\text{Mod } A$, any trivial module (with only the zero element) is a zero object, and we denote this module by 0 . This is allowed, since any other zero module is uniquely isomorphic to it.

1.4. Products and Coproducts. Let \mathbf{C} be a category. By a *collection of objects of \mathbf{C}* indexed by a (small) set I , we mean a function $I \rightarrow \text{Ob}(\mathbf{C})$, $i \mapsto C_i$. We usually denote this collection like this: $\{C_i\}_{i \in I}$.

Given a collection $\{C_i\}_{i \in I}$ of objects of \mathbf{C} , its *product* is a pair $(C, \{p_i\}_{i \in I})$ consisting of an object $C \in \mathbf{C}$, and a collection $\{p_i\}_{i \in I}$ of morphisms $p_i : C \rightarrow C_i$, called *projections*. The pair $(C, \{p_i\}_{i \in I})$ must have this universal property: given any object D and morphisms $f_i : D \rightarrow C_i$, there is a unique morphism $f : D \rightarrow C$ s.t. $f_i = p_i \circ f$. Of course if a product $(C, \{p_i\}_{i \in I})$ exists, then it is unique up to a unique isomorphism; and we usually write $\prod_{i \in I} C_i := C$, leaving the projection morphisms implicit.

Example 1.4.1. In Set and $\text{Mod } A$ all products exist, and they are the usual cartesian products.

For a collection $\{C_i\}_{i \in I}$ of objects of \mathbf{C} , their *coproduct* is a pair $(C, \{e_i\}_{i \in I})$, consisting of an object C and a collection $\{e_i\}_{i \in I}$ of morphisms $e_i : C_i \rightarrow C$, called *embeddings*. The pair $(C, \{e_i\}_{i \in I})$ must have this universal property: given any object D and morphisms $f_i : C_i \rightarrow D$, there is a unique morphism $f : C \rightarrow D$

s.t. $f_i = f \circ e_i$. If a coproduct $(C, \{e_i\}_{i \in I})$ exists, then it is unique up to a unique isomorphism; and we write $\coprod_{i \in I} C_i := C$, leaving the embeddings implicit.

Example 1.4.2. In **Set** the coproduct is the disjoint union. In **Mod** A the coproduct is the direct sum.

cmnt: move direct and inverse limits to this location?

1.5. Equivalence of Categories. Recall that a functor $F : C \rightarrow D$ is an *equivalence* if there exists a functor $G : D \rightarrow C$, and isomorphisms of functors (i.e. natural isomorphisms) $G \circ F \xrightarrow{\cong} \text{Id}_C$ and $F \circ G \xrightarrow{\cong} \text{Id}_D$. Such a functor G is called a *quasi-inverse* of F , and it is unique up to isomorphism (if it exists), and it is denoted by F^{-1} .

The functor $F : C \rightarrow D$ is *full* (resp. *faithful*) if every $C_0, C_1 \in C$ the function

$$F : \text{Hom}_C(C_0, C_1) \rightarrow \text{Hom}_D(F(C_0), F(C_1))$$

is surjective (resp. injective).

We know that $F : C \rightarrow D$ is an equivalence iff these two conditions hold:

- (i) F is essentially surjective on objects. This means that for every $D \in D$ there is some $C \in C$ and an isomorphism $F(C) \xrightarrow{\cong} D$.
- (ii) F is fully faithful (i.e. full and faithful).

Exercise 1.5.1. If you are not sure about the last claim (characterization of equivalences), then prove it. (Hint: use the axiom of choice to construct a quasi-inverse of F .)

Example 1.5.2. Let C and D be categories. A functor $F : C \rightarrow D$ is called an *isomorphism of categories* if it is bijective on sets of objects and on sets of morphisms. It is clear that an isomorphism of categories is an equivalence. If F is an isomorphism of categories, then it has an inverse isomorphism $F^{-1} : D \rightarrow C$, which is unique. In practice, it is quite rare to find an isomorphism of categories.

1.6. Bifunctors. Let C and D be categories. Their product is the category $C \times D$ defined as follows: the set of objects is

$$\text{Ob}(C \times D) := \text{Ob}(C) \times \text{Ob}(D).$$

The sets of morphisms are

$$\text{Hom}_{C \times D}((C_0, D_0), (C_1, D_1)) := \text{Hom}_C(C_0, C_1) \times \text{Hom}_D(D_0, D_1).$$

The composition is

$$(f_1, g_1) \circ (f_0, g_0) := (f_1 \circ f_0, g_1 \circ g_0),$$

and the identity morphisms are $(\text{id}_C, \text{id}_D)$.

A *bifunctor*

$$F : C \times D \rightarrow E$$

is by definition a functor from the product category $C \times D$ to E . We say “bifunctor” because it is a functor of two arguments: $F(C, D) \in E$. This will be especially useful when considering additive categories, because then we can talk about “additive bifunctors”.

1.7. Representable Functors. Let \mathbf{C} be a category and $C \in \mathbf{C}$ an object. We get a functor

$$Y_C : \mathbf{C}^{\text{op}} \rightarrow \mathbf{Set}, \quad Y_C := \text{Hom}_{\mathbf{C}}(-, C),$$

called the *Yoneda functor*. This functor sends an object C' to the set $\text{Hom}_{\mathbf{C}}(C', C)$, and a morphism $\psi : C' \rightarrow C''$ in \mathbf{C} to the function

$$Y_C(\psi) := \text{Hom}(\psi, \text{id}_C) : \text{Hom}_{\mathbf{C}}(C'', C) \rightarrow \text{Hom}_{\mathbf{C}}(C', C).$$

Now suppose we are given a morphism $\phi : C_0 \rightarrow C_1$ in \mathbf{C} . There is a morphism of functors (a natural transformation)

$$Y_\phi := \text{Hom}_{\mathbf{C}}(-, \phi) : Y_{C_0} \rightarrow Y_{C_1}.$$

Here is the first formulation of the *Yoneda Lemma*.

Proposition 1.7.1 (Yoneda Lemma v1). *Let \mathbf{C} be a category, let $C_0, C_1 \in \mathbf{C}$ be objects, and let $\eta : Y_{C_0} \rightarrow Y_{C_1}$ be a morphism of functors $\mathbf{C}^{\text{op}} \rightarrow \mathbf{Set}$.*

- (1) *There exists a unique morphism $\phi : C_0 \rightarrow C_1$ in \mathbf{C} such that $Y_\phi = \eta$.*
- (2) *If $\eta : Y_{C_0} \rightarrow Y_{C_1}$ is an isomorphism of functors, then $\phi : C_0 \rightarrow C_1$ is an isomorphism in \mathbf{C} .*

See [KaSc2, Section 1.4] for a proof. The proof is not hard, but it is very confusing.

A functor $F : \mathbf{C}^{\text{op}} \rightarrow \mathbf{Set}$ is called *representable* if there is an isomorphism of functors $f : F \xrightarrow{\cong} Y_C$ for some object $C \in \mathbf{C}$. By Proposition 1.7.1 the pair (C, f) is unique up to a unique isomorphism (if it exists). Note that the isomorphism of sets $f_C : F(C) \xrightarrow{\cong} Y_C(C)$ gives a special element $\tilde{f} \in F(C)$ such that $f_C(\tilde{f}) = \text{id}_C$.

Here is a fancier way to state this result. Consider the category $\text{Fun}(\mathbf{C}^{\text{op}}, \mathbf{Set})$, whose objects are the functors $F : \mathbf{C}^{\text{op}} \rightarrow \mathbf{Set}$, and whose morphisms are the morphisms of functors. There is a set-theoretic difficulty here: the sets of objects and morphisms of $\text{Fun}(\mathbf{C}^{\text{op}}, \mathbf{Set})$ are too big (unless \mathbf{C} is a small category); so this is not a U-category, and we must enlarge the universe.

Proposition 1.7.2 (Yoneda Lemma v2). *The Yoneda functor*

$$Y : \mathbf{C} \rightarrow \text{Fun}(\mathbf{C}^{\text{op}}, \mathbf{Set}), \quad C \mapsto Y_C, \quad \phi \mapsto Y_\phi$$

is fully faithful.

In other words, the Yoneda Lemma says that the functor Y is an equivalence from \mathbf{C} to the category of representable functors $\mathbf{C}^{\text{op}} \rightarrow \mathbf{Set}$.

Dually, any $C \in \mathbf{C}$ gives rise to a functor

$$Y'_C : \mathbf{C} \rightarrow \mathbf{Set}, \quad Y'_C := \text{Hom}_{\mathbf{C}}(C, -).$$

The identity automorphism id_C is a special element of the set $Y'_C(C)$.

A functor $F : \mathbf{C} \rightarrow \mathbf{Set}$ is called *corepresentable* if $F \cong Y'_C$ for some object $C \in \mathbf{C}$. The object C is said to corepresent the functor F . The dual Yoneda Lemma (v2) says that the functor Y' is an equivalence from \mathbf{C}^{op} to the category of corepresentable functors $\mathbf{C} \rightarrow \mathbf{Set}$.

2. ABELIAN CATEGORIES AND ADDITIVE FUNCTORS

The concept of *abelian category* is an extremely useful abstraction of module categories, introduced by Grothendieck in 1957. Before defining it (in Definition 2.3.8), we need some preparation.

2.1. Linear Categories.

Definition 2.1.1. Let \mathbb{K} be a commutative ring. A \mathbb{K} -linear category is a category \mathbb{M} , endowed with a \mathbb{K} -module structure on each of the sets of morphisms $\text{Hom}_{\mathbb{M}}(M_0, M_1)$. The condition is this:

- For all $M_0, M_1, M_2 \in \mathbb{M}$ the composition function

$$\begin{aligned} \text{Hom}_{\mathbb{M}}(M_1, M_2) \times \text{Hom}_{\mathbb{M}}(M_0, M_1) &\rightarrow \text{Hom}_{\mathbb{M}}(M_0, M_2) \\ (\phi_1, \phi_0) &\mapsto \phi_1 \circ \phi_0 \end{aligned}$$

is \mathbb{K} -bilinear.

If $\mathbb{K} = \mathbb{Z}$, we say that \mathbb{M} is a *linear category*.

Let \mathbb{K} be a commutative ring. By *central \mathbb{K} -ring* we mean a ring A , with a ring homomorphism $\mathbb{K} \rightarrow A$, such that the image of \mathbb{K} is inside the center of A . (Many texts would call such A a “unital associative \mathbb{K} -algebra”.)

Example 2.1.2. Let \mathbb{K} be any nonzero commutative ring, and let n be a positive integer. Then the ring of matrices $A := \text{Mat}_n(\mathbb{K})$ is a central \mathbb{K} -ring.

Proposition 2.1.3. *Let \mathbb{M} be a \mathbb{K} -linear category.*

- (1) *For any object $M \in \mathbb{M}$, the set*

$$\text{End}_{\mathbb{M}}(M) := \text{Hom}_{\mathbb{M}}(M, M),$$

with its given addition operation, and with the operation of composition, is a central \mathbb{K} -ring.

- (2) *For any two objects $M_0, M_1 \in \mathbb{M}$, the set $\text{Hom}_{\mathbb{M}}(M_0, M_1)$, with its given addition operation, and with the operations of composition, is a left module over the ring $\text{End}_{\mathbb{M}}(M_1)$, and a right module over the ring $\text{End}_{\mathbb{M}}(M_0)$. Furthermore, these left and right actions commute with each other.*

Proof. Exercise. □

This result can be reversed:

Example 2.1.4. Let A be a central \mathbb{K} -ring. Define a category \mathbb{M} like this: there is a single object M , and its set of morphisms is $\text{Hom}_{\mathbb{M}}(M, M) := A$. Composition in \mathbb{M} is the multiplication of A . Then \mathbb{M} is a \mathbb{K} -linear category.

Because of the above, in a linear category \mathbb{M} , we often denote the identity automorphism of an object M by $1_M := \text{id}_M \in \text{End}_{\mathbb{M}}(M)$.

For a central \mathbb{K} -ring A , the opposite ring A^{op} has the same \mathbb{K} -module structure as A , but the multiplication is reversed.

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Exercise 2.1.5. Let A be a nonzero ring. Let $P, Q \in \text{Mod } A$ be distinct free A -modules of rank 1.

- (1) Prove that there is a ring isomorphism $\text{End}_{\text{Mod } A}(P) \cong A^{\text{op}}$. Is this ring isomorphism canonical?
- (2) Let \mathcal{M} be the full subcategory of $\text{Mod } A$ on the set of objects $\{P, Q\}$. Compare the linear category \mathcal{M} to the ring of matrices $\text{Mats}_2(A^{\text{op}})$.

2.2. Additive Categories.

Definition 2.2.1. An *additive category* is a linear category \mathcal{M} satisfying these conditions:

- (i) \mathcal{M} has a zero object 0 .
- (ii) \mathcal{M} has finite coproducts.

Observe that $\text{Hom}_{\mathcal{M}}(M, N) \neq \emptyset$ for any $M, N \in \mathcal{M}$, since this is an abelian group. Also

$$\text{Hom}_{\mathcal{M}}(M, 0) = \text{Hom}_{\mathcal{M}}(0, M) = 0,$$

the zero abelian group. We denote the unique arrows $0 \rightarrow M$ and $M \rightarrow 0$ also by 0 . So the numeral 0 has a lot of meanings; but they are (hopefully) clear from the contexts. The coproduct in a linear category \mathcal{M} is usually denoted by \bigoplus ; cf. Example 1.4.2.

Example 2.2.2. Let A be a \mathbb{K} -central ring. The category $\text{Mod } A$ is a \mathbb{K} -linear additive category. The full subcategory $\mathcal{F} \subseteq \text{Mod } A$ on the free modules is also additive.

Proposition 2.2.3. *Let \mathcal{M} be a linear category. Let $\{M_i\}_{i \in I}$ be a finite collection of objects of \mathcal{M} , and assume the coproduct $M = \bigoplus_{i \in I} M_i$ exists, with embeddings $e_i : M_i \rightarrow M$.*

- (1) *For any i let $p_i : M \rightarrow M_i$ be the unique morphism s.t. $p_i \circ e_i = 1_{M_i}$, and $p_i \circ e_j = 0$ for $j \neq i$. Then $(M, \{p_i\}_{i \in I})$ is a product of the collection $\{M_i\}_{i \in I}$.*
- (2) $\sum_{i \in I} e_i \circ p_i = 1_M$.

Exercise 2.2.4. Prove this proposition.

Part (1) of Proposition 2.2.3 directly implies:

Corollary 2.2.5. *An additive category has finite products.*

Definition 2.2.6. Let \mathcal{M} be an additive category, and let \mathcal{N} be a full subcategory of \mathcal{M} . We say that \mathcal{N} is a *full additive subcategory* of \mathcal{M} if \mathcal{N} contains the zero object, and is closed under finite direct sums.

Exercise 2.2.7. In the situation of Definition 2.2.6, show that the category \mathcal{N} is itself additive.

Example 2.2.8. Consider the linear category \mathcal{M} from Example 2.1.4, built from a ring A . It does not have a zero object (unless the ring A is the zero ring), so it is not additive.

A more puzzling question is this: Does \mathcal{M} have finite direct sums? This turns out to be equivalent to whether or not $A \cong A \oplus A$ as right A -modules. To see why, choose a fully faithful additive functor $F : \mathcal{M} \rightarrow \text{Mod } A^{\text{op}}$, that sends the unique

object $M \in \mathbf{M}$ to a rank 1 free right A -module P . (We identify right A -modules with left A^{op} -modules.) Compare to Exercise 2.1.5.

Let $I := \{1, 2\}$, and let $\{M_i\}_{i \in I}$ be the only possible collection in \mathbf{M} indexed by I (i.e. $M_i = M$). If there is a coproduct in \mathbf{M} , then it must be $M_1 \oplus M_2 \cong M$. According to Proposition 2.4.2, we get

$$P \oplus P \cong F(M_1) \oplus F(M_2) \cong F(M) \cong P$$

in $\text{Mod } A^{\text{op}}$.

One can show that when A is nonzero and commutative, or nonzero and noetherian, then $A \not\cong A \oplus A$ in $\text{Mod } A^{\text{op}}$. On the other hand, if we take a field \mathbb{K} , and a countable rank \mathbb{K} -module N , then $A := \text{End}_{\mathbb{K}}(N)$ will satisfy $A \cong A \oplus A$.

Proposition 2.2.9. *Let \mathbf{M} be a linear category, and $N \in \mathbf{M}$. The following conditions are equivalent:*

- (i) *The ring $\text{End}_{\mathbf{M}}(N)$ is trivial.*
- (ii) *N is a zero object of \mathbf{M} .*

Proof. (ii) \Rightarrow (i): Since the set $\text{End}_{\mathbf{M}}(N)$ is a singleton, it must be the trivial ring ($1 = 0$).

(i) \Rightarrow (ii): If the ring $\text{End}_{\mathbf{M}}(N)$ is trivial, then all left and right modules over it must be trivial. Now use Proposition 2.1.3(2). \square

2.3. Abelian Categories.

Definition 2.3.1. Let \mathbf{M} be an additive category, and let $f : M \rightarrow N$ be a morphism in \mathbf{M} . A *kernel* of f is a pair (K, k) , consisting of an object $K \in \mathbf{M}$ and a morphism $k : K \rightarrow M$, with these properties:

- (i) $f \circ k = 0$.
- (ii) If $k' : K' \rightarrow M$ is a morphism in \mathbf{M} such that $f \circ k' = 0$, then there is a unique morphism $g : K' \rightarrow K$ such that $k' = k \circ g$.

In other words, the object K represents the functor $\text{Mod } \mathbf{M}^{\text{op}} \rightarrow \text{Ab}$,

$$K' \mapsto \{k' \in \text{Hom}_{\mathbf{M}}(K', M) \mid f \circ k' = 0\}.$$

The kernel of f is of course unique up to a unique isomorphism (if it exists), and we denote it by $\text{Ker}(f)$. Sometimes $\text{Ker}(f)$ refers only to the object K , and other times it refers only to the morphism k ; as usual, this should be clear from the context.

Definition 2.3.2. Let \mathbf{M} be an additive category, and let $f : M \rightarrow N$ be a morphism in \mathbf{M} . A *cokernel* of f is a pair (C, c) , consisting of an object $C \in \mathbf{M}$ and a morphism $c : N \rightarrow C$, with these properties:

- (i) $c \circ f = 0$.
- (ii) If $c' : N \rightarrow C'$ is a morphism in \mathbf{M} such that $c' \circ f = 0$, then there is a unique morphism $g : C \rightarrow C'$ such that $c' = g \circ c$.

In other words, the object C corepresents the functor $\mathbf{M} \rightarrow \text{Ab}$,

$$C' \mapsto \{c' \in \text{Hom}_{\mathbf{M}}(N, C') \mid c' \circ f = 0\}.$$

The cokernel of f is of course unique up to a unique isomorphism (if it exists), and we denote it by $\text{Coker}(f)$. Sometimes $\text{Coker}(f)$ refers only to the object C , and other times it refers only to the morphism c ; as usual, this should be clear from the context.

Example 2.3.3. In $\text{Mod } A$ all kernels and cokernels exist. Given $f : M \rightarrow N$, the kernel is $k : K \rightarrow M$, where

$$K := \{m \in M \mid f(m) = 0\},$$

and the k is the inclusion. The cokernel is $c : N \rightarrow C$, where $C := N/f(M)$, and c is the canonical projection.

Proposition 2.3.4. Let \mathbf{M} be an additive category, and let $f : M \rightarrow N$ be a morphism in \mathbf{M} .

- (1) If $k : K \rightarrow M$ is a kernel of f , then k is a monomorphism.
- (2) If $c : N \rightarrow C$ is a cokernel of f , then c is an epimorphism.

Proof. Exercise. □

Definition 2.3.5. Assume the additive category \mathbf{M} has kernels and cokernels. Let $f : M \rightarrow N$ be a morphism in \mathbf{M} .

- (1) Define the *image* of f to be

$$\text{Im}(f) := \text{Ker}(\text{Coker}(f)).$$

- (2) Define the *coimage* of f to be

$$\text{Coim}(f) := \text{Coker}(\text{Ker}(f)).$$

The image is familiar, but the coimage is not. The next diagram should help. We start with a morphism $f : M \rightarrow N$ in \mathbf{M} . The kernel and cokernel of f fit into this diagram:

$$K \xrightarrow{k} M \xrightarrow{f} N \xrightarrow{c} C.$$

Inserting $\alpha := \text{Coker}(k) = \text{Coim}(f)$ and $\beta := \text{Ker}(c) = \text{Im}(f)$ we get the following commutative diagram (solid arrows):

$$(2.3.6) \quad \begin{array}{ccccccc} K & \xrightarrow{k} & M & \xrightarrow{f} & N & \xrightarrow{c} & C \\ & \searrow & \downarrow \alpha & \searrow \gamma & \uparrow \beta & \nearrow & \\ & 0 & M' & \xrightarrow{f'} & N' & & \\ & & & & & & 0 \end{array}$$

Since $c \circ f = 0$ there is a unique morphism γ making the diagram commutative. Now $\beta \circ \gamma \circ k = f \circ k = 0$; and β is a monomorphism; so $\gamma \circ k = 0$. Hence there is a unique morphism $f' : M' \rightarrow N'$ making the diagram commutative. We conclude that $f : M \rightarrow N$ induces a morphism

$$(2.3.7) \quad f' : \text{Coim}(f) \rightarrow \text{Im}(f).$$

Definition 2.3.8. An *abelian category* is an additive category \mathbf{M} with these extra properties:

- (i) All morphisms in \mathbf{M} admit kernels and cokernels.
- (ii) For any morphism $f : M \rightarrow N$ in \mathbf{M} , the induced morphism f' in equation (2.3.7) is an isomorphism.

Here is a less precise but (maybe) easier to remember way to state property (ii). Because $M' = \text{Coker}(\text{Ker}(f))$ and $N' = \text{Ker}(\text{Coker}(f))$, we see that

$$(2.3.9) \quad \text{Coker}(\text{Ker}(f)) = \text{Ker}(\text{Coker}(f)).$$

From now on we forget all about the coimage.

Exercise 2.3.10. For any ring A , prove that the category $\text{Mod } A$ is abelian.

This includes the category $\text{Ab} = \text{Mod } \mathbb{Z}$, from which the name derives.

Definition 2.3.11. Let M be an abelian category, and let N be a full subcategory of M . We say that N is a *full abelian subcategory* of M if N is closed under finite direct sums, kernels and cokernels.

Exercise 2.3.12. In the situation of Definition 2.3.11, the category N is itself abelian.

Example 2.3.13. Let M_1 be the category of finitely generated abelian groups, and let M_0 be the category of finite abelian groups. Then M_1 is a full abelian subcategory of Ab , and M_0 is a full abelian subcategory of M_1 .

Exercise 2.3.14. Let N be the full subcategory of Ab whose objects are the finitely generated free abelian groups. It is an additive subcategory of Ab (since it is closed under direct sums).

- (1) Show that N is closed under kernels in Ab .
- (2) Show that N is not closed under cokernels in Ab , so it is not a full abelian subcategory of Ab .
- (3) Show that N has cokernels (not the same as those of Ab). Still, it fails to be an abelian category.

Exercise 2.3.15. The category Grp is not linear of course. Still, it does have a zero object (the trivial group). Show that Grp has kernels and cokernels, but condition (ii) of Definition 2.3.8 fails.

Exercise 2.3.16. Let Hilb be the category of Hilbert spaces over \mathbb{C} . The morphisms are the continuous \mathbb{C} -linear homomorphisms. Show that Hilb is a \mathbb{C} -linear additive category with kernels and cokernels, but it is not an abelian category.

Exercise 2.3.17. Let A be a ring. Show that A is *left noetherian* iff the category $\text{Mod}_f A$ of finitely generated left modules is a full abelian subcategory of $\text{Mod } A$.

Example 2.3.18. Let (X, \mathcal{A}) be a ringed space; namely X is a topological space and \mathcal{A} is a sheaf of rings on X (see [Har, Sections II.1-2]). We denote by $\text{PMod } \mathcal{A}$ the category of presheaves of left \mathcal{A} -modules on X . This is an abelian category. Given a morphism $f : \mathcal{M} \rightarrow \mathcal{N}$ in $\text{PMod } \mathcal{A}$, its kernel is the presheaf \mathcal{K} defined by

$$\Gamma(U, \mathcal{K}) := \text{Ker}(f : \Gamma(U, \mathcal{M}) \rightarrow \Gamma(U, \mathcal{N}))$$

on every open set $U \subseteq X$. The cokernel is the presheaf \mathcal{C} defined by

$$\Gamma(U, \mathcal{C}) := \text{Coker}(f : \Gamma(U, \mathcal{M}) \rightarrow \Gamma(U, \mathcal{N})).$$

Now let $\text{Mod } \mathcal{A}$ be the full subcategory of $\text{PMod } \mathcal{A}$ consisting of sheaves. It is a full additive subcategory of $\text{PMod } \mathcal{A}$, closed under kernels. We know that $\text{Mod } \mathcal{A}$ is not closed under cokernels inside $\text{PMod } \mathcal{A}$, and hence it is not a full abelian subcategory.

However $\text{Mod } \mathcal{A}$ is itself an abelian category, but with different cokernels. Indeed, for a morphism $f : \mathcal{M} \rightarrow \mathcal{N}$ in $\text{Mod } \mathcal{A}$, its cokernel $\text{Coker}_{\text{Mod } \mathcal{A}}(f)$ is the sheafification of the presheaf $\text{Coker}_{\text{PMod } \mathcal{A}}(f)$.

Here is a general result about abelian categories.

Theorem 2.3.19 (Freyd & Mitchell). *Let \mathcal{M} be a small abelian category. Then \mathcal{M} is equivalent to a full abelian subcategory of $\text{Mod } A$, for a suitable ring A .*

This means that most of the time we can pretend that $\mathcal{M} \subseteq \text{Mod } A$. This is a helpful heuristic; although in practice it is not a very useful fact.

Proposition 2.3.20. *Let \mathcal{M} be a linear category.*

- (1) *The opposite category \mathcal{M}^{op} has a canonical structure of linear category.*
- (2) *If \mathcal{M} is additive, then \mathcal{M}^{op} is also additive.*
- (3) *If \mathcal{M} is abelian, then \mathcal{M}^{op} is also abelian.*

Proof. (1) Since

$$\text{Hom}_{\mathcal{M}^{\text{op}}}(M, N) = \text{Hom}_{\mathcal{M}}(N, M),$$

this is an abelian group. The bilinearity of the composition in \mathcal{M}^{op} is clear.

(2) The zero objects in \mathcal{M} and \mathcal{M}^{op} are the same. Existence of finite coproducts in \mathcal{M}^{op} is because of existence of finite products in \mathcal{M} ; see Proposition 2.2.3(1).

(3) \mathcal{M}^{op} has kernels and cokernels, since $\text{Ker}_{\mathcal{M}^{\text{op}}}(f) = \text{Coker}_{\mathcal{M}}(f)$ and vice versa. Also the symmetric condition (ii) of Definition 2.3.8 holds. \square

Proposition 2.3.21. *Let $f : M \rightarrow N$ be a morphism in an abelian category \mathcal{M} .*

- (1) *f is a monomorphism iff $\text{Ker}(f) = 0$.*
- (2) *f is an epimorphism iff $\text{Coker}(f) = 0$.*
- (3) *f is an isomorphism iff it is both a monomorphism and an epimorphism.*

Exercise 2.3.22. Prove this proposition.

2.4. Additive Functors.

Definition 2.4.1. Let \mathcal{M} and \mathcal{N} be \mathbb{K} -linear categories. A functor $F : \mathcal{M} \rightarrow \mathcal{N}$ is called a \mathbb{K} -linear functor if for every $M_0, M_1 \in \mathcal{M}$ the function

$$F : \text{Hom}_{\mathcal{M}}(M_0, M_1) \rightarrow \text{Hom}_{\mathcal{N}}(F(M_0), F(M_1))$$

is a \mathbb{K} -linear homomorphism.

A \mathbb{Z} -linear functor is also called an *additive functor*.

Additive functors commute with finite direct sums. More precisely:

Proposition 2.4.2. *Let $F : \mathcal{M} \rightarrow \mathcal{N}$ be an additive functor between linear categories, let $\{M_i\}_{i \in I}$ be a finite collection of objects of \mathcal{M} , and assume that the direct sum $(M, \{e_i\}_{i \in I})$ of the collection $\{M_i\}_{i \in I}$ exists in \mathcal{M} . Then $(F(M), \{F(e_i)\}_{i \in I})$ is a direct sum of the collection $\{F(M_i)\}_{i \in I}$ in \mathcal{N} .*

Exercise 2.4.3. Prove Proposition 2.4.2. (Hint: use Proposition 2.2.3.)

Note that the proposition above also talks about finite products, because of Proposition 2.2.3.

Example 2.4.4. Let $f : A \rightarrow B$ be a ring homomorphism. The forgetful functor

$$\text{Res}_f : \text{Mod } B \rightarrow \text{Mod } A,$$

called restriction of scalars, is additive. The induction functor

$$\text{Ind}_f : \text{Mod } A \rightarrow \text{Mod } B,$$

sometimes called extension of scalars, defined by $\text{Ind}_f(M) := B \otimes_A M$, is also additive.

Proposition 2.4.5. *Let $F : \mathbf{M} \rightarrow \mathbf{N}$ be an additive functor between linear categories. Then:*

- (1) *For any $M \in \mathbf{M}$ the function*

$$F : \text{End}_{\mathbf{M}}(M) \rightarrow \text{End}_{\mathbf{N}}(F(M))$$

is a ring homomorphism.

- (2) *For any $M_0, M_1 \in \mathbf{M}$ the function*

$$F : \text{Hom}_{\mathbf{M}}(M_0, M_1) \rightarrow \text{Hom}_{\mathbf{N}}(F(M_0), F(M_1))$$

is a homomorphism of left $\text{End}_{\mathbf{M}}(M_1)$ -modules, and of right $\text{End}_{\mathbf{M}}(M_0)$ -modules.

- (3) *If M is a zero object of \mathbf{M} , then $F(M)$ is a zero object of \mathbf{N} .*

Proof. (1) By Definition 2.4.1 the function F respects addition. By the definition of a functor, it respects multiplication and units.

(2) Immediate from the definitions, like (1).

(3) Combine part (1) with Proposition 2.2.9. □

Definition 2.4.6. Let $F : \mathbf{M} \rightarrow \mathbf{N}$ be an additive functor between abelian categories.

- (1) F is called *left exact* if it commutes with kernels. Namely for any morphism $\phi : M_0 \rightarrow M_1$ in \mathbf{M} , with kernel $k : K \rightarrow M_0$, the morphism $F(k) : F(K) \rightarrow F(M_0)$ is a kernel of $F(\phi) : F(M_0) \rightarrow F(M_1)$.
- (2) F is called *right exact* if it commutes with cokernels. Namely for any morphism $\phi : M_0 \rightarrow M_1$ in \mathbf{M} , with cokernel $c : M_1 \rightarrow C$, the morphism $F(c) : F(M_1) \rightarrow F(C)$ is a cokernel of $F(\phi) : F(M_0) \rightarrow F(M_1)$.
- (3) F is called *exact* if it is both left exact and right exact.

This is illustrated in the following diagrams. Suppose $\phi : M_0 \rightarrow M_1$ is a morphism in \mathbf{M} , with kernel K and cokernel C . Applying F to the diagram

$$K \xrightarrow{k} M_0 \xrightarrow{\phi} M_1 \xrightarrow{c} C$$

we get the solid arrows in

$$\begin{array}{ccccccc}
 F(K) & \xrightarrow{F(k)} & F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{F(c)} & F(C) \\
 & \searrow \psi & \uparrow & & \downarrow & & \nearrow \chi \\
 & & \text{Ker}_{\mathbf{N}}(F(\phi)) & & \text{Coker}_{\mathbf{N}}(F(\phi)) & &
 \end{array}$$

Because \mathbf{N} is abelian, we get the vertical dashed arrows: the kernel and cokernel of $F(\phi)$. The slanted dashed arrows exist and are unique because $F(\phi) \circ F(k) = 0$ and $F(c) \circ F(\phi) = 0$. Left exactness requires ψ to be an isomorphism, and right exactness requires χ to be an isomorphism.

Definition 2.4.7. Let \mathbf{M} be an abelian category. An *exact sequence* in \mathbf{M} is a diagram

$$\dots \rightarrow M_0 \xrightarrow{\phi_0} M_1 \xrightarrow{\phi_1} M_2 \rightarrow \dots$$

(finite or infinite on either side), such that for every index i for which ϕ_{i-1} and ϕ_i are both defined, the composition $\phi_i \circ \phi_{i-1}$ is zero, and the induced morphism $\text{Im}(\phi_{i-1}) \rightarrow \text{Ker}(\phi_i)$ is an isomorphism.

A *short exact sequence* is an exact sequence of the form

$$(2.4.8) \quad 0 \rightarrow M_0 \xrightarrow{\phi_0} M_1 \xrightarrow{\phi_1} M_2 \rightarrow 0.$$

Proposition 2.4.9. *Let $F : \mathbf{M} \rightarrow \mathbf{N}$ be an additive functor between abelian categories.*

- (1) *The functor F is left exact iff for every short exact sequence (2.4.8) in \mathbf{M} , the sequence*

$$0 \rightarrow F(M_0) \xrightarrow{F(\phi_0)} F(M_1) \xrightarrow{F(\phi_1)} F(M_2)$$

is exact in \mathbf{N} .

- (2) *The functor F is right exact iff for every short exact sequence (2.4.8) in \mathbf{M} , the sequence*

$$F(M_0) \xrightarrow{F(\phi_0)} F(M_1) \xrightarrow{F(\phi_1)} F(M_2) \rightarrow 0$$

is exact in \mathbf{N} .

Exercise 2.4.10. Prove Proposition 2.4.9. (Hint: $M_0 \cong \text{Ker}(M_1 \rightarrow M_2)$ etc.)

Example 2.4.11. Let A be a commutative ring, and let M be a fixed A -module. Define functors $F, G : \text{Mod } A \rightarrow \text{Mod } A$ and $H : (\text{Mod } A)^{\text{op}} \rightarrow \text{Mod } A$ like this: $F(N) := M \otimes_A N$, $G(N) := \text{Hom}_A(M, N)$ and $H(N) := \text{Hom}_A(N, M)$. Then F is right exact, and G and H are left exact.

Proposition 2.4.12. *Let $F : \mathbf{M} \rightarrow \mathbf{N}$ be an additive functor between abelian categories. If F is an equivalence then it is exact.*

Proof. We will prove that F respects kernels; the proof for cokernels is similar. Take a morphism $\phi : M_0 \rightarrow M_1$ in \mathbf{M} , with kernel K . We have this diagram (solid arrows):

$$\begin{array}{ccccc} M & & & & \\ | & \searrow & \theta & & \\ \psi \downarrow & & & & \\ K & \xrightarrow{k} & M_0 & \xrightarrow{\phi} & M_1 \end{array}$$

Applying F we obtain this diagram (solid arrows):

$$\begin{array}{ccccc} N = F(M) & & & & \\ | & \searrow & \bar{\theta} & & \\ F(\psi) \downarrow & & & & \\ F(K) & \xrightarrow{F(k)} & F(M_0) & \xrightarrow{F(\phi)} & F(M_1) \end{array}$$

in \mathbf{N} . Suppose $\bar{\theta} : N \rightarrow F(M_0)$ is a morphism in \mathbf{N} s.t. $F(\phi) \circ \bar{\theta} = 0$. Since F is essentially surjective on objects, there is some $M \in \mathbf{M}$ with an isomorphism $\alpha : F(M) \xrightarrow{\cong} N$. After replacing N with $F(M)$ and $\bar{\theta}$ with $\bar{\theta} \circ \alpha$, we can assume that $N = F(M)$.

Now since F is fully faithful, there is a unique $\theta : M \rightarrow M_0$ s.t. $F(\theta) = \bar{\theta}$; and $\phi \circ \theta = 0$. So there is a unique $\psi : M \rightarrow K$ s.t. $\theta = k \circ \psi$. It follows that $F(\psi) : F(M) \rightarrow F(K)$ is the unique morphism s.t. $\bar{\theta} = F(k) \circ F(\psi)$. \square

Here is a result that could afford another proof of the previous proposition.

Proposition 2.4.13. *Let $F : \mathcal{M} \rightarrow \mathcal{N}$ be an additive functor between linear categories. Assume F is an equivalence, with quasi-inverse G . Then $G : \mathcal{N} \rightarrow \mathcal{M}$ is an additive functor.*

Exercise 2.4.14. Prove Proposition 2.4.13.

We end this subsection with a discussion of contravariant functors. Suppose \mathcal{M} and \mathcal{N} are linear categories. A contravariant functor $F : \mathcal{M} \rightarrow \mathcal{N}$ is said to be additive if it satisfies the condition in Definition 2.4.1, with the obvious changes.

Proposition 2.4.15. *Let \mathcal{M} and \mathcal{N} be linear categories. Put on \mathcal{M}^{op} the canonical linear structure (see Proposition 2.3.20).*

- (1) *The functor $\text{Op} : \mathcal{M} \rightarrow \mathcal{M}^{\text{op}}$ is an additive contravariant functor.*
- (2) *If $F : \mathcal{M} \rightarrow \mathcal{N}$ is an additive contravariant functor, then $F \circ \text{Op} : \mathcal{M}^{\text{op}} \rightarrow \mathcal{N}$ is an additive functor; and vice versa.*

Exercise 2.4.16. Prove Proposition 2.4.15.

In view of Proposition 2.4.9, we can give an unambiguous definition of left and right exact contravariant functors. Let $F : \mathcal{M} \rightarrow \mathcal{N}$ be an additive contravariant functor between abelian categories. We call F a *left exact contravariant functor* if for any short exact sequence (2.4.8) in \mathcal{M} , the sequence

$$0 \rightarrow F(M_2) \xrightarrow{F(\phi_1)} F(M_1) \xrightarrow{F(\phi_0)} F(M_0)$$

in \mathcal{N} is exact. The functor is a *right exact contravariant functor* if the same holds, except that the 0 is on the right side. And F is an *exact contravariant functor* if it sends any short exact sequence (2.4.8) to a short exact sequence.

Proposition 2.4.17. *Let \mathcal{M} and \mathcal{N} be abelian categories. Recall that \mathcal{M}^{op} is also an abelian category.*

- (1) *The functor $\text{Op} : \mathcal{M} \rightarrow \mathcal{M}^{\text{op}}$ is an exact contravariant functor.*
- (2) *If $F : \mathcal{M} \rightarrow \mathcal{N}$ is an exact contravariant functor, then $F \circ \text{Op} : \mathcal{M}^{\text{op}} \rightarrow \mathcal{N}$ is an exact functor; and vice versa. Likewise for left exactness and right exactness.*

Exercise 2.4.18. Prove Proposition 2.4.17.

Sometimes \mathcal{M} and \mathcal{M}^{op} are equivalent as abelian categories, as the next exercise shows. For a counterexample see Remark 2.6.21 below.

Exercise 2.4.19. Let \mathbb{K} be a field, and consider the category $\mathcal{M} := \text{Mod}_f \mathbb{K}$ of finitely generated \mathbb{K} -modules (traditionally known as “finite dimensional vector spaces over \mathbb{K} ”). This is a \mathbb{K} -linear abelian category. Find a \mathbb{K} -linear equivalence $F : \mathcal{M}^{\text{op}} \rightarrow \mathcal{M}$.

2.5. Projective Objects. In this subsection \mathcal{M} is an abelian category.

A *splitting* of an epimorphism $\psi : M \rightarrow M''$ in \mathcal{M} is a morphism $\alpha : M'' \rightarrow M$ s.t. $\psi \circ \alpha = 1_{M''}$. A splitting of a monomorphism $\phi : M' \rightarrow M$ is a morphism $\beta : M \rightarrow M'$ s.t. $\beta \circ \phi = 1_{M'}$. A splitting of a short exact sequence

$$(2.5.1) \quad 0 \rightarrow M' \xrightarrow{\phi} M \xrightarrow{\psi} M'' \rightarrow 0$$

is a splitting of the epimorphism ψ , or equivalently a splitting of the monomorphism ϕ . The short exact sequence is said to be *split* if it has some splitting.

Exercise 2.5.2. Show how to get from a splitting of ϕ to a splitting of ψ , and vice versa. Show how any of those gives rise to an isomorphism $M \cong M' \oplus M''$.

Definition 2.5.3. An object $P \in \mathbf{M}$ is called a *projective object* if for any morphism $\gamma : P \rightarrow N$ and any *epimorphism* $\psi : M \twoheadrightarrow N$, there exists a morphism $\tilde{\gamma} : P \rightarrow M$ such that $\psi \circ \tilde{\gamma} = \gamma$.

This is described in the following commutative diagram in \mathbf{M} :

$$\begin{array}{ccc}
 & & P \\
 & \nearrow \tilde{\gamma} & \downarrow \gamma \\
 M & \xrightarrow{\psi} & N
 \end{array}$$

Proposition 2.5.4. *The following conditions are equivalent for $P \in \mathbf{M}$:*

- (i) P is projective.
- (ii) The additive functor

$$\mathrm{Hom}_{\mathbf{M}}(P, -) : \mathbf{M} \rightarrow \mathbf{Ab}$$

is exact.

- (iii) Any short exact sequence (2.5.1) with $M'' = P$ is split.

Proof. Exercise. □

Definition 2.5.5. We say \mathbf{M} has enough projectives if every $M \in \mathbf{M}$ admits an epimorphism $P \rightarrow M$ from a projective object P .

Exercise 2.5.6. Let A be a ring.

- (1) Prove that an A -module P is projective iff it is a direct summand of a free module; i.e. $P \oplus P' \cong Q$ for some module P' and free module Q .
- (2) Prove that the category $\mathbf{Mod} A$ has enough projectives.

Exercise 2.5.7. Let \mathbf{M} be the category of finite abelian groups. Prove that the only projective object in \mathbf{M} is 0. So \mathbf{M} does not have enough projectives. (Hint: use Proposition 2.5.4.)

Example 2.5.8. Consider the scheme $X := \mathbf{P}_{\mathbb{K}}^1$, the projective line over a field \mathbb{K} . (If the reader prefers, he/she can assume \mathbb{K} is algebraically closed, so X is a classical algebraic variety.) The structure sheaf (sheaf of functions) is \mathcal{O}_X . The category $\mathbf{Coh} \mathcal{O}_X$ of coherent \mathcal{O}_X -modules is abelian (it is a full abelian subcategory of $\mathbf{Mod} \mathcal{O}_X$, cf. Example 2.3.18). One can show that the only projective object of $\mathbf{Coh} \mathcal{O}_X$ is 0, but this is quite involved.

Let us only indicate why \mathcal{O}_X is not projective. Denote by t_0, t_1 the homogeneous coordinates of X . These belong to $\Gamma(X, \mathcal{O}_X(1))$, so each determines a homomorphism of sheaves $t_j : \mathcal{O}_X(i) \rightarrow \mathcal{O}_X(i+1)$. We get a sequence

$$0 \rightarrow \mathcal{O}_X(-2) \xrightarrow{\begin{bmatrix} t_0 & t_1 \end{bmatrix}} \mathcal{O}_X(-1)^2 \xrightarrow{\begin{bmatrix} -t_1 \\ t_0 \end{bmatrix}} \mathcal{O}_X \rightarrow 0$$

in $\mathbf{Coh} \mathcal{O}_X$, which is known to be exact. Because $\Gamma(X, \mathcal{O}_X) = \mathbb{K}$, and $\Gamma(X, \mathcal{O}_X(-1)) = 0$, this sequence is not split.

2.6. Injective Objects. In this subsection \mathbf{M} is an abelian category.

Definition 2.6.1. An object $I \in \mathbf{M}$ is called an *injective object* if for any morphism $\gamma : M \rightarrow I$ and any *monomorphism* $\psi : M \hookrightarrow N$, there exists a morphism $\tilde{\gamma} : N \rightarrow I$ such that $\tilde{\gamma} \circ \psi = \gamma$.

This is depicted in the following commutative diagram in \mathbf{M} :

$$\begin{array}{ccc}
 & I & \\
 \gamma \uparrow & \swarrow \tilde{\gamma} & \\
 M & \xrightarrow{\psi} & N
 \end{array}$$

Proposition 2.6.2. *The following conditions are equivalent for $I \in \mathbf{M}$:*

- (i) *I is injective.*
- (ii) *The additive functor*

$$\text{Hom}_{\mathbf{M}}(-, I) : \mathbf{M}^{\text{op}} \rightarrow \mathbf{Ab}$$

is exact.

- (iii) *Any short exact sequence (2.5.1) with $M' = I$ is split.*

Exercise 2.6.3. Prove Proposition 2.6.2.

Recall that $\text{Op} : \mathbf{M} \rightarrow \mathbf{M}^{\text{op}}$ is an exact functor.

Proposition 2.6.4. *An object $J \in \mathbf{M}$ is injective if and only if the object $\text{Op}(J) \in \mathbf{M}^{\text{op}}$ is projective.*

Exercise 2.6.5. Prove Proposition 2.6.4.

Example 2.6.6. Let A be a ring. Unlike projectives, the structure of injective objects in $\text{Mod } A$ is very complicated, and not much is known (except that they exist). However if A is a commutative noetherian ring then we know this: every injective module I is a direct sum of indecomposable injective modules; and the indecomposables are parametrized by $\text{Spec } A$, the set of prime ideals of A . These facts are due to Matlis; see Subsection 14.3 in the book.

Definition 2.6.7. We say \mathbf{M} *has enough injectives* if every $M \in \mathbf{M}$ admits a monomorphism $M \rightarrow I$ to an injective object I .

Here are a few results about injective objects. Recall that modules over a ring are always left modules by default.

Proposition 2.6.8. *Let $f : A \rightarrow B$ be a ring homomorphism, and let I be an injective A -module. Then $J := \text{Hom}_A(B, I)$ is an injective B -module.*

Proof. Note that B is a left A -module via f , and a right B -module. This makes J into a left B -module. In a formula: for $\phi \in J$ and $b, b' \in B$ we have $(b \cdot \phi)(b') = \phi(b' \cdot b)$.

Now given any $N \in \text{Mod } B$ there is an isomorphism

$$(2.6.9) \quad \text{Hom}_B(N, J) = \text{Hom}_B(N, \text{Hom}_A(B, I)) \cong \text{Hom}_A(N, I).$$

This is a natural isomorphism (of functors in N). So the functor $\text{Hom}_B(-, J)$ is exact, and hence J is injective. \square

Theorem 2.6.10 (Baer Criterion). *Let A be a ring and I an A -module. Assume that every A -module homomorphism $\mathfrak{a} \rightarrow I$ from a left ideal $\mathfrak{a} \subseteq A$ extends to a homomorphism $A \rightarrow I$. Then the module I is injective.*

Proof. Consider an A -module M , a submodule $N \subseteq M$, and a homomorphism $\gamma : N \rightarrow I$. We have to prove that γ extends to a homomorphism $M \rightarrow I$. Look at the pairs (N', γ') consisting of a submodule $N' \subseteq M$ that contains N , and a homomorphism $\gamma' : N' \rightarrow I$ that extends γ . The set of all such pairs is ordered by inclusion, and it satisfies the conditions of Zorn's Lemma. Therefore there exists a maximal pair (N', γ') . We claim that $N' = M$.

Otherwise, there is an element $m \in M$ that does not belong to N' . Define $N'' := N' + A \cdot m$, so $N' \subsetneq N'' \subseteq M$. Let

$$\mathfrak{a} := \{a \in A \mid a \cdot m \in N'\},$$

which is a left ideal of A . There is a short exact sequence

$$0 \rightarrow \mathfrak{a} \xrightarrow{\alpha} N' \oplus A \rightarrow N'' \rightarrow 0$$

of A -modules, where $\alpha(a) := (a \cdot m, -a)$. Let $\phi : \mathfrak{a} \rightarrow I$ be the homomorphism $\phi(a) := \gamma'(a \cdot m)$. By assumption, it extends to a homomorphism $\tilde{\phi} : A \rightarrow I$. We get a homomorphism

$$\gamma' + \tilde{\phi} : N' \oplus A \rightarrow I$$

that vanishes on the image of α . Thus there is an induced homomorphism $\gamma'' : N'' \rightarrow I$. This contradicts the maximality of (N', γ') . \square

Lemma 2.6.11. *The \mathbb{Z} -module \mathbb{Q}/\mathbb{Z} is injective.*

Proof. By the Baer criterion, it is enough to consider a homomorphism $\gamma : \mathfrak{a} \rightarrow \mathbb{Q}/\mathbb{Z}$ for an ideal $\mathfrak{a} = n \cdot \mathbb{Z} \subseteq \mathbb{Z}$. We may assume that $n \neq 0$. Say $\gamma(n) = r + \mathbb{Z}$ with $r \in \mathbb{Q}$. Then we can extend γ to $\tilde{\gamma} : \mathbb{Z} \rightarrow \mathbb{Q}/\mathbb{Z}$ with $\tilde{\gamma}(1) := r/n + \mathbb{Z}$. \square

Lemma 2.6.12. *Let $\{I_x\}_{x \in X}$ be a collection of injective objects of \mathbf{M} . If the product $\prod_{x \in X} I_x$ exists in \mathbf{M} , then it is an injective object.*

Proof. Exercise. \square

Theorem 2.6.13. *Let A be any ring. The category $\text{Mod } A$ has enough injectives.*

Proof. Step 1. Here $A = \mathbb{Z}$. Take any nonzero \mathbb{Z} -module M and any nonzero $m \in M$. Consider the cyclic submodule $M' := \mathbb{Z} \cdot m \subseteq M$. There is a homomorphism $\gamma' : M' \rightarrow \mathbb{Q}/\mathbb{Z}$ s.t. $\gamma'(m) \neq 0$. Indeed, if $M' \cong \mathbb{Z}$, then we take any $r \in \mathbb{Q} - \mathbb{Z}$; and if $M' \cong \mathbb{Z}/(n)$ for some $n > 0$, then we take $r := 1/n$. In either case, we define $\gamma'(m) := r + \mathbb{Z} \in \mathbb{Q}/\mathbb{Z}$. Since \mathbb{Q}/\mathbb{Z} is an injective \mathbb{Z} -module, γ' extends to a homomorphism $\gamma : M \rightarrow \mathbb{Q}/\mathbb{Z}$. By construction we have $\gamma(m) \neq 0$.

Step 2. Now A is any ring, M is any nonzero A -module, and $m \in M$ a nonzero element. Define the A -module $I := \text{Hom}_{\mathbb{Z}}(A, \mathbb{Q}/\mathbb{Z})$, which, according to Lemma 2.6.11 and Proposition 2.6.8, is an injective A -module. Let $\gamma : M \rightarrow \mathbb{Q}/\mathbb{Z}$ be a \mathbb{Z} -linear homomorphism such that $\gamma(m) \neq 0$. Such γ exists by step 1. Let $\theta : I \rightarrow \mathbb{Q}/\mathbb{Z}$ be the \mathbb{Z} -linear homomorphism that sends an element $\chi \in I$ to $\chi(1) \in \mathbb{Q}/\mathbb{Z}$. The adjunction formula (2.6.9) gives an A -module homomorphism $\psi : M \rightarrow I$ s.t. $\theta \circ \psi = \gamma$. We note that $(\theta \circ \psi)(m) = \gamma(m) \neq 0$, and hence $\psi(m) \neq 0$.

Step 3. Here A and M are arbitrary. Let I be as in step 2. For any nonzero $m \in M$ there is an A -linear homomorphism $\psi_m : M \rightarrow I$ such that $\psi_m(m) \neq 0$.

For $m = 0$ let $\psi_0 : M \rightarrow I$ be an arbitrary homomorphism (e.g. $\psi_0 = 0$). Define the A -module $J := \prod_{m \in M} I$. There is a homomorphism $\psi := \prod_{m \in M} \psi_m : M \rightarrow J$, and it is easy to check that ψ is a monomorphism. By Lemma 2.6.12, J is an injective A -module. \square

Exercise 2.6.14. At the price of getting a bigger injective module, we can make the construction of injective resolutions functorial. Let $I := \text{Hom}_{\mathbb{Z}}(A, \mathbb{Q}/\mathbb{Z})$ as above. Given an A -module M , consider the set

$$X(M) := \text{Hom}_A(M, I) \cong \text{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}).$$

Let $J(M) := \prod_{\psi \in X(M)} I$. There is a “tautological” homomorphism $\phi_M : M \rightarrow J(M)$. Show that ϕ_M is a monomorphism, $J : M \mapsto J(M)$ is a functor, and $\phi : \text{Id} \rightarrow J$ is a natural transformation.

Is the functor $J : \text{Mod } A \rightarrow \text{Mod } A$ additive?

Example 2.6.15. Let \mathbf{N} be the category of torsion abelian groups, and \mathbf{M} the category of finite abelian groups. Then $\mathbf{N} \subseteq \mathbf{Ab}$ and $\mathbf{M} \subseteq \mathbf{N}$ are full abelian subcategories. \mathbf{M} has no projectives nor injectives except 0 (see Exercise 2.5.7 regarding projectives). The only projective in \mathbf{N} is 0. However, it can be shown that \mathbf{N} has enough injectives; see [Har, Lemma III.3.2] or [Ye1, Proposition 4.6].

Proposition 2.6.16. *If A is a left noetherian ring, then any direct sum of injective A -modules is an injective module.*

Exercise 2.6.17. Prove Proposition 2.6.16. (Hint: use the Baer criterion.)

Exercise 2.6.18. Here we study injectives in the category $\mathbf{Ab} = \text{Mod } \mathbb{Z}$. By Lemma 2.6.11, the module $I := \mathbb{Q}/\mathbb{Z}$ is injective. For a (positive) prime number p , we denote by $\widehat{\mathbb{Z}}_p$ the ring of p -adic integers, and by $\widehat{\mathbb{Q}}_p$ its field of fractions (namely the p -adic completions of \mathbb{Z} and \mathbb{Q} respectively). Define the abelian group $I_p := \widehat{\mathbb{Q}}_p/\widehat{\mathbb{Z}}_p$.

- (1) Show that I_p is an injective object of \mathbf{Ab} .
- (2) Show that I_p is indecomposable (i.e. it is not the direct sum of two nonzero objects).
- (3) Show that $I \cong \bigoplus_p I_p$.
- (4) The theory (see Subsection 14.3) tells us that there is another indecomposable injective object in \mathbf{Ab} , besides the I_p . Try to identify it.

Remark 2.6.19. Let \mathbb{K} be a field and $A := \mathbb{K}[t]$, the polynomial ring in one variable. As we very well know, the categories $\text{Mod } A$ and $\text{Mod } \mathbb{Z}$ share many properties. Let $A^* := \text{Hom}_{\mathbb{K}}(A, \mathbb{K})$, which is an injective A -module (because \mathbb{K} is an injective \mathbb{K} -module). The structure of A^* , as a direct sum of indecomposable injectives, was used to cook up a counterexample in [Ye5, Section 6].

The abelian category $\text{Mod } \mathcal{A}$ associated to a ringed space (X, \mathcal{A}) was introduced in Example 2.3.18.

Proposition 2.6.20. *Let (X, \mathcal{A}) be a ringed space. The category $\text{Mod } \mathcal{A}$ has enough injectives.*

Proof. Let \mathcal{M} be an \mathcal{A} -module. Take a point $x \in X$. The stalk \mathcal{M}_x is a module over the ring \mathcal{A}_x , and by Theorem 2.6.13 we can find an embedding $\phi_x : \mathcal{M}_x \rightarrow I_x$ into an injective \mathcal{A}_x -module. Let $g_x : \{x\} \rightarrow X$ be the inclusion, which we may view as a map of ringed spaces from $(\{x\}, \mathcal{A}_x)$ to (X, \mathcal{A}) . Define $\mathcal{I}_x := g_{x*}(I_x)$, which is

an \mathcal{A} -module (in fact it is a constant sheaf supported on the closed set $\overline{\{x\}} \subseteq X$). The adjunction formula gives rise to a sheaf homomorphism $\psi_x : \mathcal{M} \rightarrow \mathcal{I}_x$. Since the functor $g_x^* : \text{Mod } \mathcal{A} \rightarrow \text{Mod } \mathcal{A}_x$ is exact, the adjunction formula shows that \mathcal{I}_x is an injective object of $\text{Mod } \mathcal{A}$.

Finally let $\mathcal{J} := \prod_{x \in X} \mathcal{I}_x$. This is an injective \mathcal{A} -module. There is a homomorphism $\psi := \prod_{x \in X} \psi_x : \mathcal{M} \rightarrow \mathcal{J}$ in $\text{Mod } \mathcal{A}$. This is a monomorphism, since for every point x , letting \mathcal{J}_x be the stalk of the sheaf \mathcal{J} at x , the composition $\mathcal{M}_x \xrightarrow{\psi_x} \mathcal{J}_x \xrightarrow{p_x} \mathcal{I}_x$ is the embedding $\phi_x : \mathcal{M}_x \rightarrow \mathcal{I}_x$. \square

Remark 2.6.21. Let A be a ring, and consider the abelian category $\mathbf{M} = \text{Mod } A$, the category of A -modules. A reasonable question to ask is this: Are the abelian categories \mathbf{M} and \mathbf{M}^{op} equivalent? The answer is most likely negative, but we do not know a reference for it.

We do know that this is false for $A = \mathbb{Z}$. Note that in this case $\text{Mod } \mathbb{Z} = \text{Ab}$. Here is a proof that there does not exist an additive equivalence $F : \text{Ab}^{\text{op}} \rightarrow \text{Ab}$. Suppose we had such an equivalence. Consider the object $M := \mathbb{Z} \in \text{Ab}$, and let $N := F(M) \in \text{Ab}$. Because M is an indecomposable projective object, and $F : \text{Ab} \rightarrow \text{Ab}$ is a contravariant equivalence, the object N has to be an indecomposable injective. The endomorphism rings are

$$\text{End}_{\text{Ab}}(N) \cong \text{End}_{\text{Ab}}(M)^{\text{op}} = \mathbb{Z}^{\text{op}} = \mathbb{Z}.$$

However, the structure theorem for injectives over commutative noetherian rings (Theorem 14.3.14) says that the only indecomposable injectives in $\text{Mod } \mathbb{Z} = \text{Ab}$ are $N = \widehat{\mathbb{Q}}_p / \widehat{\mathbb{Z}}_p$ and $N = \mathbb{Q}$; and their endomorphism rings are $\widehat{\mathbb{Z}}_p$ and \mathbb{Q} respectively.

3. DIFFERENTIAL GRADED ALGEBRA

In this section we fix a nonzero commutative base ring \mathbb{K} (e.g. the ring of integers \mathbb{Z} or a field). Throughout, “DG” stands for “differential graded”.

There is some material about DG algebra in a few published references, such as the book [Mac1] and the papers [Kel] and [To]. However, for our purposes we need a much more detailed understanding of this theory, and this is what the present section provides.

3.1. Graded Algebra. Before entering the DG world, it is good to understand the graded world.

A *graded \mathbb{K} -module* is a \mathbb{K} -module M equipped with a decomposition $M = \bigoplus_{i \in \mathbb{Z}} M^i$ into \mathbb{K} -submodules. The \mathbb{K} -module M^i is called the degree i component of M . The elements of M^i are called homogeneous elements of degree i .

Suppose M and N are graded \mathbb{K} -modules. For any integer i let

$$(M \otimes_{\mathbb{K}} N)^i := \bigoplus_{j \in \mathbb{Z}} (M^j \otimes_{\mathbb{K}} N^{i-j}).$$

Then

$$(3.1.1) \quad M \otimes_{\mathbb{K}} N = \bigoplus_{i \in \mathbb{Z}} (M \otimes_{\mathbb{K}} N)^i,$$

is a graded \mathbb{K} -module.

A \mathbb{K} -linear homomorphism $\phi : M \rightarrow N$ is said to be of degree i if $\phi(M^j) \subseteq N^{j+i}$ for all j . We denote by $\text{Hom}_{\mathbb{K}}(M, N)^i$ the \mathbb{K} -module of degree i homomorphisms $M \rightarrow N$. In other words

$$\text{Hom}_{\mathbb{K}}(M, N)^i = \prod_{j \in \mathbb{Z}} \text{Hom}_{\mathbb{K}}(M^j, N^{j+i}).$$

Then

$$(3.1.2) \quad \text{Hom}_{\mathbb{K}}(M, N) := \bigoplus_{i \in \mathbb{Z}} \text{Hom}_{\mathbb{K}}(M, N)^i$$

is a graded \mathbb{K} -module. A degree 0 homomorphism $\phi : M \rightarrow N$ is sometimes called a *strict homomorphism of graded \mathbb{K} -modules*.

If M_0, M_1, M_2 are graded \mathbb{K} -modules, and $\phi_k : M_{k-1} \rightarrow M_k$ are \mathbb{K} -linear homomorphisms of degrees i_k , then $\phi_2 \circ \phi_1 : M_0 \rightarrow M_2$ is a \mathbb{K} -linear homomorphism of degree $i_1 + i_2$. The identity automorphism $1_M : M \rightarrow M$ has degree 0.

A *graded ring* is a ring A , equipped with a decomposition as an abelian group $A = \bigoplus_{i \in \mathbb{Z}} A^i$, such that the unit element $1 \in A^0$, and $A^i \cdot A^j \subseteq A^{i+j}$. A *central graded \mathbb{K} -ring* is a graded ring A , together with a ring homomorphism $\mathbb{K} \rightarrow A^0$, such that the image of \mathbb{K} is central in A (i.e. $\lambda \cdot a = a \cdot \lambda$ for all $\lambda \in \mathbb{K}$ and $a \in A$). A *homomorphism of central graded \mathbb{K} -rings* $f : A \rightarrow B$ is a ring homomorphism that respects the gradings and the homomorphisms from \mathbb{K} . As always for ring homomorphisms, f must preserve units, i.e. $f(1_A) = 1_B$.

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Example 3.1.3. Let M be a graded \mathbb{K} -module. Then the graded module

$$\text{End}_{\mathbb{K}}(M) := \text{Hom}_{\mathbb{K}}(M, M),$$

with the operation of composition, is a central graded \mathbb{K} -ring.

Let A be a graded ring. A pair of homogeneous elements $a \in A^i$ and $b \in A^j$ are said to *graded-commute* with each other if

$$(3.1.4) \quad b \cdot a = (-1)^{i \cdot j} \cdot a \cdot b.$$

This formula is the prototype of the *Koszul sign rule*, which is a heuristic that helps generate consistent multilinear formulas in the graded setting. The Koszul sign rule is best demonstrated in examples.

Example 3.1.5. Suppose that for $k = 0, 1$ we are given graded \mathbb{K} -module homomorphisms $\phi_k : M_k \rightarrow N_k$ of degrees i_k . Then the homomorphism

$$\phi_0 \otimes \phi_1 \in \text{Hom}_{\mathbb{K}}(M_0 \otimes_{\mathbb{K}} M_1, N_0 \otimes_{\mathbb{K}} N_1)^{i_0+i_1}$$

acts on a tensor $m_0 \otimes m_1 \in M_0 \otimes_{\mathbb{K}} M_1$, with $m_k \in M_k^{j_k}$, like this:

$$(\phi_0 \otimes \phi_1)(m_0 \otimes m_1) := (-1)^{i_1 \cdot j_0} \cdot \phi_0(m_0) \otimes \phi_1(m_1) \in N_0 \otimes_{\mathbb{K}} N_1.$$

The sign is because ϕ_1 and m_0 were transposed.

Example 3.1.6. Suppose we are given graded \mathbb{K} -module homomorphisms $\phi_0 : N_0 \rightarrow M_0$ and $\phi_1 : M_1 \rightarrow N_1$ of degrees i_0 and i_1 . Then the homomorphism

$$\text{Hom}(\phi_0, \phi_1) \in \text{Hom}_{\mathbb{K}}(\text{Hom}_{\mathbb{K}}(M_0, M_1), \text{Hom}_{\mathbb{K}}(N_0, N_1))^{i_0+i_1}$$

acts on $\gamma \in \text{Hom}_{\mathbb{K}}(M_0, M_1)^j$ as follows: for an element $n_0 \in N_0^k$ we have

$$\text{Hom}(\phi_0, \phi_1)(\gamma)(n_0) := (-1)^{i_0 \cdot (i_1+j)} (\phi_1 \circ \gamma \circ \phi_0)(n_0) \in N_1^{k+i_0+i_1+j}.$$

The sign is because ϕ_0 jumped across ϕ_1 and γ .

Example 3.1.7. Let A and B be central graded \mathbb{K} -rings. Then $A \otimes_{\mathbb{K}} B$ is a central graded \mathbb{K} -ring, with multiplication

$$(a_0 \otimes b_0) \cdot (a_1 \otimes b_1) := (-1)^{i_1 \cdot j_0} \cdot (a_0 \cdot a_1) \otimes (b_0 \cdot b_1)$$

for elements $a_k \in A^{i_k}$ and $b_k \in B^{j_k}$.

Example 3.1.8. The Koszul sign rule influences the meaning of commutativity for graded rings. A graded ring A is called *weakly commutative* if any two homogeneous elements in it graded-commute with each other.

There is a stronger notion of commutativity, that is not directly related to the Koszul sign rule. We call a graded ring A *strongly commutative* if besides being weakly commutative, it also has this property: if $a \in A^i$ and i is odd, then $a^2 = 0$. See Definition 15.5.5 and the remark following it.

Exercise 3.1.9. Let A be a central graded \mathbb{K} -ring. A homogeneous element $a \in A$ is called graded-central if it graded-commutes with all other homogeneous elements. The *graded center* of A is the \mathbb{K} -linear span of all graded-central homogeneous elements in A . Let us denote it by $\text{Cent}(A)$. Show that $\text{Cent}(A)$ is a graded subring of A ; it is weakly commutative; and it contains the image of \mathbb{K} .

Let A be a central graded \mathbb{K} -ring. A *graded left A -module* is a left A -module M , equipped with a \mathbb{K} -module decomposition $M = \bigoplus_{i \in \mathbb{Z}} M^i$, such that $A^i \cdot M^j \subseteq M^{i+j}$. We can also talk about graded right A -modules, and graded bimodules. But our default option is that modules are left modules.

If M is a graded \mathbb{K} -module, A is a central graded \mathbb{K} -ring, and $f : A \rightarrow \text{End}_{\mathbb{K}}(M)$ is a graded \mathbb{K} -ring homomorphism, then M becomes a graded A -module, with action $a \cdot m := f(a)(m)$. Any graded A -module structure on M arises this way.

Lemma 3.1.10. *Let A be a central graded \mathbb{K} -ring, let M be a right graded A -module, and let N be a left graded A -module. Then the \mathbb{K} -module $M \otimes_A N$ has a direct sum decomposition*

$$M \otimes_A N = \bigoplus_{i \in \mathbb{Z}} (M \otimes_A N)^i,$$

where $(M \otimes_A N)^i$ is the \mathbb{K} -linear span of the tensors $m \otimes n$ with $m \in M^j$ and $n \in N^{i-j}$.

Proof. There is a canonical surjection of \mathbb{K} -modules

$$M \otimes_{\mathbb{K}} N \rightarrow M \otimes_A N.$$

Its kernel is the \mathbb{K} -submodule $L \subseteq M \otimes_{\mathbb{K}} N$ generated by the elements

$$(m \cdot a) \otimes n - m \otimes (a \cdot n),$$

for $m \in M^j$, $n \in N^k$ and $a \in A^l$. So L is a graded submodule of $M \otimes_{\mathbb{K}} N$, and therefore so is the quotient. Finally, by formula (3.1.1) the i -th homogeneous component of $M \otimes_A N$ is precisely $(M \otimes_A N)^i$. \square

Definition 3.1.11. Let A be a central graded \mathbb{K} -ring, and let M, N be graded A -modules. For any $i \in \mathbb{Z}$ define $\text{Hom}_A(M, N)^i$ to be the subset of $\text{Hom}_{\mathbb{K}}(M, N)^i$ consisting of the homomorphisms $\phi : M \rightarrow N$ such that

$$\phi(a \cdot m) = (-1)^{i \cdot k} \cdot a \cdot \phi(m)$$

for all $a \in A^k$. Next let

$$\text{Hom}_A(M, N) := \bigoplus_{i \in \mathbb{Z}} \text{Hom}_A(M, N)^i.$$

Suppose \mathcal{C} is a \mathbb{K} -linear category (Definition 2.1.1). Since the composition of morphisms is \mathbb{K} -bilinear, for any triple of objects $M_0, M_1, M_2 \in \mathcal{C}$, composition can be expressed as a \mathbb{K} -linear homomorphism

$$\begin{aligned} \text{Hom}_{\mathcal{C}}(M_1, M_2) \otimes_{\mathbb{K}} \text{Hom}_{\mathcal{C}}(M_0, M_1) &\rightarrow \text{Hom}_{\mathcal{C}}(M_0, M_2) \\ \phi_1 \otimes \phi_0 &\mapsto \phi_1 \circ \phi_0. \end{aligned}$$

We refer to it as the composition homomorphism. It will be used in the following definition.

Definition 3.1.12. A *graded \mathbb{K} -linear category* is a \mathbb{K} -linear category \mathcal{C} , endowed with a grading on each of the \mathbb{K} -modules $\text{Hom}_{\mathcal{C}}(M_0, M_1)$. The conditions are these:

- (a) For any object M , the identity automorphism 1_M has degree 0.
- (b) For any triple of objects $M_0, M_1, M_2 \in \mathcal{C}$, the composition homomorphism

$$\text{Hom}_{\mathcal{C}}(M_1, M_2) \otimes_{\mathbb{K}} \text{Hom}_{\mathcal{C}}(M_0, M_1) \rightarrow \text{Hom}_{\mathcal{C}}(M_0, M_2)$$

is a strict homomorphism of graded \mathbb{K} -modules.

In item (b) we use the graded module structure on a tensor product from equation (3.1.1). A morphism $\phi \in \text{Hom}_{\mathbb{C}}(M_0, M_1)^i$ is called a morphism of degree i .

Definition 3.1.13. Let \mathbb{C} be a graded \mathbb{K} -linear category. The *strict subcategory* of \mathbb{C} is the subcategory \mathbb{C}^0 on all objects of \mathbb{C} , but the morphisms are only the degree 0 morphisms.

Example 3.1.14. Let A be a central graded \mathbb{K} -ring. Define $\mathbf{GMod} A$ to be the category whose objects are the graded A -modules. For $M, N \in \mathbf{GMod} A$, the set of morphisms is the graded \mathbb{K} -module

$$\text{Hom}_{\mathbf{GMod} A}(M, N) := \text{Hom}_A(M, N)$$

from Definition 3.1.11. Then $\mathbf{GMod} A$ is a graded \mathbb{K} -linear category. The morphisms in the subcategory $\mathbf{GMod}^0 A := (\mathbf{GMod} A)^0$ are the strict homomorphisms of graded A -modules, as defined earlier in this subsection. We often write $\mathbf{G}(A) := \mathbf{GMod} A$ and $\mathbf{G}^0(A) := \mathbf{GMod}^0 A$.

Definition 3.1.15. Let \mathbb{C} and \mathbb{D} be graded \mathbb{K} -linear categories. A functor $F : \mathbb{C} \rightarrow \mathbb{D}$ is called a *graded \mathbb{K} -linear functor* if it satisfies this condition:

▷ For any pair of objects $M_0, M_1 \in \mathbb{C}$, the function

$$F : \text{Hom}_{\mathbb{C}}(M_0, M_1) \rightarrow \text{Hom}_{\mathbb{D}}(F(M_0), F(M_1))$$

is a strict homomorphism of graded \mathbb{K} -modules.

Example 3.1.16. Let A be a central graded \mathbb{K} -ring. We can view A as a category \mathbf{A} with a single object, and it is a \mathbb{K} -linear graded category. If $f : A \rightarrow B$ is a homomorphism of central graded \mathbb{K} -rings, then passing to single-object categories we get a \mathbb{K} -linear graded functor $F : \mathbf{A} \rightarrow \mathbf{B}$.

Recall that “morphism of functors” is synonymous with “natural transformation”.

Definition 3.1.17. Let $F, G : \mathbb{C} \rightarrow \mathbb{D}$ be \mathbb{K} -linear graded functors between \mathbb{K} -linear graded categories, and let $i \in \mathbb{Z}$. A *degree i morphism of graded functors* $\eta : F \rightarrow G$ is a collection $\eta = \{\eta_M\}_{M \in \mathbb{C}}$ of morphisms

$$\eta_M \in \text{Hom}_{\mathbb{D}}(F(M), G(M))^i,$$

such that for any morphism $\phi \in \text{Hom}_{\mathbb{C}}(M_0, M_1)^j$, there is equality

$$G(\phi) \circ \eta_{M_0} = (-1)^{i \cdot j} \cdot \eta_{M_1} \circ F(\phi)$$

inside

$$\text{Hom}_{\mathbb{D}}(F(M_0), G(M_1))^{i+j}.$$

Definition 3.1.18. Let \mathbf{M} be a \mathbb{K} -linear abelian category. A *graded object in \mathbf{M}* is a collection $\{M^i\}_{i \in \mathbb{Z}}$ of objects $M^i \in \mathbf{M}$.

Because we did not assume that \mathbf{M} has countable direct sums, the graded objects are “external” to \mathbf{M} ; cf. Example 3.1.22.

Suppose $M = \{M^i\}_{i \in \mathbb{Z}}$ and $N = \{N^i\}_{i \in \mathbb{Z}}$ are graded objects in \mathbf{M} . For any integer i we define the \mathbb{K} -module

$$(3.1.19) \quad \text{Hom}_{\mathbf{M}}(M, N)^i := \prod_{j \in \mathbb{Z}} \text{Hom}_{\mathbf{M}}(M^j, N^{j+i}).$$

We get a graded \mathbb{K} -module

$$(3.1.20) \quad \mathrm{Hom}_{\mathbf{M}}(M, N) := \bigoplus_{i \in \mathbb{Z}} \mathrm{Hom}_{\mathbf{M}}(M, N)^i.$$

Definition 3.1.21. Let \mathbf{M} be a \mathbb{K} -linear abelian category. The *category of graded objects in \mathbf{M}* is the \mathbb{K} -linear graded category $\mathbf{G}(\mathbf{M})$, whose objects are the graded objects in \mathbf{M} , and the morphism sets are the graded modules

$$\mathrm{Hom}_{\mathbf{G}(\mathbf{M})}(M, N) := \mathrm{Hom}_{\mathbf{M}}(M, N)$$

from equation (3.1.20). The composition operation is the obvious one.

Example 3.1.22. Suppose $\mathbf{M} = \mathrm{Mod} A$, the category of modules over a central \mathbb{K} -ring A . For any $M = \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{G}(\mathbf{M})$ let $F(M) := \bigoplus_{i \in \mathbb{Z}} M^i$. Then $F(M)$ is a graded A -module, as discussed earlier, so $F(M)$ is an object of the category $\mathbf{G}(A)$ from Example 3.1.14. It is not hard to verify that

$$F : \mathbf{G}(\mathbf{M}) \rightarrow \mathbf{G}(A)$$

is an isomorphism of \mathbb{K} -linear graded categories.

In the next definition we combine graded rings and linear categories, to concoct a new hybrid.

Definition 3.1.23. Let \mathbf{M} be a \mathbb{K} -linear abelian category, and let A be a central graded \mathbb{K} -ring. A *graded A -module in \mathbf{M}* is an object $M \in \mathbf{G}(\mathbf{M})$, together with graded \mathbb{K} -ring homomorphism $f : A \rightarrow \mathrm{End}_{\mathbf{M}}(M)$.

What the definition says is that any element $a \in A^i$ gives rise to a degree i endomorphism $f(a)$ of the graded object $M = \{M^i\}_{i \in \mathbb{Z}}$. In turn, this means that for every j , $f(a) : M^j \rightarrow M^{j+i}$ is a morphism in \mathbf{M} . The operation f satisfies $f(1_A) = 1_M$ and $f(a_1 \cdot a_2) = f(a_1) \circ f(a_2)$

Example 3.1.24. If $A = \mathbb{K}$, then $\mathbf{G}(A, \mathbf{M}) = \mathbf{G}(\mathbf{M})$; and if $\mathbf{M} = \mathrm{Mod} \mathbb{K}$, then $\mathbf{G}(A, \mathbf{M}) = \mathbf{G}(A)$.

The next definition is a variant of Definition 3.1.11.

Definition 3.1.25. Let \mathbf{M} be a \mathbb{K} -linear abelian category, and let A be a central graded \mathbb{K} -ring. For $M, N \in \mathbf{G}(A, \mathbf{M})$ and $i \in \mathbb{Z}$ we define $\mathrm{Hom}_{A, \mathbf{M}}(M, N)^i$ to be the subset of $\mathrm{Hom}_{\mathbf{M}}(M, N)^i$ consisting of the morphisms $\phi : M \rightarrow N$ such that

$$\phi \circ f_M(a) = (-1)^{i \cdot k} \cdot f_N(a) \circ \phi$$

for all $a \in A^k$. Next let

$$\mathrm{Hom}_{A, \mathbf{M}}(M, N) := \bigoplus_{i \in \mathbb{Z}} \mathrm{Hom}_{A, \mathbf{M}}(M, N)^i.$$

This is a graded \mathbb{K} -module.

Definition 3.1.26. Let \mathbf{M} be a \mathbb{K} -linear abelian category, and let A be a central graded \mathbb{K} -ring. The *category of graded A -modules in \mathbf{M}* is the \mathbb{K} -linear graded category $\mathbf{G}(A, \mathbf{M})$ whose objects are the graded A -modules in \mathbf{M} , and the morphism sets are the graded \mathbb{K} -modules

$$\mathrm{Hom}_{\mathbf{G}(A, \mathbf{M})}(M_0, M_1) := \mathrm{Hom}_{A, \mathbf{M}}(M_0, M_1)$$

from Definition 3.1.25.

Notice that forgetting the action of A is a faithful \mathbb{K} -linear graded functor $\mathbf{G}(A, M) \rightarrow \mathbf{G}(M)$. As in any graded category, there is the subcategory $\mathbf{G}^0(A, M) \subseteq \mathbf{G}(A, M)$ of strict morphisms.

Exercise 3.1.27. Show that $\mathbf{G}^0(A, M)$ is an abelian category.

Remark 3.1.28. The reader may have noticed that we can talk about the graded category $\mathbf{G}(M)$ for any \mathbb{K} -linear category M , regardless if it is abelian or not. We chose to restrict attention to the abelian case for a pedagogical reason: this will hopefully reduce confusion between the many sorts of graded (and later DG) categories that occur in our discussion.

3.2. DG \mathbb{K} -modules.

Definition 3.2.1. A *DG \mathbb{K} -module* is a graded \mathbb{K} -module $M = \bigoplus_{i \in \mathbb{Z}} M^i$, together with a \mathbb{K} -linear operator $d_M : M \rightarrow M$ of degree 1, called the differential, satisfying $d_M \circ d_M = 0$.

When there is no danger of confusion, we may write d instead of d_M .

Definition 3.2.2. Let M and N be DG \mathbb{K} -modules. A *strict homomorphism of DG \mathbb{K} -modules* is a \mathbb{K} -linear homomorphism $\phi : M \rightarrow N$ that commutes with the differentials and respects the gradings. The resulting category is denoted by $\mathbf{DGMod}_{\text{str}} \mathbb{K}$.

It is easy to see that $\mathbf{DGMod}_{\text{str}} \mathbb{K}$ is a \mathbb{K} -linear abelian category. We shall sometimes use the notation $\mathbf{C}_{\text{str}}(\mathbb{K}) := \mathbf{DGMod}_{\text{str}} \mathbb{K}$.

Remark 3.2.3. The name “strict morphism of DG modules”, and the corresponding notation $\mathbf{DGMod}_{\text{str}} \mathbb{K}$, are new. We introduced them to distinguish the abelian category $\mathbf{DGMod}_{\text{str}} \mathbb{K}$ from the DG category $\mathbf{DGMod} \mathbb{K}$ that contains it; cf. Definitions 3.4.1 and 3.4.4.

Suppose M and N are DG \mathbb{K} -modules. Their tensor product $M \otimes_{\mathbb{K}} N$ was defined, as a graded module, in equation (3.1.1). We put on it the differential

$$(3.2.4) \quad d(m \otimes n) := d_M(m) \otimes n + (-1)^i \cdot m \otimes d_N(n)$$

for $m \in M^i$ and $n \in N^j$. In this way $M \otimes_{\mathbb{K}} N$ becomes a DG \mathbb{K} -module. We sometimes write $d_{M \otimes_{\mathbb{K}} N}$ for the differential.

The graded module $\text{Hom}_{\mathbb{K}}(M, N)$ was introduced in equation (3.1.2). There is a differential on it:

$$(3.2.5) \quad d(\phi) := d_N \circ \phi - (-1)^i \cdot \phi \circ d_M$$

for $\phi \in \text{Hom}_{\mathbb{K}}(M, N)^i$. When we need to emphasize where d acts, we sometimes denote it by $d_{\text{Hom}_{\mathbb{K}}(M, N)}$.

Let M be a DG \mathbb{K} -module. The module of degree i cocycles of M is

$$(3.2.6) \quad Z^i(M) := \text{Ker}(d|_{M^i}) \subseteq M^i,$$

and the module of degree i coboundaries is

$$(3.2.7) \quad B^i(M) := \text{Im}(d|_{M^{i-1}}) \subseteq M^i.$$

Since $d \circ d = 0$ we have $B^i(N) \subseteq Z^i(N)$. The i -th cohomology is

$$(3.2.8) \quad H^i(M) := Z^i(M)/B^i(M).$$

These are all \mathbb{K} -modules, and in fact they are functors

$$Z^i, B^i, H^i : \text{DGMod}_{\text{str}} \mathbb{K} \rightarrow \text{Mod } \mathbb{K}.$$

Rephrasing Definition 3.2.2, for DG \mathbb{K} -modules M and N there is equality

$$(3.2.9) \quad \text{Hom}_{\text{DGMod}_{\text{str}} \mathbb{K}}(M, N) = Z^0(\text{Hom}_{\mathbb{K}}(M, N))$$

of submodules of $\text{Hom}_{\mathbb{K}}(M, N)$.

3.3. DG Rings and Modules.

Definition 3.3.1. A *DG ring* is a graded ring $A = \bigoplus_{i \in \mathbb{Z}} A^i$, together with an operator $d_A : A \rightarrow A$ of degree 1 called the differential, satisfying the equation $d_A \circ d_A = 0$, and the graded Leibniz rule

$$d_A(a \cdot b) = d_A(a) \cdot b + (-1)^i \cdot a \cdot d_A(b)$$

for all $a \in A^i$ and $b \in A^j$.

We sometimes write d instead of d_A .

Definition 3.3.2. Let A and B be DG rings. A *homomorphism of DG rings* $f : A \rightarrow B$ is a ring homomorphism that commutes with the differentials and respects the gradings. The resulting category is denoted by DGRing .

Rings are viewed as DG rings concentrated in degree 0 (and with trivial differentials). Thus the category of rings Ring is a full subcategory of DGRing .

Definition 3.3.3. We say that A is a *central DG \mathbb{K} -ring* if there is a given DG ring homomorphism $\mathbb{K} \rightarrow A$, whose image is central in A .

We denote by $\text{DGRing}/_{\text{ce}} \mathbb{K}$ the category of central DG \mathbb{K} -rings, in which the morphisms $f : A \rightarrow B$ are the homomorphisms in DGRing that respect the given structural homomorphisms from \mathbb{K} .

Of course for $\mathbb{K} = \mathbb{Z}$ we have $\text{DGRing}/_{\text{ce}} \mathbb{K} = \text{DGRing}$.

Let A be a central DG \mathbb{K} -ring. From the definition it follows that the differential d_A is \mathbb{K} -linear. Hence the image of \mathbb{K} is contained in the $Z^0(A)$.

Here are few examples of DG rings. First a silly example.

Example 3.3.4. Let A be a central graded \mathbb{K} -ring. Then A , with the trivial differential, is a central DG \mathbb{K} -ring.

Example 3.3.5. Let X be a differentiable (i.e. of type C^∞) manifold over \mathbb{R} . The de Rham complex A of X is a central DG \mathbb{R} -ring, with the wedge product and the exterior differential. See [KaSc1, Section 2.9.7] for details. This is a strongly commutative DG ring, in the sense of Example 3.1.8.

The next example is the algebraic analogue of the previous one.

Example 3.3.6. Let C be a commutative \mathbb{K} -ring. Then the algebraic de Rham complex $A := \Omega_{C/\mathbb{K}} = \bigoplus_{p \geq 0} \Omega_{C/\mathbb{K}}^p$ is a central DG \mathbb{K} -ring. It is also a strongly commutative DG ring. See [Eis, Exercise 16.15] or [Mats, Section 25] for details.

Example 3.3.7. Let M be a DG \mathbb{K} -module. Consider the DG \mathbb{K} -module

$$\text{End}_{\mathbb{K}}(M) := \text{Hom}_{\mathbb{K}}(M, M).$$

Composition of endomorphisms is an associative multiplication on $\text{End}_{\mathbb{K}}(M)$ that respects the grading, and the graded Leibniz rule holds. We see that $\text{End}_{\mathbb{K}}(M)$ is a central DG \mathbb{K} -ring.

Example 3.3.8. Let C be a commutative ring and let $c \in C$ be an element. The *Koszul complex* of c is the DG C -module $K(C; c)$ defined as follows. In degree 0 we let $K^0(C; c) := C$. In degree -1 , $K^{-1}(C; c)$ is a free C -module of rank 1, with basis element x . All other homogeneous components are trivial. The differential d is determined by what it does to the basis element $x \in K^{-1}(C; c)$, and we let $d(x) := c \in K^0(C; c)$.

We want to make $K(C; c)$ into a strongly commutative DG ring (in the sense of Example 3.1.8). Since x is an odd element, this dictates the relation $x^2 = 0$.

Example 3.3.9. Let A and B be central DG \mathbb{K} -rings. The graded ring $A \otimes_{\mathbb{K}} B$ from Example 3.1.7, with the differential (3.2.4), is a central DG \mathbb{K} -ring.

Example 3.3.10. Let C be a commutative ring and let $\mathbf{c} = (c_1, \dots, c_n)$ be a sequence of elements in C . By combining Examples 3.3.8 and 3.3.9 we obtain the Koszul complex

$$K(C; \mathbf{c}) := K(C; c_1) \otimes_C \cdots \otimes_C K(C; c_n).$$

This is a strongly commutative DG C -ring. In the classical literature the multiplicative structure of $K(C; \mathbf{c})$ has usually been ignored; see [Eis] and [Mats].

Definition 3.3.11. Let A be a central DG \mathbb{K} -ring. The *opposite DG ring* A^{op} is the same DG \mathbb{K} -module as A , but the multiplication \cdot^{op} is reversed and twisted by signs:

$$a \cdot^{\text{op}} b := (-1)^{i \cdot j} \cdot b \cdot a$$

for $a \in A^i$ and $b \in A^j$.

Exercise 3.3.12. Verify that A^{op} is a central DG \mathbb{K} -ring.

Note that A is weakly commutative iff $A = A^{\text{op}}$.

Definition 3.3.13. Let A be a central DG \mathbb{K} -ring. A *left DG A -module* is a graded left A -module $M = \bigoplus_{i \in \mathbb{Z}} M^i$, with an operator $d_M : M \rightarrow M$ of degree 1 called the differential, satisfying $d_M \circ d_M = 0$ and

$$d_M(a \cdot m) = d_A(a) \cdot m + (-1)^i \cdot a \cdot d_M(m)$$

for $a \in A^i$ and $m \in M^j$.

Right DG A -modules are defined likewise, but we won't deal with them much. This is because right DG A -modules are left DG modules over the opposite DG ring A^{op} . More precisely, if M is a right DG A -module, then the formula

$$(3.3.14) \quad a \cdot m := (-1)^{i \cdot j} \cdot m \cdot a,$$

for $a \in A^i$ and $m \in M^j$, makes M into a left DG A^{op} -module.

So we make this convention for the rest of the book, extending Convention 1.2.3(2):

Convention 3.3.15. By default, DG modules are *left* DG modules.

Proposition 3.3.16. *Let A be a central DG \mathbb{K} -ring, and let M be a DG \mathbb{K} -module.*

- (1) *Suppose $f : A \rightarrow \text{End}_{\mathbb{K}}(M)$ is a DG \mathbb{K} -ring homomorphism. Then the formula $a \cdot m := f(a)(m)$, for $a \in A^i$ and $m \in M^j$, makes M into a DG A -module.*
- (2) *Conversely, any DG A -module structure on M , that's compatible with the DG \mathbb{K} -module structure, arises in this way from a DG \mathbb{K} -ring homomorphism $f : A \rightarrow \text{End}_{\mathbb{K}}(M)$.*

Exercise 3.3.17. Prove this proposition.

Definition 3.3.18. Let M and N be DG A -modules. A *strict homomorphism of DG A -modules* is a \mathbb{K} -linear homomorphism $\phi : M \rightarrow N$ that respects the differentials, the gradings and the action of A . The resulting category is denoted by $\mathbf{DGM}_{\text{str}} A$.

We shall sometimes write $\mathbf{C}_{\text{str}}(A) := \mathbf{DGM}_{\text{str}} A$.

Exercise 3.3.19. Let A be a DG ring. Show that the cocycles $Z(A) := \bigoplus_{i \in \mathbb{Z}} Z^i(A)$ are a graded subring of A , and the coboundaries $B(A) := \bigoplus_{i \in \mathbb{Z}} B^i(A)$ are a two-sided ideal of $Z(A)$. Conclude that the cohomology $H(A) := \bigoplus_{i \in \mathbb{Z}} H^i(A)$ is a graded ring.

Let $f : A \rightarrow B$ be a homomorphism of DG rings. Show that $H(f) : H(A) \rightarrow H(B)$ is a graded ring homomorphism.

Exercise 3.3.20. Let A be a DG ring. Given a DG A -module M , show that its cohomology $H(M)$ is a graded $H(A)$ -module. If $\phi : M \rightarrow N$ is a homomorphism in $\mathbf{C}_{\text{str}}(A)$, then $H(\phi) : H(M) \rightarrow H(N)$ is a homomorphism in $\mathbf{G}^0(H(A))$.

Definition 3.3.21. Let A be a central DG \mathbb{K} -ring, let M be a right DG A -module, and let N be a left DG A -module. By Lemma 3.1.10, $M \otimes_A N$ is a graded \mathbb{K} -module. We make it into a DG \mathbb{K} -module with the differential from formula (3.2.4).

Definition 3.3.22. Let A be a central DG \mathbb{K} -ring, and let M, N be left DG A -modules. The graded \mathbb{K} -module $\text{Hom}_A(M, N)$ from Definition 3.1.11 is made into a DG \mathbb{K} -module with the differential from (3.2.5).

Generalizing formula (3.2.9), for DG A -modules M and N there is equality

$$\text{Hom}_{\mathbf{C}_{\text{str}}(A)}(M, N) = Z^0(\text{Hom}_A(M, N)).$$

3.4. DG Categories. In Definition 3.1.12 we saw graded categories. Here is the DG version.

Definition 3.4.1. A \mathbb{K} -linear DG category is a \mathbb{K} -linear category \mathbf{C} , endowed with a DG \mathbb{K} -module structure on each of the morphism \mathbb{K} -modules $\text{Hom}_{\mathbf{C}}(M_0, M_1)$. The conditions are these:

- (a) For any object M , the identity automorphism 1_M is a degree 0 cocycle in $\text{Hom}_{\mathbf{C}}(M, M)$.
- (b) For any triple of objects $M_0, M_1, M_2 \in \mathbf{C}$, the composition homomorphism

$$\text{Hom}_{\mathbf{C}}(M_1, M_2) \otimes_{\mathbb{K}} \text{Hom}_{\mathbf{C}}(M_0, M_1) \rightarrow \text{Hom}_{\mathbf{C}}(M_0, M_2)$$

is a strict homomorphism of DG \mathbb{K} -modules.

Definition 3.4.2. Let \mathbf{C} be a \mathbb{K} -linear DG category.

- (1) A morphism $\phi \in \text{Hom}_{\mathbf{C}}(M, N)^i$ is called a *degree i morphism*.
- (2) A morphism $\phi \in \text{Hom}_{\mathbf{C}}(M, N)$ is called a *cocycle* if $d(\phi) = 0$.
- (3) A morphism $\phi : M \rightarrow N$ in \mathbf{C} is called a *strict morphism* if it is a degree 0 cocycle.

Lemma 3.4.3. Let \mathbf{C} be a \mathbb{K} -linear DG category, and for $i = 0, 1, 2$ let $\phi_i : M_i \rightarrow M_{i+1}$ be a morphism in \mathbf{C} of degree k_i .

- (1) The morphism $\phi_1 \circ \phi_0$ has degree $k_0 + k_1$, and
- $$d(\phi_1 \circ \phi_0) = d(\phi_1) \circ \phi_0 + (-1)^{k_1} \cdot \phi_1 \circ d(\phi_0).$$
- (2) If ϕ_0 and ϕ_1 are cocycles, then so is $\phi_1 \circ \phi_0$.
- (3) If ϕ_1 is a coboundary, and ϕ_0 and ϕ_2 are cocycles, then $\phi_2 \circ \phi_1 \circ \phi_0$ is a coboundary.

Proof. (1) This is just a rephrasing of item (b) in Definition 3.4.1.

(2) This is immediate from (1).

(3) Say $\phi_1 = d(\psi_1)$ for some degree $k_1 - 1$ morphism $\psi_1 : M_1 \rightarrow M_2$. Then

$$\phi_2 \circ \phi_1 \circ \phi_0 = d((-1)^{k_2} \cdot \phi_2 \circ \psi_1 \circ \phi_0).$$

□

The previous lemma makes the next definition possible.

Definition 3.4.4. Let \mathbf{C} be a \mathbb{K} -linear DG category.

- (1) The *strict category* of \mathbf{C} is the category $\text{Str}(\mathbf{C}) = \mathbf{C}_{\text{str}}$, with the same objects as \mathbf{C} , but with strict morphisms only. Thus

$$\text{Hom}_{\text{Str}(\mathbf{C})}(M, N) = Z^0(\text{Hom}_{\mathbf{C}}(M, N)).$$

- (2) The *homotopy category* of \mathbf{C} is the category $\text{Ho}(\mathbf{C})$, with the same objects as \mathbf{C} , and with morphism sets

$$\text{Hom}_{\text{Ho}(\mathbf{C})}(M, N) := H^0(\text{Hom}_{\mathbf{C}}(M, N)).$$

- (3) We denote by

$$P : \text{Str}(\mathbf{C}) \rightarrow \text{Ho}(\mathbf{C})$$

the functor which is the identity on objects, and sends a strict morphism to its homotopy class.

The categories $\text{Str}(\mathbf{C})$ and $\text{Ho}(\mathbf{C})$ are \mathbb{K} -linear. The inclusion functor $\text{Str}(\mathbf{C}) \rightarrow \mathbf{C}$ and the functor $P : \text{Str}(\mathbf{C}) \rightarrow \text{Ho}(\mathbf{C})$ are \mathbb{K} -linear. The first is faithful (injective on morphisms), and the second is full (surjective on morphisms).

Example 3.4.5. If \mathbf{A} is a \mathbb{K} -linear DG category, then for every object $x \in \mathbf{A}$, its set of endomorphisms $A := \text{End}_{\mathbf{A}}(x)$ is a central DG \mathbb{K} -ring. Conversely, any central DG \mathbb{K} -ring A can be viewed as a \mathbb{K} -linear DG category with a single object.

Example 3.4.6. Let A be a central DG \mathbb{K} -ring. The set of DG A -modules forms a \mathbb{K} -linear DG category $\text{DGMod } A$, in which the morphism DG modules are

$$\text{Hom}_{\text{DGMod } A}(M, N) := \text{Hom}_A(M, N)$$

from Definition 3.3.22. We shall often write $\mathbf{C}(A) := \text{DGMod } A$.

The strict category here is

$$\text{Str}(\text{DGMod } A) = \text{DGMod}_{\text{str}} A;$$

cf. Definition 3.3.18.

Here is a useful result, to be used later.

Proposition 3.4.7. Let $\phi : M \rightarrow N$ be a degree i isomorphism in the \mathbb{K} -linear DG category \mathbf{C} . Assume ϕ is a cocycle, namely $d(\phi) = 0$. Then its inverse $\phi^{-1} : N \rightarrow M$ is also a cocycle.

Proof. According the Leibniz rule (Lemma 3.4.3(1)), and the fact that 1_M is a cocycle, we have

$$0 = d(1_M) = d(\phi^{-1} \circ \phi) = d(\phi^{-1}) \circ \phi + (-1)^{-i} \cdot \phi^{-1} \circ d(\phi) = d(\phi^{-1}) \circ \phi.$$

Because ϕ is an isomorphism, we conclude that $d(\phi^{-1}) = 0$. \square

Remark 3.4.8. The fact that the concept of “DG category” includes both DG rings (Example 3.4.5) and DG modules over them (Example 3.4.6) is a source of frequent confusion. See Remarks 3.1.28 and 3.7.7.

Remark 3.4.9. For other accounts of DG categories see the relatively old references [Kel], [BoKa], or the recent [To]. An internet search can give plenty more information, including the relation to simplicial and infinity categories.

In this book we shall be exclusively concerned with the categories $\mathbf{C}(A, M)$, to be introduced in Subsection 3.7, that have a lot more structure than other DG categories. See Remark 3.7.7 regarding the DG category $\mathbf{C}(A) = \mathbf{C}(A, \text{Mod } \mathbb{K})$ of left DG modules over a \mathbb{K} -linear DG category A , in the sense of [Kel].

3.5. DG Functors. Here C and D are \mathbb{K} -linear DG categories (see Definition 3.4.1). When we forget differentials, C and D become \mathbb{K} -linear graded categories. So we can talk about graded functors $C \rightarrow D$, as in Definition 3.1.15.

The differential of the DG \mathbb{K} -module $\text{Hom}_C(M_0, M_1)$, for objects $M_0, M_1 \in C$, will be denoted by d_C . Likewise in D .

Recall the meaning of a strict homomorphism of DG \mathbb{K} -modules: it has degree 0 and commutes with the differentials.

Definition 3.5.1. Let C and D be \mathbb{K} -linear DG categories. A functor $F : C \rightarrow D$ is called a \mathbb{K} -linear DG functor if it satisfies this condition:

▷ For any pair of objects $M_0, M_1 \in C$, the function

$$F : \text{Hom}_C(M_0, M_1) \rightarrow \text{Hom}_D(F(M_0), F(M_1))$$

is a strict homomorphism of DG \mathbb{K} -modules.

In other words, F is a DG functor if it is a graded functor, and

$$(3.5.2) \quad d_D \circ F = F \circ d_C$$

as degree 1 homomorphisms

$$\text{Hom}_C(M_0, M_1) \rightarrow \text{Hom}_D(F(M_0), F(M_1)).$$

Example 3.5.3. Let $f : A \rightarrow B$ be a homomorphism of central DG \mathbb{K} -rings. Define the DG categories C and D as follows: $\text{Ob}(C) := \{x\}$, $\text{End}_C(x) := A$, $\text{Ob}(D) := \{y\}$ and $\text{End}_D(y) := B$. Then f becomes a \mathbb{K} -linear DG functor $F : C \rightarrow D$.

Other examples of DG functors, more relevant to our study, will be given in Subsection 5.4.

Definition 3.5.4. Let $F, G : C \rightarrow D$ be \mathbb{K} -linear DG functors.

- (1) A degree i morphism of DG functors $\eta : F \rightarrow G$ is a degree i morphism of graded functors, as in Definition 3.1.17.
- (2) Let $\eta : F \rightarrow G$ be a degree i morphism of DG functors. For any object $M \in C$ there is a degree $i + 1$ morphism

$$d_D(\eta_M) : F(M) \rightarrow G(M)$$

in \mathcal{D} . We let

$$d_{\mathcal{D}}(\eta) := \{d_{\mathcal{D}}(\eta_M)\}_{M \in \mathcal{C}}.$$

- (3) A *strict morphism of DG functors* is a degree 0 morphism of graded functors $\eta : F \rightarrow G$ such that $d_{\mathcal{D}}(\eta) = 0$.

Proposition 3.5.5. *In the situation of Definition 3.5.4, the collection of morphisms $d_{\mathcal{D}}(\eta)$ is a degree $i + 1$ morphism of DG functors $F \rightarrow G$.*

Exercise 3.5.6. Prove this proposition.

The categories $\text{Str}(\mathcal{C}) = \mathcal{C}_{\text{str}}$ and $\text{Ho}(\mathcal{C})$ were introduced in Definition 3.4.4.

Proposition 3.5.7. *Let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a \mathbb{K} -linear DG functor. Then F induces \mathbb{K} -linear functors*

$$\text{Str}(F) : \text{Str}(\mathcal{C}) \rightarrow \text{Str}(\mathcal{D})$$

and

$$\text{Ho}(F) : \text{Ho}(\mathcal{C}) \rightarrow \text{Ho}(\mathcal{D}).$$

Proof. Because F is a DG functor, it sends 0-cocycles in $\text{Hom}_{\mathcal{C}}(M_0, M_1)$ to 0-cocycles in $\text{Hom}_{\mathcal{D}}(F(M_0), F(M_1))$. The same for 0-coboundaries. \square

By abuse of notation, and when there is no danger for confusion, we will sometimes write F instead of $\text{Str}(F)$ or $\text{Ho}(F)$.

Exercise 3.5.8. Let \mathcal{A} and \mathcal{C} be \mathbb{K} -linear DG categories, and assume \mathcal{A} is small. Define $\text{DGFun}(\mathcal{A}, \mathcal{C})$ to be the set of \mathbb{K} -linear DG functors $F : \mathcal{A} \rightarrow \mathcal{C}$. Show that $\text{DGFun}(\mathcal{A}, \mathcal{C})$ is a \mathbb{K} -linear DG category, where the morphisms are from Definition 3.5.4(1), and their differentials are from Definition 3.5.4(2).

3.6. Complexes in Abelian Categories. Here we recall facts about complexes from the classical homological theory, and place them within our context. In this subsection \mathcal{M} is a \mathbb{K} -linear abelian category.

A *complex* of objects of \mathcal{M} , or a complex in \mathcal{M} , is a diagram

$$(3.6.1) \quad (\dots \rightarrow M^{-1} \xrightarrow{d_M^{-1}} M^0 \xrightarrow{d_M^0} M^1 \xrightarrow{d_M^1} M^2 \rightarrow \dots)$$

of objects and morphisms in \mathcal{M} , such that $d_M^{i+1} \circ d_M^i = 0$. The collection of objects $M := \{M^i\}_{i \in \mathbb{Z}}$ is nothing but a graded object of \mathcal{M} , as defined in Subsection 3.1. The collection of morphisms $d_M := \{d_M^i\}_{i \in \mathbb{Z}}$ is called a *differential*, or a *coboundary operator*. Thus a complex is a pair (M, d_M) made up of a graded object M and a differential d_M on it. We sometimes write d instead of d_M or d_M^i . At other times we leave the differential implicit, and just refer to the complex as M .

Let N be another complex in \mathcal{M} . A *strict morphism of complexes* $\phi : M \rightarrow N$ is a collection $\phi = \{\phi^i\}_{i \in \mathbb{Z}}$ of morphisms $\phi^i : M^i \rightarrow N^i$ in \mathcal{M} , such that

$$(3.6.2) \quad d_N^i \circ \phi^i = \phi^{i+1} \circ d_M^i.$$

Note that a strict morphism $\phi : M \rightarrow N$ can be viewed as a commutative diagram

$$\begin{array}{ccccccc} \dots & \longrightarrow & M^i & \xrightarrow{d_M^i} & M^{i+1} & \longrightarrow & \dots \\ & & \phi^i \downarrow & & \phi^{i+1} \downarrow & & \\ \dots & \longrightarrow & N^i & \xrightarrow{d_N^i} & N^{i+1} & \longrightarrow & \dots \end{array}$$

in \mathcal{M} . The identity automorphism 1_M of the complex M is a strict morphism.

Remark 3.6.3. In most textbooks, what we call “strict morphism of complexes” is simply called a “morphism of complexes”. See Remark 3.2.3 for an explanation.

Let us denote by $\mathbf{C}_{\text{str}}(\mathbf{M})$ the category of complexes in \mathbf{M} , with strict morphisms. This is a \mathbb{K} -linear abelian category. Indeed, the direct sum of complexes is the degree-wise direct sum, i.e. $(M \oplus N)^i = M^i \oplus N^i$. The same for kernels and cokernels. If \mathbf{N} is a full abelian subcategory of \mathbf{M} , then $\mathbf{C}_{\text{str}}(\mathbf{N})$ is a full abelian subcategory of $\mathbf{C}_{\text{str}}(\mathbf{M})$.

Any single object $M \in \mathbf{M}$ can be viewed as a complex

$$M' := (\cdots \rightarrow 0 \rightarrow M \rightarrow 0 \rightarrow \cdots),$$

where M is in degree 0; the differential of this complex is of course zero. The assignment $M \mapsto M'$ is a fully faithful \mathbb{K} -linear functor $\mathbf{M} \rightarrow \mathbf{C}_{\text{str}}(\mathbf{M})$.

Let M, N be complexes in \mathbf{M} . As in (3.1.20) there is a graded \mathbb{K} -module $\text{Hom}_{\mathbf{M}}(M, N)$. It is a DG \mathbb{K} -module with differential d given by the formula

$$(3.6.4) \quad d(\phi) := d_N \circ \phi - (-1)^i \cdot \phi \circ d_M$$

for $\phi \in \text{Hom}_{\mathbf{M}}(M, N)^i$. It is easy to check that $d \circ d = 0$. We sometimes denote this differential by $d_{\text{Hom}_{\mathbf{M}}(M, N)}$.

Thus, an element $\phi \in \text{Hom}_{\mathbf{M}}(M, N)^i$ is a collection $\phi = \{\phi^j\}_{j \in \mathbb{Z}}$ of morphisms $\phi^j : M^j \rightarrow N^{j+i}$. In a diagram, for $i = 2$, it looks like this:

$$\begin{array}{ccccccccc} \cdots & \longrightarrow & M^j & \xrightarrow{d} & M^{j+1} & \xrightarrow{d} & M^{j+2} & \xrightarrow{d} & M^{j+3} & \longrightarrow & \cdots \\ & & & & \searrow^{\phi^j} & & \searrow^{\phi^{j+1}} & & & & \\ \cdots & \longrightarrow & N^j & \xrightarrow{d} & N^{j+1} & \xrightarrow{d} & N^{j+2} & \xrightarrow{d} & N^{j+3} & \longrightarrow & \cdots \end{array}$$

Warning: since ϕ does not have to commute with the differentials, this is usually not a commutative diagram!

For a triple of complexes M_0, M_1, M_2 and degrees i_0, i_1 there are \mathbb{K} -linear homomorphisms

$$\text{Hom}_{\mathbf{M}}(M_1, M_2)^{i_1} \otimes_{\mathbb{K}} \text{Hom}_{\mathbf{M}}(M_0, M_1)^{i_0} \rightarrow \text{Hom}_{\mathbf{M}}(M_0, M_2)^{i_0+i_1},$$

$$\phi_1 \otimes \phi_0 \mapsto \phi_1 \circ \phi_0.$$

Lemma 3.6.5. *The composition homomorphism*

$$\text{Hom}_{\mathbf{M}}(M_1, M_2) \otimes_{\mathbb{K}} \text{Hom}_{\mathbf{M}}(M_0, M_1) \rightarrow \text{Hom}_{\mathbf{M}}(M_0, M_2)$$

is a strict homomorphism of DG \mathbb{K} -modules.

Exercise 3.6.6. Prove the lemma.

The lemma justifies the next definition.

Definition 3.6.7. Let $\mathbf{C}(\mathbf{M})$ be the \mathbb{K} -linear DG category whose objects are the complexes in \mathbf{M} , and the morphism DG \mathbb{K} -modules are $\text{Hom}_{\mathbf{M}}(M, N)$ from formulas (3.1.20) and (3.6.4).

It is clear, from comparing formulas (3.6.4) and (3.6.2), that the strict morphisms of complexes defined at the top of this subsection are the same as those from Definition 3.4.4(1). In other words, $\text{Str}(\mathbf{C}(\mathbf{M})) = \mathbf{C}_{\text{str}}(\mathbf{M})$.

Remark 3.6.8. A possible ambiguity could arise in the meaning of $\text{Hom}_{\mathbf{M}}(M, N)$ if $M, N \in \mathbf{M}$: does it mean the \mathbb{K} -module of morphisms in the category \mathbf{M} ? Or, if we view M and N as complexes by the canonical embedding $\mathbf{M} \subseteq \mathbf{C}(\mathbf{M})$, does $\text{Hom}_{\mathbf{M}}(M, N)$ mean the complex of \mathbb{K} -modules defined for complexes? It turns out that there is no actual difficulty: since the complex of \mathbb{K} -modules $\text{Hom}_{\mathbf{M}}(M, N)$ is concentrated in degree 0, we may view it as a single \mathbb{K} -module, and this is precisely the \mathbb{K} -module of morphisms in the category \mathbf{M} .

When $\mathbf{M} = \text{Mod } A$ for a ring A , there is no essential distinction between complexes and DG modules. The next proposition is the DG version of Example 3.1.22.

Proposition 3.6.9. *Let A be a central \mathbb{K} -ring. Given a complex $M \in \mathbf{C}(\text{Mod } A)$, with notation as in (3.6.1), define the DG A -module*

$$F(M) := \bigoplus_{i \in \mathbb{Z}} M^i,$$

with differential $d := \sum_{i \in \mathbb{Z}} d_M^i$. Then the functor

$$F : \mathbf{C}(\text{Mod } A) \rightarrow \text{DGMod } A$$

is an isomorphism of \mathbb{K} -linear DG categories.

Exercise 3.6.10. Prove this proposition. (Hint: choose good notation.)

3.7. The DG Category $\mathbf{C}(A, \mathbf{M})$. We now combine material from previous subsections. The concept introduced in the definition below is new. It is the DG version of Definition 3.1.23.

Definition 3.7.1. Let \mathbf{M} be a \mathbb{K} -linear abelian category, and let A be a central DG \mathbb{K} -ring. A *DG A -module in \mathbf{M}* is an object $M \in \mathbf{C}(\mathbf{M})$, together with a DG \mathbb{K} -ring homomorphism $f : A \rightarrow \text{End}_{\mathbf{M}}(M)$.

If M is a DG A -module in \mathbf{M} , then after forgetting the differentials, M becomes a graded A -module in \mathbf{M} .

Definition 3.7.2. Let \mathbf{M} be a \mathbb{K} -linear abelian category, let A be a central DG \mathbb{K} -ring, and let M, N be DG A -modules in \mathbf{M} . In Definition 3.1.25 we introduced the graded \mathbb{K} -module $\text{Hom}_{A, \mathbf{M}}(M, N)$. This is made into a DG \mathbb{K} -module with differential

$$d(\phi) := d_N \circ \phi - (-1)^i \cdot \phi \circ d_M$$

for $\phi \in \text{Hom}_{A, \mathbf{M}}(M, N)^i$.

When we have to be specific, we denote the differential of $\text{Hom}_{A, \mathbf{M}}(M, N)$ by d_{Hom} , $d_{A, \mathbf{M}}$, or $d_{\text{Hom}_{A, \mathbf{M}}(M, N)}$.

As we have seen before (in Lemmas 3.6.5 and 3.4.3), given morphisms

$$\phi_k \in \text{Hom}_{A, \mathbf{M}}(M_k, M_{k+1})^{i_k}$$

for $k \in \{0, 1\}$, we have

$$\phi_1 \circ \phi_0 \in \text{Hom}_{A, \mathbf{M}}(M_0, M_2)^{i_0+i_1},$$

and

$$d(\phi_1 \circ \phi_0) = d(\phi_1) \circ \phi_0 + (-1)^{i_1} \cdot \phi_1 \circ d(\phi_0).$$

Also the identity automorphism $1_M = \text{id}_M$ belongs to $\text{Hom}_{A, \mathbf{M}}(M, M)^0$, and $d(1_M) = 0$. Therefore the next definition is legitimate.

Definition 3.7.3. Let \mathbf{M} be a \mathbb{K} -linear abelian category, and let A be a central DG \mathbb{K} -ring. The \mathbb{K} -linear DG category of DG A -modules in \mathbf{M} is denoted by $\mathbf{C}(A, \mathbf{M})$. The morphism DG modules are

$$\mathrm{Hom}_{\mathbf{C}(A, \mathbf{M})}(M_0, M_1) := \mathrm{Hom}_{A, \mathbf{M}}(M_0, M_1)$$

from Definition 3.7.2. The composition is that of $\mathbf{C}(\mathbf{M})$.

Notice that forgetting the action of A is a faithful \mathbb{K} -linear DG functor $\mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(\mathbf{M})$. On the other hand, forgetting the differentials is a fully faithful \mathbb{K} -linear graded functor $\mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{G}(A, \mathbf{M})$.

Example 3.7.4. If $A = \mathbb{K}$, then $\mathbf{C}(A, \mathbf{M}) = \mathbf{C}(\mathbf{M})$; and if $\mathbf{M} = \mathrm{Mod} \mathbb{K}$, then $\mathbf{C}(A, \mathbf{M}) = \mathbf{C}(A) = \mathrm{DGMod} A$.

Definition 3.7.5. In the situation of Definition 3.7.3:

- (1) The strict category of $\mathbf{C}(A, \mathbf{M})$ (see Definition 3.4.4(1)) is denoted by $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$.
- (2) The homotopy category of $\mathbf{C}(A, \mathbf{M})$ (see Definition 3.4.4(2)) is denoted by $\mathbf{K}(A, \mathbf{M})$.

The next proposition is merely an interpretation of the definitions; but it is worth recording.

Proposition 3.7.6. *Let $\phi : M \rightarrow N$ be a morphism in $\mathbf{C}(A, \mathbf{M})$. The next two conditions are equivalent:*

- (i) ϕ is strict.
- (ii) ϕ has degree 0 and $\phi \circ d_M = d_N \circ \phi$.

Remark 3.7.7. Here is a generalization of Definition 3.7.3. Instead of a central DG \mathbb{K} -ring A we can take a small \mathbb{K} -linear DG category A . We then define the \mathbb{K} -linear DG category

$$\mathbf{C}(A, \mathbf{M}) := \mathrm{DGFun}(A, \mathbf{C}(\mathbf{M}))$$

as in Exercise 3.5.8.

This is indeed a generalization of Definition 3.7.3: when A has a single object x , and we write $A := \mathrm{End}_A(x)$, then the functor $M \mapsto M(x)$ is an isomorphism of DG categories $\mathbf{C}(A, \mathbf{M}) \xrightarrow{\cong} \mathbf{C}(A, \mathbf{M})$.

In the special case of $\mathbf{M} = \mathrm{Mod} \mathbb{K}$, the DG category $\mathbf{C}(A, \mathbf{M})$ is what Keller [Kel] calls the DG category of *left DG A -modules*.

Practically everything we do in this book for $\mathbf{C}(A, \mathbf{M})$ holds in the more general context of $\mathbf{C}(A, \mathbf{M})$. However, in the more general context a lot of the intuition is lost, and some aspects become pretty cumbersome. This is the reason we decided to stick with the less general context.

3.8. Contravariant DG Functors. In this subsection we address the issue of reversing arrows in DG categories. As before we work over a commutative base ring \mathbb{K} .

Definition 3.8.1. Let \mathbf{C} and \mathbf{D} be \mathbb{K} -linear DG categories. A *contravariant \mathbb{K} -linear DG functor* $F : \mathbf{C} \rightarrow \mathbf{D}$ consists of a function

$$F : \mathrm{Ob}(\mathbf{C}) \rightarrow \mathrm{Ob}(\mathbf{D}),$$

and for each pair $M_0, M_1 \in \mathrm{Ob}(\mathbf{C})$ a homomorphism

$$F : \mathrm{Hom}_{\mathbf{C}}(M_0, M_1) \rightarrow \mathrm{Hom}_{\mathbf{D}}(F(M_1), F(M_0))$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$. The conditions are:

- (a) Units: $F(1_M) = 1_{F(M)}$.
- (b) Graded reversed composition: given morphisms

$$\phi_k \in \text{Hom}_{\mathbf{C}}(M_k, M_{k+1})^{i_k}$$

for $k \in \{0, 1\}$, there is equality

$$F(\phi_1 \circ \phi_0) = (-1)^{i_0 \cdot i_1} \cdot F(\phi_0) \circ F(\phi_1)$$

inside

$$\text{Hom}_{\mathbf{D}}(F(M_2), F(M_0))^{i_0+i_1}.$$

Warning: a contravariant DG functor is not literally a contravariant functor. Indeed, when the degrees i_0 and i_1 are odd, we could fail to have equality between the morphisms $F(\phi_1 \circ \phi_0)$ and $F(\phi_0) \circ F(\phi_1)$.

Here is the categorical version of Definition 3.3.11.

Definition 3.8.2. Let \mathbf{C} be a \mathbb{K} -linear DG category. The *opposite DG category* \mathbf{C}^{op} has the same set of objects. The morphism DG modules are

$$\text{Hom}_{\mathbf{C}^{\text{op}}}(M_0, M_1) := \text{Hom}_{\mathbf{C}}(M_1, M_0).$$

The composition \circ^{op} of \mathbf{C}^{op} is reversed and multiplied by signs:

$$\phi_0 \circ^{\text{op}} \phi_1 := (-1)^{i_0 \cdot i_1} \cdot \phi_1 \circ \phi_0$$

for morphisms

$$\phi_k \in \text{Hom}_{\mathbf{C}}(M_k, M_{k+1})^{i_k}.$$

One needs to verify that this is indeed a DG category. This is basically the same verification as in Exercise 3.3.12.

As before, we define the operation $\text{Op} : \mathbf{C} \rightarrow \mathbf{C}^{\text{op}}$ to be the identity on objects, and the identity on morphisms in reversed order, i.e.

$$\text{Op} = \text{id} : \text{Hom}_{\mathbf{C}}(M_0, M_1) \xrightarrow{\cong} \text{Hom}_{\mathbf{C}^{\text{op}}}(M_1, M_0).$$

Note that $(\mathbf{C}^{\text{op}})^{\text{op}} = \mathbf{C}$, and we denote the inverse operation $\mathbf{C}^{\text{op}} \rightarrow \mathbf{C}$ also by Op .

Proposition 3.8.3. *Let \mathbf{C} and \mathbf{D} be \mathbb{K} -linear DG categories.*

- (1) *The operations $\text{Op} : \mathbf{C} \rightarrow \mathbf{C}^{\text{op}}$ and $\text{Op} : \mathbf{C}^{\text{op}} \rightarrow \mathbf{C}$ are contravariant \mathbb{K} -linear DG functors.*
- (2) *If $F : \mathbf{C} \rightarrow \mathbf{D}$ is a contravariant \mathbb{K} -linear DG functor, then the composition $F \circ \text{Op} : \mathbf{C}^{\text{op}} \rightarrow \mathbf{D}$ is a \mathbb{K} -linear DG functor; and vice versa.*

Exercise 3.8.4. Prove the previous proposition.

Definitions 3.8.2 and 3.8.1 make sense for graded categories, by forgetting differentials. Thus for graded categories \mathbf{C} and \mathbf{D} we can talk about contravariant graded functors $\mathbf{C} \rightarrow \mathbf{D}$, and about the graded category \mathbf{C}^{op} .

We already met $\mathbf{G}(\mathbf{M})$, the category of graded objects in a \mathbb{K} -linear abelian category \mathbf{M} ; see Definition 3.1.21. It is a \mathbb{K} -linear graded category. Its objects are collections $M = \{M^i\}_{i \in \mathbb{Z}}$ of objects $M^i \in \mathbf{M}$.

Let \mathbf{M} and \mathbf{N} be \mathbb{K} -linear abelian categories, and let $F : \mathbf{M} \rightarrow \mathbf{N}$ be a contravariant \mathbb{K} -linear functor. For a graded object $M = \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{G}(\mathbf{M})$ let us define the graded object

$$(3.8.5) \quad \mathbf{G}(F)(M) := \{N^i\}_{i \in \mathbb{Z}} \in \mathbf{G}(\mathbf{N}), \quad N^i := F(M^{-i}) \in \mathbf{N}.$$

Next consider a pair of objects $M_0, M_1 \in \mathbf{G}(\mathbf{M})$ and a degree i morphism $\phi : M_0 \rightarrow M_1$ in $\mathbf{G}(\mathbf{M})$. Thus

$$\phi = \{\phi^j\}_{j \in \mathbb{Z}} \in \text{Hom}_{\mathbf{G}(\mathbf{M})}(M_0, M_1)^i,$$

where, as in formula (3.1.19), the j -th component of ϕ is

$$\phi^j \in \text{Hom}_{\mathbf{M}}(M_0^j, M_1^{j+i}).$$

We have objects $N_k := \mathbf{G}(F)(M_k) \in \mathbf{G}(\mathbf{N})$, for $k \in \{0, 1\}$, defined by (3.8.5). Explicitly, $N_k = \{N_k^i\}_{i \in \mathbb{Z}}$ and $N_k^i = F(M_k^{-i})$. For any $j \in \mathbb{Z}$ define the morphism

$$(3.8.6) \quad \psi^j := (-1)^{i \cdot j} \cdot F(\phi^{-j-i}) \in \text{Hom}_{\mathbf{N}}(N_1^j, N_0^{j+i}).$$

Collecting them we obtain a morphism

$$(3.8.7) \quad \mathbf{G}(F)(\phi) := \{\psi^j\}_{j \in \mathbb{Z}} \in \text{Hom}_{\mathbf{G}(\mathbf{N})}(N_1, N_0)^i.$$

Lemma 3.8.8. *The assignments (3.8.5) and (3.8.7) produce a contravariant \mathbb{K} -linear graded functor*

$$\mathbf{G}(F) : \mathbf{G}(\mathbf{M}) \rightarrow \mathbf{G}(\mathbf{N}).$$

Proof. Since for morphisms of degree 0 there is no sign twist, the identity automorphism $1_M = \{1_{M^i}\}_{i \in \mathbb{Z}}$ of $M = \{M^i\}_{i \in \mathbb{Z}}$ in $\mathbf{G}(\mathbf{M})$ is sent to the identity automorphism of $\mathbf{G}(F)(M)$ in $\mathbf{G}(\mathbf{N})$.

Next we look at morphisms

$$\phi_0 = \{\phi_0^j\}_{j \in \mathbb{Z}} \in \text{Hom}_{\mathbf{G}(\mathbf{M})}(M_0, M_1)^{i_0}$$

and

$$\phi_1 = \{\phi_1^j\}_{j \in \mathbb{Z}} \in \text{Hom}_{\mathbf{G}(\mathbf{M})}(M_1, M_2)^{i_1}.$$

The composition $\phi_1 \circ \phi_0$ has degree $i_0 + i_1$, and the j -th component of $\phi_1 \circ \phi_0$ is $\phi_1^{j+i_0} \circ \phi_0^j$. Therefore the j -th component of $\mathbf{G}(F)(\phi_1 \circ \phi_0)$ is

$$(3.8.9) \quad \begin{aligned} \mathbf{G}(F)(\phi_1 \circ \phi_0)^j &= (-1)^{j \cdot (i_0+i_1)} \cdot F(\phi_1^{-j-i_1} \circ \phi_0^{-j-(i_0+i_1)}) \\ &= (-1)^{j \cdot (i_0+i_1)} \cdot F(\phi_0^{-j-(i_0+i_1)}) \circ F(\phi_1^{-j-i_1}). \end{aligned}$$

On the other hand, the j -th component of $\mathbf{G}(F)(\phi_k)$ is

$$\mathbf{G}(F)(\phi_k)^j = (-1)^{j \cdot i_k} \cdot F(\phi_k^{-j-i_k}).$$

So the j -th component of

$$(-1)^{i_0 \cdot i_1} \cdot \mathbf{G}(F)(\phi_0) \circ \mathbf{G}(F)(\phi_1)$$

is

$$(3.8.10) \quad \begin{aligned} &(-1)^{i_0 \cdot i_1} \cdot (\mathbf{G}(F)(\phi_0) \circ \mathbf{G}(F)(\phi_1))^j \\ &= (-1)^{i_0 \cdot i_1} \cdot (-1)^{(j+i_1) \cdot i_0} \cdot F(\phi_0^{-(j+i_1)-i_0}) \circ (-1)^{j \cdot i_1} \cdot F(\phi_1^{-j-i_1}). \end{aligned}$$

We see that the morphisms (3.8.9) and (3.8.10) are equal. \square

Now we consider a complex $(M, d_M) \in \mathbf{C}(\mathbf{M})$. This is made up of a graded object $M = \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{G}(\mathbf{M})$ together with a differential $d_M = \{d_M^i\}_{i \in \mathbb{Z}}$, where $d_M^i : M^i \rightarrow M^{i+1}$. We can view d_M as an element of

$$\text{End}_{\mathbf{G}(\mathbf{M})}(M)^1 = \text{Hom}_{\mathbf{G}(\mathbf{M})}(M, M)^1.$$

We specify a differential $d_{\mathbf{G}(F)(M)}$ on the graded object $\mathbf{G}(F)(M) \in \mathbf{G}(\mathbf{N})$ as follows:

$$(3.8.11) \quad d_{\mathbf{G}(F)(M)} := -\mathbf{G}(F)(d_M) \in \text{End}_{\mathbf{G}(\mathbf{N})}(\mathbf{G}(F)(M))^1.$$

To be explicit, the component

$$d_{\mathbf{C}(F)(M)}^i : \mathbf{G}(F)(M)^i = F(M^{-i}) \rightarrow F(M^{-i-1}) = \mathbf{G}(F)(M)^{i+1}$$

of $d_{\mathbf{C}(F)(M)}$ is, by (3.8.6),

$$d_{\mathbf{C}(F)(M)}^i = (-1)^{i+1} \cdot F(d_M^{-i-1}).$$

This shows that our formula coincides with the one in [KaSc1, Remark 1.1.88].

Lemma 3.8.12. *The assignments (3.8.5), (3.8.7) and (3.8.11) produce a contravariant \mathbb{K} -linear DG functor*

$$\mathbf{C}(F) : \mathbf{C}(M) \rightarrow \mathbf{C}(N).$$

Proof. We must prove that for a pair of DG modules (M_0, d_{M_0}) and (M_1, d_{M_1}) in $\mathbf{C}(M)$ the strict homomorphism of graded \mathbb{K} -modules

$$\mathbf{G}(F) : \mathrm{Hom}_{\mathbf{G}(M)}(M_0, M_1) \rightarrow \mathrm{Hom}_{\mathbf{G}(N)}(\mathbf{G}(F)(M_1), \mathbf{G}(F)(M_0))$$

respects differentials. Take any

$$\phi \in \mathrm{Hom}_{\mathbf{G}(M)}(M_0, M_1)^i.$$

By definition we have

$$d(\phi) = d_{M_1} \circ \phi - (-1)^i \cdot \phi \circ d_{M_0}.$$

Using the fact that $\mathbf{G}(F)$ is a contravariant graded functor, we obtain these equalities:

$$\begin{aligned} \mathbf{G}(F)(d(\phi)) &= (-1)^i \cdot \mathbf{G}(F)(\phi) \circ \mathbf{G}(F)(d_{M_1}) - (-1)^i \cdot (-1)^i \cdot \mathbf{G}(F)(d_{M_0}) \circ \mathbf{G}(F)(\phi) \\ &= d_{\mathbf{C}(F)(M_0)} \circ \mathbf{G}(F)(\phi) - (-1)^i \cdot \mathbf{G}(F)(\phi) \circ d_{\mathbf{C}(F)(M_1)} \\ &= d(\mathbf{G}(F)(\phi)). \end{aligned}$$

□

The sign appearing in formula (3.8.11) might seem arbitrary. Besides being the only sign for which Lemma 3.8.12 holds, there is another explanation, which can be seen in the next exercise.

Exercise 3.8.13. Take $M = N := \mathrm{Mod} \mathbb{K}$, and consider the contravariant additive functor $F := \mathrm{Hom}_{\mathbb{K}}(-, \mathbb{K})$ from M to itself. Let $M \in \mathbf{C}(M)$; we can view M as a complex of \mathbb{K} -modules or as a DG \mathbb{K} -module, as done in Proposition 3.6.9. Show that

$$\mathbf{C}(F)(M) \cong \mathrm{Hom}_{\mathbb{K}}(M, \mathbb{K})$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$, where the second object is the graded module from formula (3.1.20), with the differential d from formula (3.2.5).

The next theorem will help us later when studying contravariant triangulated functors.

Theorem 3.8.14. *Let A be a central DG \mathbb{K} -ring and let M be a \mathbb{K} -linear abelian category. There is a canonical \mathbb{K} -linear isomorphism of DG categories*

$$\mathrm{Flip} : \mathbf{C}(A, M)^{\mathrm{op}} \xrightarrow{\cong} \mathbf{C}(A^{\mathrm{op}}, M^{\mathrm{op}}).$$

Proof. According to Proposition 3.8.3 there is a contravariant DG functor

$$\mathrm{Op} : \mathbf{C}(A, \mathbf{M})^{\mathrm{op}} \rightarrow \mathbf{C}(A, \mathbf{M}).$$

It is bijective on objects and morphisms. We are going to construct a contravariant DG functor

$$E : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(A^{\mathrm{op}}, \mathbf{M}^{\mathrm{op}})$$

which is also bijective on objects and morphisms. The composed DG functor

$$\mathrm{Flip} := E \circ \mathrm{Op} : \mathbf{C}(A, \mathbf{M})^{\mathrm{op}} \rightarrow \mathbf{C}(A^{\mathrm{op}}, \mathbf{M}^{\mathrm{op}})$$

will have the desired properties.

Let us construct E . We start with the contravariant additive functor

$$F := \mathrm{Op} : \mathbf{M} \rightarrow \mathbf{M}^{\mathrm{op}}.$$

Lemma 3.8.12 says that

$$\mathbf{C}(F) : \mathbf{C}(\mathbf{M}) \rightarrow \mathbf{C}(\mathbf{M}^{\mathrm{op}})$$

is a contravariant DG functor. Recall that an object of $\mathbf{C}(A, \mathbf{M})$ is a triple (M, d_M, f_M) , where $M \in \mathbf{G}(\mathbf{M})$; d_M is a differential on the graded object M ; and

$$f_M : A \rightarrow \mathrm{End}_{\mathbf{C}(\mathbf{M})}(M)$$

is a DG ring homomorphism. See Definitions 3.1.25, 3.7.1 and 3.7.3. Define

$$(N, d_N) := \mathbf{C}(F)(M, d_M) \in \mathbf{C}(\mathbf{M}^{\mathrm{op}}).$$

Since

$$\mathbf{C}(F) : \mathrm{End}_{\mathbf{C}(\mathbf{M})}(M, d_M) \rightarrow \mathrm{End}_{\mathbf{C}(\mathbf{M}^{\mathrm{op}})}(N, d_N)$$

is a DG ring anti-homomorphism (by which we mean the single object version of a contravariant DG functor), and $\mathrm{Op} : A^{\mathrm{op}} \rightarrow A$ is also such an anti-homomorphism, it follows that

$$f_N := \mathbf{C}(F) \circ f_M \circ \mathrm{Op} : A^{\mathrm{op}} \rightarrow \mathrm{End}_{\mathbf{C}(\mathbf{M}^{\mathrm{op}})}(N, d_N)$$

is a DG ring homomorphism. Thus

$$E(M, d_M, f_M) := (N, d_N, f_N)$$

is an object of $\mathbf{C}(A^{\mathrm{op}}, \mathbf{M}^{\mathrm{op}})$. In this way we have a function

$$E : \mathrm{Ob}(\mathbf{C}(A, \mathbf{M})) \rightarrow \mathrm{Ob}(\mathbf{C}(A^{\mathrm{op}}, \mathbf{M}^{\mathrm{op}})),$$

and it is clearly bijective.

The operation of E on morphisms is of course that of $\mathbf{C}(F)$. It remains to verify that the resulting morphisms in $\mathbf{C}(\mathbf{M}^{\mathrm{op}})$ respect the action of elements of A^{op} . Namely that the condition in Definition 3.1.25 is satisfied. Take any morphism

$$\phi \in \mathrm{Hom}_{\mathbf{C}(A, \mathbf{M})}((M_0, d_{M_0}, f_{M_0}), (M_1, d_{M_1}, f_{M_1}))^i$$

and any element $a \in (A^{\mathrm{op}})^j$; and write

$$(N_k, d_{N_k}, f_{N_k}) := E(M_k, d_{M_k}, f_{M_k})$$

and

$$\psi := \mathbf{G}(F)(\phi) \in \mathrm{Hom}_{\mathbf{C}(\mathbf{M}^{\mathrm{op}})}((N_1, d_{N_1}), (N_0, d_{N_0}))^i.$$

We have to prove that

$$\psi \circ f_{N_1}(a) = (-1)^{i \cdot j} \cdot f_{N_0}(a) \circ \psi.$$

This is done using Lemma 3.8.8, like in the proof of Lemma 3.8.12; and we leave this final touch to the reader. \square

Remark 3.8.15. Combined with Proposition 3.8.3, Theorem 3.8.14 allows us to replace a contravariant DG functor

$$F : \mathbf{C}(A, M) \rightarrow \mathbf{D}$$

with a usual, covariant, DG functor

$$F \circ \text{Flip}^{-1} : \mathbf{C}(A^{\text{op}}, M^{\text{op}}) \rightarrow \mathbf{D}.$$

This replacement is going to be very useful when discussing formal properties, such as existence of derived functors etc.

However, in practical terms (e.g. for producing resolutions of DG modules), the category $\mathbf{C}(A^{\text{op}}, M^{\text{op}})$ is not very helpful. The reason is that the opposite abelian category M^{op} is almost always a synthetic construction (it does not “really exist in concrete terms”). See Remark 2.6.21, that explains why \mathbf{Ab}^{op} is not equivalent to \mathbf{Ab} .

We are going to manoeuvre between the two approaches for reversal of morphisms, each time choosing the more useful approach.

4. TRANSLATIONS AND STANDARD CONES

As before, we fix a \mathbb{K} -linear abelian category \mathbf{M} , and a central DG \mathbb{K} -ring A . In this section we study the translation functor and the standard cone of a strict morphism, all in the context of the DG category $\mathbf{C}(A, \mathbf{M})$.

4.1. The Translation Functor. The translation functor goes back to the beginnings of derived categories – see Remark 4.1.11. The treatment in this subsection (with the operator t) is taken from [Ye11, Section 1].

Definition 4.1.1. Let $M = \{M^i\}_{i \in \mathbb{Z}}$ be a graded module in \mathbf{M} , i.e. an object of $\mathbf{G}(\mathbf{M})$. The *translation* of M is the object

$$T(M) = \{T(M)^i\}_{i \in \mathbb{Z}} \in \mathbf{G}(\mathbf{M})$$

defined as follows: the graded component of degree i of $T(M)$ is $T(M)^i := M^{i+1}$.

Definition 4.1.2 (The little t operator). Let $M = \{M^i\}_{i \in \mathbb{Z}}$ be a graded module in \mathbf{M} , i.e. an object of $\mathbf{G}(\mathbf{M})$. We define

$$t_M : M \rightarrow T(M)$$

to be the degree -1 morphism of graded objects of \mathbf{M} , that in every degree $i + 1$ is identity morphism

$$t_M := 1_{M^{i+1}} : M^{i+1} \xrightarrow{\cong} M^{i+1} = T(M)^i$$

of the object M^{i+1} in \mathbf{M} .

Note that the morphism

$$t_M \in \mathrm{Hom}_{\mathbf{G}(\mathbf{M})}(M, T(M))^{-1}$$

is invertible, with inverse

$$t_M^{-1} \in \mathrm{Hom}_{\mathbf{G}(\mathbf{M})}(T(M), M)^1.$$

Definition 4.1.3. Let $M = \{M^i\}_{i \in \mathbb{Z}}$ be a DG A -module in \mathbf{M} , i.e. an object of $\mathbf{C}(A, \mathbf{M})$. The *translation* of M is the object

$$T(M) \in \mathbf{C}(A, \mathbf{M})$$

defined as follows.

- (1) As graded object of \mathbf{M} , it is as specified in Definition 4.1.1.
- (2) The differential $d_{T(M)}$ is defined by the formula

$$d_{T(M)} := -t_M \circ d_M \circ t_M^{-1}.$$

- (3) Let $f_M : A \rightarrow \mathrm{End}_{\mathbf{M}}(M)$ be the DG ring homomorphism that determines the action of A on M . Then

$$f_{T(M)} : A \rightarrow \mathrm{End}_{\mathbf{M}}(T(M))$$

is defined by

$$f_{T(M)}(a) := (-1)^j \cdot t_M \circ f_M(a) \circ t_M^{-1}$$

for $a \in A^j$.

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Thus, the differential $d_{\mathbf{T}(M)} = \{d_{\mathbf{T}(M)}^i\}_{i \in \mathbb{Z}}$ makes this diagram in \mathbf{M} commutative for every i :

$$\begin{array}{ccc} \mathbf{T}(M)^i & \xrightarrow{d_{\mathbf{T}(M)}^i} & \mathbf{T}(M)^{i+1} \\ \uparrow t_M & & \uparrow t_M \\ M^{i+1} & \xrightarrow{-d_M^{i+1}} & M^{i+2} \end{array}$$

And the left A -module structure makes this diagram in \mathbf{M} commutative for every i and every $a \in A^j$:

$$\begin{array}{ccc} \mathbf{T}(M)^i & \xrightarrow{f_{\mathbf{T}(M)}(a)} & \mathbf{T}(M)^{i+j} \\ \uparrow t_M & & \uparrow t_M \\ M^{i+1} & \xrightarrow{(-1)^j \cdot f_M(a)} & M^{i+j+1} \end{array}$$

Warning: t_M is not a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, because it has degree -1 .

Proposition 4.1.4. *The morphisms t_M and t_M^{-1} are cocycles, in the DG \mathbb{K} -modules $\text{Hom}_{A, \mathbf{M}}(M, \mathbf{T}(M))$ and $\text{Hom}_{A, \mathbf{M}}(\mathbf{T}(M), M)$ respectively.*

Proof. We use the notation d_{Hom} for the differential in the DG module $\text{Hom}_{A, \mathbf{M}}(M, \mathbf{T}(M))$. Let us calculate. Because t_M has degree -1 , we have

$$\begin{aligned} d_{\text{Hom}}(t_M) &= d_{\mathbf{T}(M)} \circ t_M + t_M \circ d_M \\ &= (-t_M \circ d_M \circ t_M^{-1}) \circ t_M + t_M \circ d_M = 0. \end{aligned}$$

As for t_M^{-1} : this is done using the graded Leibniz rule, just like in the proof Proposition 3.4.7. \square

Definition 4.1.5. Given a morphism

$$\phi \in \text{Hom}_{A, \mathbf{M}}(M, N)^i,$$

we define the morphism

$$\mathbf{T}(\phi) \in \text{Hom}_{A, \mathbf{M}}(\mathbf{T}(M), \mathbf{T}(N))^i$$

to be

$$\mathbf{T}(\phi) := (-1)^i \cdot t_N \circ \phi \circ t_M^{-1}.$$

To clarify this definition, let us write $\phi = \{\phi^j\}_{j \in \mathbb{Z}}$, so that $\phi^j : M^j \rightarrow N^{j+i}$ is a morphism in \mathbf{M} . Then

$$\mathbf{T}(\phi)^j : \mathbf{T}(M)^j \rightarrow \mathbf{T}(N)^{j+i}$$

is

$$\mathbf{T}(\phi)^j = (-1)^i \cdot t_N \circ \phi^{j+1} \circ t_M^{-1}.$$

The corresponding commutative diagram in \mathbf{M} , for each i, j , is:

$$(4.1.6) \quad \begin{array}{ccc} \mathbf{T}(M)^j & \xrightarrow{\mathbf{T}(\phi)^j} & \mathbf{T}(N)^{j+i} \\ \uparrow t_M & & \uparrow t_N \\ M^{j+1} & \xrightarrow{(-1)^i \cdot \phi^{j+1}} & N^{j+i} \end{array}$$

Theorem 4.1.7. *Let \mathbf{M} be \mathbb{K} -linear abelian category and let A be a central DG \mathbb{K} -ring.*

(1) The assignments $M \mapsto T(M)$ and $\phi \mapsto T(\phi)$ are a \mathbb{K} -linear DG functor

$$T : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(A, \mathbf{M}).$$

(2) The collection $t := \{t_M\}_{M \in \mathbf{C}(A, \mathbf{M})}$ is a degree -1 isomorphism

$$t : \text{Id} \rightarrow T$$

of DG functors from $\mathbf{C}(A, \mathbf{M})$ to itself.

Proof. (1) Take morphisms $\phi_1 : M_0 \rightarrow M_1$ and $\phi_2 : M_1 \rightarrow M_2$, of degrees i_1 and i_2 respectively. Then

$$\begin{aligned} T(\phi_2 \circ \phi_1) &= (-1)^{i_1+i_2} \cdot t_{M_2} \circ (\phi_2 \circ \phi_1) \circ t_{M_0}^{-1} \\ &= (-1)^{i_1+i_2} \cdot t_{M_2} \circ \phi_2 \circ (t_{M_1}^{-1} \circ t_{M_1}) \circ \phi_1 \circ t_{M_0}^{-1} \\ &= ((-1)^{i_2} \cdot t_{M_2} \circ \phi_2 \circ t_{M_1}^{-1}) \circ ((-1)^{i_1} \cdot t_{M_1} \circ \phi_1 \circ t_{M_0}^{-1}) \\ &= T(\phi_2) \circ T(\phi_1). \end{aligned}$$

Clearly $T(1_M) = 1_M$, and

$$T(\lambda \cdot \phi + \psi) = \lambda \cdot T(\phi) + T(\psi)$$

for all $\lambda \in \mathbb{K}$ and $\phi, \psi \in \text{Hom}_{A, \mathbf{M}}(M_0, M_1)^i$. So T is a \mathbb{K} -linear graded functor.

By Proposition 4.1.4 we know that $d \circ t = -t \circ d$ and $d \circ t^{-1} = -t^{-1} \circ d$. This implies that for any morphism ϕ in $\mathbf{C}(A, \mathbf{M})$, we have $T(d(\phi)) = d(T(\phi))$. So T is a DG functor.

(2) Take any $\phi \in \text{Hom}_{A, \mathbf{M}}(M_0, M_1)^i$. We have to prove that

$$t_{M_1} \circ \phi = (-1)^i \cdot T(\phi) \circ t_{M_0}$$

as elements of $\text{Hom}_{A, \mathbf{M}}(M_0, T(M_1))^{i+1}$. But by Definition 4.1.5 we have

$$T(\phi) \circ t_{M_0} = ((-1)^i \cdot t_{M_1} \circ \phi \circ t_{M_0}^{-1}) \circ t_{M_0} = (-1)^i \cdot t_{M_1} \circ \phi.$$

□

Definition 4.1.8. We call T the *translation functor* of the DG category $\mathbf{C}(A, \mathbf{M})$.

Corollary 4.1.9.

- (1) The functor T is an automorphism of the category $\mathbf{C}(A, \mathbf{M})$.
- (2) For any $k, l \in \mathbb{Z}$ there is an equality of functors $T^l \circ T^k = T^{l+k}$.
- (3) For any k the functor

$$T^k : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(A, \mathbf{M})$$

is an auto-equivalence of DG categories.

Proof. (1) This is because the functor T is bijective on the set of objects of $\mathbf{C}(A, \mathbf{M})$ and on the sets of morphisms.

(2) By part (1) of this corollary, the inverse T^{-1} is a uniquely defined functor (not just up to an isomorphism of functors).

(3) By part (1) of the theorem above. □

Proposition 4.1.10. Consider any $M \in \mathbf{C}(A, \mathbf{M})$.

- (1) There is equality

$$t_{T(M)} = -T(t_M)$$

of degree -1 morphisms $T(M) \rightarrow T^2(M)$ in $\mathbf{C}(A, \mathbf{M})$.

(2) *There is equality*

$$\mathfrak{t}_{T^{-1}(M)} = -T^{-1}(\mathfrak{t}_M)$$

of degree -1 morphisms

$$T^{-1}(M) \rightarrow T(T^{-1}(M)) = M = T^{-1}(T(M))$$

in $\mathbf{C}(A, M)$.

Proof. (1) This is an easy calculation, using Definition 4.1.5:

$$T(\mathfrak{t}_M) = -\mathfrak{t}_{T(M)} \circ \mathfrak{t}_M \circ \mathfrak{t}_M^{-1} = -\mathfrak{t}_{T(M)}.$$

(2) A similar calculation. □

Remark 4.1.11. There are several names in the literature for the translation functor T : *twist*, *shift* and *suspension*. There are also several notations: $T(M) = M[1] = \Sigma M$. In the later part of this book we shall use the notation $M[k] := T^k(M)$ for the k -th translation.

4.2. The Standard Cone of a Strict Morphism. As before, we fix a \mathbb{K} -linear abelian category M , and a central DG \mathbb{K} -ring A . Here is the cone construction in $\mathbf{C}(A, M)$, as it looks using the operator \mathfrak{t} .

Definition 4.2.1. Let $\phi : M \rightarrow N$ be a strict morphism in $\mathbf{C}(A, M)$. The *standard cone of ϕ* is the object $\text{Cone}(\phi) \in \mathbf{C}(A, M)$ defined as follows. As a graded A -module in M we let

$$\text{Cone}(\phi) := N \oplus T(M).$$

The differential d_{Cone} is this: if we express the graded module as a column

$$\text{Cone}(\phi) = \begin{bmatrix} N \\ T(M) \end{bmatrix},$$

then d_{Cone} is left multiplication by the matrix

$$d_{\text{Cone}} := \begin{bmatrix} d_N & \phi \circ \mathfrak{t}_M^{-1} \\ 0 & d_{T(M)} \end{bmatrix}$$

of degree 1 morphisms of graded A -module in M .

In other words,

$$d_{\text{Cone}}^i : \text{Cone}(\phi)^i \rightarrow \text{Cone}(\phi)^{i+1}$$

is

$$d_{\text{Cone}}^i = d_N^i + d_{T(M)}^i + \phi^{i+1} \circ \mathfrak{t}_M^{-1},$$

where $\phi^{i+1} \circ \mathfrak{t}_M^{-1}$ is the composed morphism

$$T(M)^i \xrightarrow{\mathfrak{t}_M^{-1}} M^{i+1} \xrightarrow{\phi^{i+1}} N^{i+1}.$$

Let us denote by

$$(4.2.2) \quad e_\phi : N \rightarrow N \oplus T(M)$$

the embedding, and by

$$(4.2.3) \quad p_\phi : N \oplus T(M) \rightarrow T(M)$$

the projection. Thus, as matrices we have

$$e_\phi = \begin{bmatrix} 1_N \\ 0 \end{bmatrix} \quad \text{and} \quad p_\phi = \begin{bmatrix} 0 & 1_{\mathbf{T}(M)} \end{bmatrix}.$$

The standard cone of ϕ sits in the exact sequence

$$(4.2.4) \quad 0 \rightarrow N \xrightarrow{e_\phi} \text{Cone}(\phi) \xrightarrow{p_\phi} \mathbf{T}(M) \rightarrow 0$$

in the abelian category $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

Definition 4.2.5. Let $\phi : M \rightarrow N$ be a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. The diagram

$$M \xrightarrow{\phi} N \xrightarrow{e_\phi} \text{Cone}(\phi) \xrightarrow{p_\phi} \mathbf{T}(M)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ is called the *standard triangle* associated to ϕ .

The cone construction is functorial, in the following sense.

Proposition 4.2.6. *Let*

$$\begin{array}{ccc} M_0 & \xrightarrow{\phi_0} & N_0 \\ \psi \downarrow & & \downarrow \chi \\ M_1 & \xrightarrow{\phi_1} & N_1 \end{array}$$

be a commutative diagram in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Then

$$(4.2.7) \quad (\chi, \mathbf{T}(\psi)) : \text{Cone}(\phi_0) \rightarrow \text{Cone}(\phi_1)$$

is a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, and the diagram

$$\begin{array}{ccccccc} M_0 & \xrightarrow{\phi_0} & N_0 & \xrightarrow{e_{\phi_0}} & \text{Cone}(\phi_0) & \xrightarrow{p_{\phi_0}} & \mathbf{T}(M_0) \\ \psi \downarrow & & \downarrow \chi & & (\chi, \mathbf{T}(\psi)) \downarrow & & \downarrow \mathbf{T}(\psi) \\ M_1 & \xrightarrow{\phi_1} & N_1 & \xrightarrow{e_{\phi_1}} & \text{Cone}(\phi_1) & \xrightarrow{p_{\phi_1}} & \mathbf{T}(M_1) \end{array}$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ is commutative.

Proof. This is a simple consequence of the definitions. □

5. PROPERTIES OF DG FUNCTORS

In this section we fix central DG \mathbb{K} -rings A and B , and \mathbb{K} -linear abelian categories \mathbf{M} and \mathbf{N} . The \mathbb{K} -linear DG categories $\mathbf{C}(A, \mathbf{M})$ and $\mathbf{C}(B, \mathbf{N})$ were introduced in Subsection 3.7. Graded functors, DG functors, and morphisms between them, were introduced in Subsection 3.5.

Some of the material in this section is new – such as the gauge in Definition 5.1.1, and its role in the characterization of DG functors in Theorem 5.1.2. We think that Theorem 5.3.7, which says that a DG functor commutes with cones, is also a new result.

5.1. The Gauge of a Graded Functor. The next definition is new.

Definition 5.1.1. Let

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N})$$

be a \mathbb{K} -linear graded functor. For any object $M \in \mathbf{C}(A, \mathbf{M})$ let

$$\gamma_{F,M} := d_{F(M)} - F(d_M) \in \text{Hom}_{B,\mathbf{N}}(F(M), F(M))^1.$$

The collection of morphisms

$$\gamma_F := \{\gamma_{F,M}\}_{M \in \mathbf{C}(A, \mathbf{M})}$$

is called the *gauge of F* .

Theorem 5.1.2. ¹ *The following two conditions are equivalent for a \mathbb{K} -linear graded functor*

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N}).$$

- (i) *F is a DG functor.*
- (ii) *The gauge γ_F is a degree 1 morphism of graded functors $\gamma_F : F \rightarrow F$.*

Proof. Recall that F is a DG functor (condition (i)) iff

$$(5.1.3) \quad (F \circ d_{A,\mathbf{M}})(\phi) = (d_{B,\mathbf{N}} \circ F)(\phi)$$

for every $\phi \in \text{Hom}_{A,\mathbf{M}}(M_0, M_1)^i$. And γ_F is a degree 1 morphism of graded functors (condition (ii)) iff

$$(5.1.4) \quad \gamma_{F,M_1} \circ F(\phi) = (-1)^i \cdot F(\phi) \circ \gamma_{F,M_0}$$

for every such ϕ .

Here is the calculation. Because F is a graded functor, we get

$$(5.1.5) \quad \begin{aligned} F(d_{A,\mathbf{M}}(\phi)) &= F(d_{M_1} \circ \phi - (-1)^i \cdot \phi \circ d_{M_0}) \\ &= F(d_{M_1}) \circ F(\phi) - (-1)^i \cdot F(\phi) \circ F(d_{M_0}) \end{aligned}$$

and

$$(5.1.6) \quad d_{B,\mathbf{N}}(F(\phi)) = d_{F(M_1)} \circ F(\phi) - (-1)^i \cdot F(\phi) \circ d_{F(M_0)}.$$

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¹This theorem is due to Rishi Vyas.

Using equations (5.1.5) and (5.1.6), and the definition of γ_F , we obtain

$$\begin{aligned}
 (F \circ d_{A,M} - d_{B,N} \circ F)(\phi) &= F(d_{A,M}(\phi)) - d_{B,N}(F(\phi)) \\
 (5.1.7) \quad &= (F(d_{M_1}) - d_{F(M_1)}) \circ F(\phi) - (-1)^i \cdot F(\phi) \circ (F(d_{M_0}) - d_{F(M_0)}) \\
 &= -\gamma_{F,M_1} \circ F(\phi) + (-1)^i \cdot F(\phi) \circ \gamma_{F,M_0}.
 \end{aligned}$$

Finally, the vanishing of the first expression in (5.1.7) is the same as equality in (5.1.3); whereas the vanishing of the last expression in (5.1.7) is the same as equality in (5.1.4). \square

5.2. The Translation Isomorphism of a DG Functor. The translation functor of $\mathbf{C}(A, M)$ will be denoted here by $T_{A,M}$. Recall that for an object $M \in \mathbf{C}(A, M)$, we have the little t operator

$$t_M \in \text{Hom}_{A,M}(M, T_{A,M}(M))^{-1}.$$

This is an isomorphism in $\mathbf{C}(A, M)$. Likewise for the DG category $\mathbf{C}(B, N)$.

Definition 5.2.1. Let

$$F : \mathbf{C}(A, M) \rightarrow \mathbf{C}(B, N)$$

be a \mathbb{K} -linear DG functor. For an object $M \in \mathbf{C}(A, M)$, let

$$\tau_{F,M} : F(T_{A,M}(M)) \rightarrow T_{B,N}(F(M))$$

be the isomorphism

$$\tau_{F,M} := t_{F(M)} \circ F(t_M)^{-1}$$

in $\mathbf{C}(B, N)$, called the *translation isomorphism* of the functor F at the object M .

The isomorphism $\tau_{F,M}$ sits in the following commutative diagram

$$\begin{array}{ccc}
 F(T_{A,M}(M)) & \xrightarrow{\tau_{F,M}} & T_{B,N}(F(M)) \\
 \uparrow F(t_M) & \nearrow t_{F(M)} & \\
 F(M) & &
 \end{array}$$

of isomorphisms in the category $\mathbf{C}(B, N)$.

Proposition 5.2.2. $\tau_{F,M}$ is an isomorphism in $\mathbf{C}_{\text{str}}(B, N)$.

Proof. We know that $\tau_{F,M}$ is an isomorphism in $\mathbf{C}(B, N)$. It suffices to prove that both $\tau_{F,M}$ and its inverse $\tau_{F,M}^{-1}$ are strict morphisms. Now by Proposition 4.1.4, t_M and t_M^{-1} are cocycles. Therefore, $F(t_M)$ and $F(t_M)^{-1} = F(t_M^{-1})$ are cocycles. For the same reason, $t_{F(M)}$ and $t_{F(M)}^{-1}$ are cocycles. But $\tau_{F,M} = t_{F(M)} \circ F(t_M)^{-1}$, and $\tau_{F,M}^{-1} = F(t_M) \circ t_{F(M)}^{-1}$. \square

Theorem 5.2.3. Let

$$F : \mathbf{C}(A, M) \rightarrow \mathbf{C}(B, N)$$

be a \mathbb{K} -linear DG functor. Then the collection $\tau_F := \{\tau_{F,M}\}_{M \in \mathbf{C}(A,M)}$ is an isomorphism

$$\tau_F : F \circ T_{A,M} \xrightarrow{\cong} T_{B,N} \circ F$$

of functors

$$\mathbf{C}_{\text{str}}(A, M) \rightarrow \mathbf{C}_{\text{str}}(B, N).$$

The slogan summarizing this theorem is “A DG functor commutes with translations”.

Proof. In view of Proposition 5.2.2, all we need to prove is that τ_F is a morphism of functors (i.e. it is a natural transformation).

Let $\phi : M_0 \rightarrow M_1$ be a morphism in $\mathbf{C}_{\text{str}}(A, M)$. We must prove that the diagram

$$\begin{array}{ccc} (F \circ T_{A,M})(M_0) & \xrightarrow{\tau_{F,M_0}} & (T_{B,N} \circ F)(M_0) \\ (F \circ T_{A,M})(\phi) \downarrow & & \downarrow (T_{B,N} \circ F)(\phi) \\ (F \circ T_{A,M})(M_1) & \xrightarrow{\tau_{F,M_1}} & (T_{B,N} \circ F)(M_1) \end{array}$$

in $\mathbf{C}_{\text{str}}(B, N)$ is commutative. This will be true if the next diagram

$$\begin{array}{ccccc} (F \circ T_{A,M})(M_0) & \xleftarrow{F(t_{M_0})} & F(M_0) & \xrightarrow{t_{F(M_0)}} & (T_{B,N} \circ F)(M_0) \\ (F \circ T_{A,M})(\phi) \downarrow & & F(\phi) \downarrow & & \downarrow (T_{B,N} \circ F)(\phi) \\ (F \circ T_{A,M})(M_1) & \xleftarrow{F(t_{M_1})} & F(M_1) & \xrightarrow{t_{F(M_1)}} & (T_{B,N} \circ F)(M_1) \end{array}$$

in $\mathbf{C}(B, N)$, whose horizontal arrows are isomorphisms, is commutative. For this to be true, it is enough to prove that both squares in this diagram are commutative. This is true by Theorem 4.1.7(2) \square

Recall that the translation T and all its powers are DG functors. To finish this subsection, we calculate their translation isomorphisms.

Proposition 5.2.4. *For any integer k , the translation isomorphism of the DG functor T^k is*

$$\tau_{T^k} = (-1)^k \cdot \text{id}_{T^{k+1}},$$

where $\text{id}_{T^{k+1}}$ is the identity automorphism of the functor T^{k+1} .

Proof. By Definition 5.2.1 and Proposition 4.1.10(1), for $k = 1$ the formula is

$$\tau_{T,M} = t_{T(M)} \circ T(t_M)^{-1} = -\text{id}_{T^2(M)},$$

where $\text{id}_{T^2(M)}$ is the identity automorphism of the DG module $T^2(M)$. Hence $\tau_T = -\text{id}_{T^2}$. For other integers k the calculation is similar. \square

5.3. Cones and DG Functors.

Definition 5.3.1. The subcategory $\mathbf{C}^0(A, M)$ of $\mathbf{C}(A, M)$ is defined to be the subcategory on all objects, but with degree 0 morphisms only.

There are inclusions of categories (faithful functors, identities on objects)

$$\mathbf{C}_{\text{str}}(A, M) \xrightarrow{\subseteq} \mathbf{C}^0(A, M) \xrightarrow{\subseteq} \mathbf{C}(A, M).$$

Forgetting the differentials is a fully faithful functor

$$(5.3.2) \quad \mathbf{C}^0(A, M) \rightarrow \mathbf{G}^0(A, M);$$

see Definition 3.1.13.

Let

$$F : \mathbf{C}(A, M) \rightarrow \mathbf{C}(B, N)$$

be a \mathbb{K} -linear DG functor. Given a morphism $\phi : M_0 \rightarrow M_1$ in $\mathbf{C}_{\text{str}}(A, M)$, we have a morphism

$$F(\phi) : F(M_0) \rightarrow F(M_1)$$

in $\mathbf{C}_{\text{str}}(B, N)$, and objects $F(\text{Cone}_{A,M}(\phi))$ and $\text{Cone}_{B,N}(F(\phi))$ in $\mathbf{C}(B, N)$. By definition (and the fully faithful functor (5.3.2)) there is a canonical isomorphism

$$(5.3.3) \quad \text{Cone}_{A,M}(\phi) \cong M_1 \oplus T_{A,M}(M_0)$$

in $\mathbf{C}^0(A, M)$. Since F is an additive functor, it commutes with finite direct sums, and therefore there is a canonical isomorphism

$$(5.3.4) \quad F(\text{Cone}_{A,M}(\phi)) \cong F(M_1) \oplus F(T_{A,M}(M_0))$$

in $\mathbf{C}^0(B, N)$. And by definition there is a canonical isomorphism

$$(5.3.5) \quad \text{Cone}_{B,N}(F(\phi)) \cong F(M_1) \oplus T_{B,N}(F(M_0))$$

in $\mathbf{C}^0(B, N)$. Warning: the isomorphisms (5.3.3), (5.3.4) and (5.3.5) are usually not strict! They are degree 0 isomorphisms of graded modules, but they might not commute with the differentials; see Proposition 3.7.6. The differentials on the right sides are diagonal matrices, but on the left sides they are upper-triangular matrices (see Definition 4.2.1).

Lemma 5.3.6. *Let*

$$F, G : \mathbf{C}(A, M) \rightarrow \mathbf{C}(B, N)$$

be \mathbb{K} -linear graded functors, and let $\eta : F \rightarrow G$ be a degree j morphism of graded functors. Suppose $M \cong M_0 \oplus M_1$ in $\mathbf{C}^0(A, M)$, with embeddings $e_i : M_i \rightarrow M$ and projections $p_i : M \rightarrow M_i$. Then

$$\eta_M = (G(e_0), G(e_1)) \circ (\eta_{M_0}, \eta_{M_1}) \circ (F(p_0), F(p_1)),$$

as degree j morphisms $F(M) \rightarrow G(M)$ in $\mathbf{C}(B, N)$.

The lemma says that the diagram

$$\begin{array}{ccc} F(M) & \xrightarrow{(F(p_0), F(p_1))} & F(M_0) \oplus F(M_1) \\ \eta_M \downarrow & & \downarrow (\eta_{M_0}, \eta_{M_1}) \\ G(M) & \xleftarrow{(G(e_0), G(e_1))} & G(M_0) \oplus G(M_1) \end{array}$$

in $\mathbf{C}(B, N)$ is commutative.

Proof. It suffices to prove that the diagram below is commutative for $i = 0, 1$:

$$\begin{array}{ccccc} & & \text{id} & & \\ & \curvearrowright & & \curvearrowleft & \\ F(M_i) & \xrightarrow{F(e_i)} & F(M) & \xrightarrow{F(p_i)} & F(M_i) \\ \eta_{M_i} \downarrow & & \eta_M \downarrow & & \eta_{M_i} \downarrow \\ G(M_i) & \xrightarrow{G(e_i)} & G(M) & \xrightarrow{G(p_i)} & G(M_i) \\ & \curvearrowleft & & \curvearrowright & \\ & & \text{id} & & \end{array}$$

This is true because η is a morphism of functors (a natural transformation). \square

Theorem 5.3.7. *Let*

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N})$$

be a \mathbb{K} -linear DG functor, and let $\phi : M_0 \rightarrow M_1$ be a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Define the isomorphism

$$\text{cone}(F, \phi) : F(\text{Cone}_{A, \mathbf{M}}(\phi)) \rightarrow \text{Cone}_{B, \mathbf{N}}(F(\phi))$$

in $\mathbf{C}^0(B, \mathbf{N})$ to be

$$\text{cone}(F, \phi) := (\text{id}_{F(M_1)}, \tau_{F, M_0}).$$

Then:

- (1) The isomorphism $\text{cone}(F, \phi)$ is strict; namely it commutes with the differentials.
- (2) The diagram

$$\begin{array}{ccccccc} F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{F(e_\phi)} & F(\text{Cone}_{A, \mathbf{M}}(\phi)) & \xrightarrow{F(p_\phi)} & F(\text{T}_{A, \mathbf{M}}(M_0)) \\ \downarrow = & & \downarrow = & & \downarrow \text{cone}(F, \phi) & & \downarrow \tau_{F, M_0} \\ F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{e_{F(\phi)}} & \text{Cone}_{B, \mathbf{N}}(F(\phi)) & \xrightarrow{p_{F(\phi)}} & \text{T}_{B, \mathbf{N}}(F(M_0)) \end{array}$$

in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$ is commutative.

When defining $\text{cone}(F, \phi)$ above, we are using the decompositions (5.3.4) and (5.3.5) in the category $\mathbf{C}^0(B, \mathbf{N})$, and the isomorphism τ_{F, M_0} from Definition 5.2.1.

The slogan summarizing this theorem is “A DG functor sends standard triangles to standard triangles”.

Proof. (1) To save space let us write $\theta := \text{cone}(F, \phi)$. We have to prove that $d_{B, \mathbf{N}}(\theta) = 0$. Let's write $P := \text{Cone}_{A, \mathbf{M}}(\phi)$ and $Q := \text{Cone}_{B, \mathbf{N}}(F(\phi))$. Recall that

$$d_{B, \mathbf{N}}(\theta) = d_Q \circ \theta - \theta \circ d_{F(P)}.$$

We have to prove that this is the zero element in $\text{Hom}_{B, \mathbf{N}}(F(P), Q)^1$.

Writing the cones as column modules:

$$P = \begin{bmatrix} M_1 \\ \text{T}_{A, \mathbf{M}}(M_0) \end{bmatrix} \quad \text{and} \quad Q = \begin{bmatrix} F(M_1) \\ \text{T}_{B, \mathbf{N}}(F(M_0)) \end{bmatrix},$$

the matrices representing the morphisms in question are

$$\theta = \begin{bmatrix} \text{id}_{F(M_1)} & 0 \\ 0 & \tau_{F, M_0} \end{bmatrix}, \quad d_P = \begin{bmatrix} d_{M_1} & \phi \circ t_{M_0}^{-1} \\ 0 & d_{\text{T}_{A, \mathbf{M}}(M_0)} \end{bmatrix}$$

and

$$d_Q = \begin{bmatrix} d_{F(M_1)} & F(\phi) \circ t_{F(M_0)}^{-1} \\ 0 & d_{\text{T}_{B, \mathbf{N}}(F(M_0))} \end{bmatrix}.$$

Let us write $\gamma := \gamma_F$ for simplicity. According to Theorem 5.1.2, the gauge $\gamma : F \rightarrow F$ is a degree 1 morphism of functors $\mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N})$. Because the

decomposition (5.3.3) is in the category $\mathbf{C}^0(A, \mathbf{M})$, Lemma 5.3.6 tells us that γ_P decomposes too, i.e.

$$\gamma_P = \begin{bmatrix} \gamma_{M_1} & 0 \\ 0 & \gamma_{\mathbf{T}_{A, \mathbf{M}}(M_0)} \end{bmatrix}.$$

By definition of γ_P we have

$$d_{F(P)} = F(d_P) + \gamma_P \in \text{Hom}_{B, \mathbf{N}}(F(P), F(P))^1.$$

It follows that

$$\begin{aligned} d_{F(P)} &= F(d_P) + \gamma_P \\ &= \begin{bmatrix} F(d_{M_1}) & F(\phi \circ \mathfrak{t}_{M_0}^{-1}) \\ 0 & F(d_{\mathbf{T}_{A, \mathbf{M}}(M_0)}) \end{bmatrix} + \begin{bmatrix} \gamma_{M_1} & 0 \\ 0 & \gamma_{\mathbf{T}_{A, \mathbf{M}}(M_0)} \end{bmatrix} \\ &= \begin{bmatrix} F(d_{M_1}) + \gamma_{M_1} & F(\phi \circ \mathfrak{t}_{M_0}^{-1}) \\ 0 & F(d_{\mathbf{T}_{A, \mathbf{M}}(M_0)}) + \gamma_{\mathbf{T}_{A, \mathbf{M}}(M_0)} \end{bmatrix} \\ &= \begin{bmatrix} d_{F(M_1)} & F(\phi \circ \mathfrak{t}_{M_0}^{-1}) \\ 0 & d_{F(\mathbf{T}_{A, \mathbf{M}}(M_0))} \end{bmatrix}. \end{aligned}$$

Finally we will check that $\theta \circ d_{F(P)}$ and $d_Q \circ \theta$ are equal as matrices of morphisms. We do that in each matrix position separately. The two left positions in the matrices $\theta \circ d_{F(P)}$ and $d_Q \circ \theta$ agree trivially. The bottom right positions in these matrices are $\tau_{F, M_0} \circ d_{F(\mathbf{T}_{A, \mathbf{M}}(M_0))}$ and $d_{\mathbf{T}_{B, \mathbf{N}}(F(M_0))} \circ \tau_{F, M_0}$ respectively; they are equal by Proposition 5.2.2. And in the top right positions we have $F(\phi \circ \mathfrak{t}_{M_0}^{-1})$ and $F(\phi) \circ \mathfrak{t}_{F(M_0)}^{-1} \circ \tau_{F, M_0}$ respectively. Now $F(\phi \circ \mathfrak{t}_{M_0}^{-1}) = F(\phi) \circ F(\mathfrak{t}_{M_0}^{-1})$; so it suffices to prove that $F(\mathfrak{t}_{M_0}^{-1}) = \mathfrak{t}_{F(M_0)}^{-1} \circ \tau_{F, M_0}$. This is immediate from the definition of τ_{F, M_0} .

(2) By definition of $\theta = \text{cone}(F, \phi)$, the diagram is commutative in $\mathbf{C}^0(B, \mathbf{N})$. But by part (1) we know that all morphisms in it lie in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$. \square

Corollary 5.3.8. *In the situation of Theorem 5.3.7, the diagram*

$$\begin{array}{ccccccc} F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{F(e_\phi)} & F(\text{Cone}_{A, \mathbf{M}}(\phi)) & \xrightarrow{\tau_{F, M_0} \circ F(p_\phi)} & \mathbf{T}_{B, \mathbf{N}}(F(M_0)) \\ = \downarrow & & = \downarrow & & \text{cone}(F, \phi) \downarrow & & = \downarrow \\ F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{e_{F(\phi)}} & \text{Cone}_{B, \mathbf{N}}(F(\phi)) & \xrightarrow{p_{F(\phi)}} & \mathbf{T}_{B, \mathbf{N}}(F(M_0)) \end{array}$$

is an isomorphism of triangles in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$.

Proof. Just rearrange the diagram in item (2) of the theorem. \square

5.4. Examples of DG Functors. Recall that \mathbf{M} and \mathbf{N} are \mathbb{K} -linear categories, and A and B are central DG \mathbb{K} -rings. Here are three examples of DG functors, of various types. These examples should serve as templates for constructing other DG functors.

Example 5.4.1. Here $A = B = \mathbb{K}$, so $\mathbf{C}(A, \mathbf{M}) = \mathbf{C}(\mathbf{M})$ and $\mathbf{C}(B, \mathbf{N}) = \mathbf{C}(\mathbf{N})$. Let $F : \mathbf{M} \rightarrow \mathbf{N}$ be a \mathbb{K} -linear functor. It extends to a functor

$$\mathbf{C}(F) : \mathbf{C}(\mathbf{M}) \rightarrow \mathbf{C}(\mathbf{N})$$

as follows: on objects, a complex

$$M = (\{M^i\}_{i \in \mathbb{Z}}, \{d_M^i\}_{i \in \mathbb{Z}}) \in \mathbf{C}(\mathbf{M})$$

goes to the complex

$$\mathbf{C}(F)(M) := (\{F(M^i)\}, \{F(d_M^i)\}) \in \mathbf{C}(\mathbf{N}).$$

A morphism $\phi = \{\phi^j\}$ in $\mathbf{C}(\mathbf{M})$ goes to the morphism $\mathbf{C}(\phi) := \{F(\phi^j)\}$ in $\mathbf{C}(\mathbf{N})$. A slightly tedious calculation shows that $\mathbf{C}(F)$ is a \mathbb{K} -linear DG functor.

Given a complex $M \in \mathbf{C}(\mathbf{M})$, let $N := \mathbf{C}(F)(M) \in \mathbf{C}(\mathbf{N})$. Then the translations are

$$\mathrm{T}_{\mathbf{N}}(N) = \mathbf{C}(F)(\mathrm{T}_{\mathbf{M}}(M));$$

and $\mathbf{C}(F)(t_M) = t_N$. So the translation isomorphism

$$\tau_{\mathbf{C}(F)} : \mathbf{C}(F) \circ \mathrm{T}_{\mathbf{M}} \xrightarrow{\cong} \mathrm{T}_{\mathbf{N}} \circ \mathbf{C}(F)$$

of functors $\mathbf{C}_{\mathrm{str}}(\mathbf{M}) \rightarrow \mathbf{C}_{\mathrm{str}}(\mathbf{N})$ is equality.

Let $\phi : M_0 \rightarrow M_1$ be a morphism in $\mathbf{C}_{\mathrm{str}}(\mathbf{M})$, whose image under $\mathbf{C}(F)$ is the morphism $\psi : N_0 \rightarrow N_1$ in $\mathbf{C}_{\mathrm{str}}(\mathbf{N})$. Then

$$\mathrm{Cone}(\psi) = N_1 \oplus \mathrm{T}_{\mathbf{N}}(N_0) = \mathbf{C}(F)(\mathrm{Cone}(\phi))$$

as graded objects of \mathbf{N} , with differential

$$d_{\mathrm{Cone}(\psi)} = \begin{bmatrix} d_{N_1} & \psi \circ t_{N_0}^{-1} \\ 0 & d_{\mathrm{T}(N_0)} \end{bmatrix} = \mathbf{C}(F) \left(\begin{bmatrix} d_{M_1} & \phi \circ t_{M_0}^{-1} \\ 0 & d_{\mathrm{T}(M_0)} \end{bmatrix} \right) = \mathbf{C}(F)(d_{\mathrm{Cone}(\phi)}).$$

We see that the cone isomorphism θ is equality, and the gauge $\gamma_{\mathbf{C}(F)}$ is zero.

The next example is much more complicated, and we work out the full details (only once – later on, such details will be left to the reader).

Example 5.4.2. Let A and B be central DG \mathbb{K} -rings, and fix some

$$N \in \mathrm{DGMod}(B \otimes_{\mathbb{K}} A^{\mathrm{op}}).$$

In other words, N is a DG B - A -bimodule. For any $M \in \mathrm{DGMod} A$ we have a DG \mathbb{K} -module

$$F(M) := N \otimes_A M,$$

as in Definition 3.3.21. The differential of $F(M)$ is

$$(5.4.3) \quad d_{F(M)} = d_N \otimes \mathrm{id}_M + \mathrm{id}_N \otimes d_M.$$

See Example 3.1.5 regarding the Koszul sign rule that's involved. But $F(M)$ has a structure of a DG B -module: for any $b \in B$, $n \in N$ and $m \in M$, the action is

$$b \cdot (n \otimes m) := (b \cdot n) \otimes m.$$

Clearly

$$F : \mathbf{C}(A) = \mathrm{DGMod} A \rightarrow \mathbf{C}(B) = \mathrm{DGMod} B$$

is a \mathbb{K} -linear functor. We will show that it is actually a DG functor.

Let $M_0, M_1 \in \mathbf{C}(A)$, and consider the \mathbb{K} -linear homomorphism

$$(5.4.4) \quad F : \mathrm{Hom}_A(M_0, M_1) \rightarrow \mathrm{Hom}_B(N \otimes_A M_0, N \otimes_A M_1).$$

Take any $\phi \in \mathrm{Hom}_A(M_0, M_1)^i$. Then

$$F(\phi) \in \mathrm{Hom}_B(N \otimes_A M_0, N \otimes_A M_1)$$

is the homomorphism that on a homogeneous tensor $n \otimes m \in (N \otimes_A M_0)^{k+j}$, with $n \in N^k$ and $m \in M_0^j$, has the value

$$F(\phi)(n \otimes m) = (-1)^{ik} \cdot n \otimes \phi(m) \in (N \otimes_A M_1)^{k+j+i}.$$

In other words,

$$(5.4.5) \quad F(\phi) = \text{id}_N \otimes \phi.$$

We see that the homomorphism $F(\phi)$ has degree i . So F is a graded functor.

Let us calculate γ_F , the gauge of F . From (5.4.5) and (5.4.3) we get

$$\gamma_{F,M} = \text{d}_N \otimes \text{id}_M,$$

which is often a nonzero endomorphism of $F(M)$. Still, take any degree i morphism $\phi : M_0 \rightarrow M_1$ in $\mathbf{C}(A)$. Then

$$\begin{aligned} \gamma_{M_1} \circ F(\phi) &= (\text{d}_N \otimes \text{id}_{M_1}) \circ (\text{id}_N \otimes \phi) \\ &= \text{d}_N \otimes \phi = (-1)^i \cdot (\text{id}_N \otimes \phi) \circ (\text{d}_N \otimes \text{id}_{M_0}) = (-1)^i \cdot F(\phi) \circ \gamma_{M_0}. \end{aligned}$$

We see that γ_F satisfies the condition of Definition 3.5.4(1), which is really Definition 3.1.17. By Theorem 5.1.2, F is a DG functor. (It is possible to calculate directly that F is a DG functor, but this takes more work.)

Finally let us figure out what is the translation isomorphism τ_F of the functor F . Take $M \in \mathbf{C}(A)$. Then

$$\tau_{F,M} : F(\mathbb{T}_A(M)) \rightarrow \mathbb{T}_B(F(M))$$

is an isomorphism in $\mathbf{C}_{\text{str}}(B)$. By Definition 5.2.1 we have $\tau_{F,M} := \mathfrak{t}_{F(M)} \circ F(\mathfrak{t}_M)^{-1}$. Take any $n \in N^k$ and $m \in M^{j+1}$, so that

$$n \otimes \mathfrak{t}_M(m) \in (N \otimes_A \mathbb{T}_A(M))^{k+j} = F(\mathbb{T}_A(M))^{k+j},$$

a typical degree $k+j$ element of $F(\mathbb{T}_A(M))$. But

$$n \otimes \mathfrak{t}_M(m) = (-1)^k \cdot (\text{id}_N \otimes \mathfrak{t}_M)(n \otimes m) = (-1)^k \cdot F(\mathfrak{t}_M)(n \otimes m).$$

Therefore

$$\tau_{F,M}(n \otimes \mathfrak{t}_M(m)) = (-1)^k \cdot \mathfrak{t}_{F(M)}(n \otimes m) \in \mathbb{T}_B(F(M))^{k+j}.$$

Observe that when N is concentrated in degree 0, we are back in the situation of Example 5.4.1, in which there are no sign twists, and $\tau_{F,M}$ is “equality”.

Example 5.4.6. Let A and B be central DG \mathbb{K} -rings, and fix some

$$N \in \text{DGMod}(A \otimes_{\mathbb{K}} B^{\text{op}}).$$

For any $M \in \text{DGMod } A$ we define

$$F(M) := \text{Hom}_A(N, M).$$

This is a DG B -module: for any $b \in B^i$ and $\phi \in \text{Hom}_A(N, M)^j$, the homomorphism $b \cdot \phi \in \text{Hom}_A(N, M)^{i+j}$ has value

$$(b \cdot \phi)(n) := (-1)^{i \cdot (j+k)} \cdot \phi(n \cdot b) \in M^{i+j+k}$$

on $n \in N^k$. As in the previous example,

$$F : \mathbf{C}(A) = \text{DGMod } A \rightarrow \mathbf{C}(B) = \text{DGMod } B$$

is a \mathbb{K} -linear graded functor.

The value of the gauge γ_F at $M \in \mathbf{C}(A)$ is

$$\gamma_{F,M} = \text{Hom}(d_N, \text{id}_M).$$

See Example 3.1.6 regarding this notation. Namely for

$$\psi \in F(M)^j = \text{Hom}_A(N, M)^j$$

we have

$$\gamma_{F,M}(\psi) = (-1)^j \cdot \psi \circ d_N.$$

It is not too hard to check that γ_F is a degree 1 morphism of functors. Hence, by Theorem 5.1.2, F is a DG functor.

The formula for the translation isomorphism τ_F is as follows. Take $M \in \mathbf{C}(A)$. Then

$$\tau_{F,M} : F(\mathbb{T}_A(M)) = \text{Hom}_A(N, \mathbb{T}_A(M)) \rightarrow \mathbb{T}_B(F(M)) = \mathbb{T}_B(\text{Hom}_A(N, M))$$

is, by definition, $\tau_{F,M} = t_{F(M)} \circ F(t_M)^{-1}$. Now

$$F(t_M)^{-1} = \text{Hom}(\text{id}_N, t_M^{-1}).$$

So given any $\psi \in F(\mathbb{T}_A(M))^k$, we have

$$\tau_{F,M}(\psi) = t_{F(M)}(t_M^{-1} \circ \psi) \in \mathbb{T}_B(F(M))^k.$$

6. TRIANGULATED CATEGORIES AND FUNCTORS

In this section we introduce triangulated categories and triangulated functors. There is one result here that seems to be new: Theorem 6.4.15, which asserts that a DG functor between DG module categories induces a triangulated functor between the associated homotopy categories.

As in previous sections, we fix a base commutative ring \mathbb{K} . All linear categories and linear functors here are implicitly assumed to be \mathbb{K} -linear. In particular, this assumption says that all DG rings are central \mathbb{K} -rings, and all DG ring homomorphisms are \mathbb{K} -linear.

6.1. T-Additive Categories. Recall that a functor is called an isomorphism of categories if it is bijective of sets of objects and on sets of morphisms; see Example 1.5.2.

Definition 6.1.1. Let \mathcal{K} be an additive category. A *translation* on \mathcal{K} is an additive automorphism T of \mathcal{K} , called the *translation functor*. The pair (\mathcal{K}, T) is called a *T-additive category*.

Remark 6.1.2. Some texts give a more relaxed definition: T is only required to be an additive auto-equivalence of \mathcal{K} . The resulting theory is more complicated (it is 2-categorical, but most texts try to suppress this fact).

Later in the book we will write $M[k] := T^k(M)$, the k -th translation of an object M .

Definition 6.1.3. Suppose $(\mathcal{K}, T_{\mathcal{K}})$ and $(\mathcal{L}, T_{\mathcal{L}})$ are T -additive categories. A *T-additive functor* between them is a pair (F, τ) , consisting of an additive functor $F : \mathcal{K} \rightarrow \mathcal{L}$, together with an isomorphism

$$\tau : F \circ T_{\mathcal{K}} \xrightarrow{\cong} T_{\mathcal{L}} \circ F$$

of functors $\mathcal{K} \rightarrow \mathcal{L}$, called a *translation isomorphism*.

Definition 6.1.4. Let (\mathcal{K}_i, T_i) be T -additive categories, for $i = 0, 1, 2$, and let

$$(F_i, \tau_i) : (\mathcal{K}_{i-1}, T_{i-1}) \rightarrow (\mathcal{K}_i, T_i)$$

be T -additive functors. The composition

$$(F, \tau) = (F_2, \tau_2) \circ (F_1, \tau_1)$$

is the T -additive functor $(\mathcal{K}_0, T_0) \rightarrow (\mathcal{K}_2, T_2)$ defined as follows: the functor is $F := F_2 \circ F_1$, and the translation isomorphism

$$\tau : F \circ T_0 \xrightarrow{\cong} T_2 \circ F$$

is $\tau := \tau_2 \circ F_2(\tau_1)$.

Definition 6.1.5. Suppose $(\mathcal{K}, T_{\mathcal{K}})$ and $(\mathcal{L}, T_{\mathcal{L}})$ are T -additive categories, and

$$(F, \tau), (G, \nu) : (\mathcal{K}, T_{\mathcal{K}}) \rightarrow (\mathcal{L}, T_{\mathcal{L}})$$

are T -additive functors. A *morphism of T-additive functors*

$$\eta : (F, \tau) \rightarrow (G, \nu)$$

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is a morphism of functors $\eta : F \rightarrow G$, such that for every object $M \in \mathbf{K}$ this diagram in \mathbf{L} is commutative:

$$\begin{array}{ccc} F(\mathbf{T}_{\mathbf{K}}(M)) & \xrightarrow{\tau_M} & \mathbf{T}_{\mathbf{L}}(F(M)) \\ \eta_{\mathbf{T}_{\mathbf{K}}(M)} \downarrow & & \downarrow \mathbf{T}_{\mathbf{L}}(\eta_M) \\ G(\mathbf{T}_{\mathbf{K}}(M)) & \xrightarrow{\nu_M} & \mathbf{T}_{\mathbf{L}}(G(M)) . \end{array}$$

We now look at the contravariant situation.

Definition 6.1.6. Suppose $(\mathbf{K}, \mathbf{T}_{\mathbf{K}})$ and $(\mathbf{L}, \mathbf{T}_{\mathbf{L}})$ are \mathbf{T} -additive categories. A *contravariant \mathbf{T} -additive functor* between them is a pair (F, τ) , consisting of a contravariant additive functor $F : \mathbf{K} \rightarrow \mathbf{L}$, together with an isomorphism

$$\tau : F \circ \mathbf{T}_{\mathbf{K}}^{-1} \xrightarrow{\cong} \mathbf{T}_{\mathbf{L}} \circ F$$

of contravariant functors $\mathbf{K} \rightarrow \mathbf{L}$, called a *translation isomorphism*.

For an additive category \mathbf{K} there is a canonical contravariant functor $\text{op} : \mathbf{K} \rightarrow \mathbf{K}^{\text{op}}$, that is the identity on objects, and reverses the arrows. Note that op is an additive anti-isomorphism of categories (i.e. a contravariant isomorphism), so its inverse op^{-1} is unique.

Definition 6.1.7. Let $(\mathbf{K}, \mathbf{T}_{\mathbf{K}})$ be a \mathbf{T} -additive category. The opposite category \mathbf{K}^{op} is made into a \mathbf{T} -additive category with translation functor

$$\mathbf{T}^{\text{op}} := \text{op} \circ \mathbf{T} \circ \text{op}^{-1} .$$

Note that this definition is designed to make

$$(\text{op}, \text{id}) : (\mathbf{K}, \mathbf{T}_{\mathbf{K}}) \rightarrow (\mathbf{K}^{\text{op}}, \mathbf{T}^{\text{op}})$$

into a contravariant isomorphism of \mathbf{T} -additive categories.

Proposition 6.1.8. *If*

$$(F, \tau) : (\mathbf{K}, \mathbf{T}_{\mathbf{K}}) \rightarrow (\mathbf{L}, \mathbf{T}_{\mathbf{L}})$$

is a contravariant \mathbf{T} -additive functor, then

$$(F \circ \text{op}, \tau) : (\mathbf{K}^{\text{op}}, \mathbf{T}_{\mathbf{K}}^{\text{op}}) \rightarrow (\mathbf{L}, \mathbf{T}_{\mathbf{L}})$$

is a \mathbf{T} -additive functor. And vice-versa.

Exercise 6.1.9. Prove Proposition 6.1.8.

The proposition above, together with Definition 6.1.5, tell us what is a morphism between contravariant \mathbf{T} -additive functors.

6.2. Triangulated Categories.

Definition 6.2.1. Let (\mathbf{K}, \mathbf{T}) be a \mathbf{T} -additive category. A *triangle* in (\mathbf{K}, \mathbf{T}) is a diagram

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

in \mathbf{K} .

Definition 6.2.2. Let (\mathbf{K}, \mathbf{T}) be a \mathbf{T} -additive category. Suppose

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

and

$$L' \xrightarrow{\alpha'} M' \xrightarrow{\beta'} N' \xrightarrow{\gamma'} \mathbf{T}(L')$$

are triangles in (\mathbf{K}, \mathbf{T}) . A *morphism of triangles* between them is a commutative diagram

$$\begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbf{T}(L) \\ \phi \downarrow & & \psi \downarrow & & \chi \downarrow & & \mathbf{T}(\phi) \downarrow \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array}$$

in \mathbf{K} .

The morphism of triangles (ϕ, ψ, χ) is called an *isomorphism* if ϕ, ψ and χ are all isomorphisms.

Remark 6.2.3. Why “triangle”? This is because sometimes a triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

is written as a diagram

$$\begin{array}{ccc} & N & \\ \gamma \swarrow & & \nwarrow \beta \\ L & \xrightarrow{\alpha} & M \end{array}$$

Here γ is a morphism of degree 1.

Definition 6.2.4. A *triangulated category* is a \mathbf{T} -additive category (\mathbf{K}, \mathbf{T}) , equipped with a set of triangles called *distinguished triangles*. The following axioms have to be satisfied:

- (TR1) (a) Any triangle that is isomorphic to a distinguished triangle is also a distinguished triangle.
- (b) For every morphism $\alpha : L \rightarrow M$ in \mathbf{K} there is a distinguished triangle

$$L \xrightarrow{\alpha} M \rightarrow N \rightarrow \mathbf{T}(L).$$

- (c) For every object M the triangle

$$M \xrightarrow{1_M} M \rightarrow 0 \rightarrow \mathbf{T}(M)$$

is distinguished.

- (TR2) A triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

is distinguished iff the triangle

$$M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L) \xrightarrow{-\mathbf{T}(\alpha)} \mathbf{T}(M)$$

is distinguished.

(TR3) Suppose

$$\begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbf{T}(L) \\ \phi \downarrow & & \psi \downarrow & & & & \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array}$$

is a commutative diagram in \mathbf{K} in which the rows are distinguished triangles. Then there exists a morphism $\chi : N \rightarrow N'$ such that the diagram

$$\begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbf{T}(L) \\ \phi \downarrow & & \psi \downarrow & & \chi \downarrow & & \mathbf{T}(\phi) \downarrow \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array} .$$

is a morphism of triangles.

(TR4) Suppose we are given these three distinguished triangles:

$$\begin{array}{l} L \xrightarrow{\alpha} M \xrightarrow{\gamma} P \rightarrow \mathbf{T}(L), \\ M \xrightarrow{\beta} N \xrightarrow{\epsilon} R \rightarrow \mathbf{T}(M), \\ L \xrightarrow{\beta \circ \alpha} N \xrightarrow{\delta} Q \rightarrow \mathbf{T}(L). \end{array}$$

Then there is a distinguished triangle

$$P \xrightarrow{\phi} Q \xrightarrow{\psi} R \xrightarrow{\rho} \mathbf{T}(P)$$

making the diagram

$$\begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\gamma} & P & \longrightarrow & \mathbf{T}(L) \\ 1 \downarrow & & \beta \downarrow & & \phi \downarrow & & 1 \downarrow \\ L & \xrightarrow{\beta \circ \alpha} & N & \xrightarrow{\delta} & Q & \longrightarrow & \mathbf{T}(L) \\ \alpha \downarrow & & 1 \downarrow & & \psi \downarrow & & \mathbf{T}(\alpha) \downarrow \\ M & \xrightarrow{\beta} & N & \xrightarrow{\epsilon} & R & \longrightarrow & \mathbf{T}(M) \\ \gamma \downarrow & & \delta \downarrow & & 1 \downarrow & & \mathbf{T}(\gamma) \downarrow \\ P & \xrightarrow{\phi} & Q & \xrightarrow{\psi} & R & \longrightarrow & \mathbf{T}(P) \end{array}$$

commutative.

Remark 6.2.5. The numbering of the axioms we use is taken from [RD]; the numbering in [Sc], [KaSc1] [KaSc2] and [Ne1] is different.

In the situation that we care about, namely $\mathbf{K} = \mathbf{K}(A, M)$, the distinguished triangles will be those triangles that are isomorphic, in $\mathbf{K}(A, M)$, to the standard triangles in $\mathbf{C}(A, M)$ from Definition 4.2.5. See Definition 6.4.3 below for the precise statement.

The object N in item (b) of axiom (TR1) is referred to as a *cone* on $\alpha : L \rightarrow M$. We should think of the cone as something combining “the cokernel” and “the kernel” of α .

Axiom (TR2) says that if we “turn” a distinguished triangle we remain with a distinguished triangle.

Axiom (TR3) says that a commutative square (ϕ, ψ) induces a morphism χ on the cones of the horizontal morphisms, that fits into a morphism of distinguished triangles (ϕ, ψ, χ) . Note however that the new morphism χ is *not unique*; in other words, *cones are not functorial*. This fact has some deep consequences in many applications. However, in the situations that will interest us, namely when $\mathbf{K} = \mathbf{K}(A, M)$, the cones come from the standard cones in $\mathbf{C}(A, M)$; and the standard cones in $\mathbf{C}(A, M)$ are functorial (Definition 4.2.6).

Remark 6.2.6. The axiom (TR4) is called the *octahedral axiom*. It is supposed to replace the isomorphism

$$(N/L)/(M/L) \cong N/M$$

for objects $L \subseteq M \subseteq N$ in an abelian category M . The octahedral axiom is needed for the theory of *t-structures*: it is used, in [BBD], to show that the heart of a *t-structure* is an abelian category. This axiom is also needed to form Verdier quotients of triangulated categories. See the book [Ne1] for a detailed discussion.

A T -additive category (K, T) that only satisfies axioms (TR1)-(TR3) is called a *pretriangulated category*. (The reader should not confuse “pretriangulated category”, as used here, with the “pretriangulated DG category” from [BoKa]; see Remark 6.4.17.) It is not known whether the octahedral axiom is a consequence of the other axioms; there was a recent paper by Maccioca (arxiv:1506.00887) claiming that, but it had a fatal error in it.

In our book the octahedral axiom does not play any role. For this reason we had excluded it from an earlier version of the book, in which we had discussed pretriangulated categories only. Our decision to include this axiom in the current version of the book, and thus to talk about triangulated categories (rather than about pretriangulated ones) is just to be more in line with the mainstream usage. With the exception of a longer proof of Theorem 6.4.4 – stating that $\mathbf{K}(A, M)$ is a triangulated category – there is virtually no change in the content of the book, and almost all definitions and results are valid for pretriangulated categories.

Proposition 6.2.7. *Let K be a triangulated category. If*

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

is a distinguished triangle in K , then $\beta \circ \alpha = 0$.

Proof. By axioms (TR1) and (TR3) we have a commutative diagram

$$\begin{array}{ccccccc} L & \xrightarrow{1_L} & L & \longrightarrow & 0 & \longrightarrow & T(L) \\ \downarrow 1_L & & \downarrow \alpha & & \downarrow & & \downarrow T(1_L) \\ L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & T(L) \end{array} .$$

We see that $\beta \circ \alpha$ factors through 0. □

Let (K, T) be a T -additive category. According to Definition 6.1.7 the opposite category K^{op} is equipped with a translation functor T^{op} . Thus (K^{op}, T^{op}) is a T -additive category.

Proposition 6.2.8. *Let \mathcal{K} be a triangulated category. For any any distinguished triangle*

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

in \mathcal{K} , we declare the triangle

$$N \xrightarrow{\text{op}(\beta)} M \xrightarrow{\text{op}(\alpha)} L \xrightarrow{\text{op}(-T^{-1}(\gamma))} T^{\text{op}}(N)$$

in \mathcal{K}^{op} to be distinguished. Then \mathcal{K}^{op} is a triangulated category.

Exercise 6.2.9. Prove the last proposition. (Hint: look at the proof of Proposition 6.3.3 below.)

6.3. Triangulated and Cohomological Functors. Suppose \mathcal{K} and \mathcal{L} are T -additive categories, with translation functors $T_{\mathcal{K}}$ and $T_{\mathcal{L}}$ respectively. The notion of T -additive functor $F : \mathcal{K} \rightarrow \mathcal{L}$ was defined in Definition 6.1.3 In that definition we also introduced the notion of morphism $\eta : F \rightarrow G$ between T -additive functors.

Definition 6.3.1. Let \mathcal{K} and \mathcal{L} be triangulated categories.

- (1) A *triangulated functor* from \mathcal{K} to \mathcal{L} is a T -additive functor

$$(F, \tau) : \mathcal{K} \rightarrow \mathcal{L}$$

that satisfies this condition: for any distinguished triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T_{\mathcal{K}}(L)$$

in \mathcal{K} , the triangle

$$F(L) \xrightarrow{F(\alpha)} F(M) \xrightarrow{F(\beta)} F(N) \xrightarrow{\tau_L \circ F(\gamma)} T_{\mathcal{L}}(F(L))$$

is a distinguished triangle in \mathcal{L} .

- (2) Suppose $(G, \nu) : \mathcal{K} \rightarrow \mathcal{L}$ is another triangulated functor. A *morphism of triangulated functors* $\eta : (F, \tau) \rightarrow (G, \nu)$ is a morphism of T -additive functors, as in Definition 6.1.5 .

Sometimes we keep the translation isomorphism τ implicit, and refer to F as a triangulated functor.

Definition 6.3.2. Let \mathcal{K} be a triangulated category, and let \mathcal{M} be an abelian category. A *cohomological functor* $F : \mathcal{K} \rightarrow \mathcal{M}$ is an additive functor, such that for every distinguished triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

in \mathcal{K} , the sequence

$$F(L) \xrightarrow{F(\alpha)} F(M) \xrightarrow{F(\beta)} F(N)$$

is exact in \mathcal{M} .

Proposition 6.3.3. *Let $F : \mathcal{K} \rightarrow \mathcal{M}$ be a cohomological functor, and let*

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

be a distinguished triangle in \mathcal{K} . Then the sequence

$$\begin{aligned} \cdots \rightarrow F(T^i(L)) \xrightarrow{F(T^i(\alpha))} F(T^i(M)) \xrightarrow{F(T^i(\beta))} F(T^i(N)) \xrightarrow{F(T^i(\gamma))} F(T^{i+1}(L)) \\ \xrightarrow{F(T^{i+1}(\alpha))} F(T^{i+1}(M)) \rightarrow \cdots \end{aligned}$$

in \mathcal{M} is exact.

Proof. By axiom (TR2) we have distinguished triangles

$$\begin{aligned} \mathbb{T}^i(L) &\xrightarrow{(-1)^i \cdot \mathbb{T}^i(\alpha)} \mathbb{T}^i(M) \xrightarrow{(-1)^i \cdot \mathbb{T}^i(\beta)} \mathbb{T}^i(N) \xrightarrow{(-1)^i \cdot \mathbb{T}^i(\gamma)} \mathbb{T}^{i+1}(L), \\ \mathbb{T}^i(M) &\xrightarrow{(-1)^i \cdot \mathbb{T}^i(\beta)} \mathbb{T}^i(N) \xrightarrow{(-1)^i \cdot \mathbb{T}^i(\gamma)} \mathbb{T}^{i+1}(L) \xrightarrow{(-1)^{i+1} \cdot \mathbb{T}^{i+1}(\alpha)} \mathbb{T}^{i+1}(M) \end{aligned}$$

and

$$\mathbb{T}^i(N) \xrightarrow{(-1)^i \cdot \mathbb{T}^i(\gamma)} \mathbb{T}^{i+1}(L) \xrightarrow{(-1)^{i+1} \cdot \mathbb{T}^{i+1}(\alpha)} \mathbb{T}^{i+1}(M) \xrightarrow{(-1)^{i+1} \cdot \mathbb{T}^{i+1}(\beta)} \mathbb{T}^{i+1}(N).$$

Now use the definition, noting that multiplying morphisms in an exact sequence by -1 preserves exactness. \square

Proposition 6.3.4. *Let \mathbb{K} be a triangulated category. For any $P \in \mathbb{K}$ the functors*

$$\mathrm{Hom}_{\mathbb{K}}(-, P) : \mathbb{K}^{\mathrm{op}} \rightarrow \mathbf{Ab}$$

and

$$\mathrm{Hom}_{\mathbb{K}}(P, -) : \mathbb{K} \rightarrow \mathbf{Ab}$$

are cohomological functors.

Proof. We will prove the covariant statement; the contravariant statement is an immediate consequence, since

$$\mathrm{Hom}_{\mathbb{K}}(M, P) = \mathrm{Hom}_{\mathbb{K}^{\mathrm{op}}}(P, M),$$

and \mathbb{K}^{op} is triangulated (with the correct triangulated structure to make this true).

Consider a distinguished triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbb{T}(L)$$

in \mathbb{K} . We have to prove that the sequence

$$\mathrm{Hom}_{\mathbb{K}}(P, L) \xrightarrow{\mathrm{Hom}(1_P, \alpha)} \mathrm{Hom}_{\mathbb{K}}(P, M) \xrightarrow{\mathrm{Hom}(1_P, \beta)} \mathrm{Hom}_{\mathbb{K}}(P, N)$$

is exact. In view of Proposition 6.2.7, all we need to show is that for any $\psi : P \rightarrow M$ s.t. $\beta \circ \psi = 0$, there is some $\phi : P \rightarrow L$ s.t. $\psi = \alpha \circ \phi$. In a picture, we must show that the diagram below (solid arrows)

$$\begin{array}{ccccccc} P & \xrightarrow{1} & P & \longrightarrow & 0 & \longrightarrow & \mathbb{T}(P) \\ | & & \downarrow \psi & & \downarrow & & | \\ \phi \downarrow & & & & & & \mathbb{T}(\phi) \downarrow \\ L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbb{T}(L) \end{array} .$$

can be completed (dashed arrow). This is true by (TR2) (= turning) and (TR3) (= extending). \square

Proposition 6.3.5. *Let \mathbb{K} be a triangulated category, and let*

$$\begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbb{T}(L) \\ \downarrow \phi & & \downarrow \psi & & \downarrow \chi & & \downarrow \mathbb{T}(\phi) \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbb{T}(L') \end{array} .$$

be a morphism of distinguished triangles. If ϕ and ψ are isomorphisms, then χ is also an isomorphism.

Proof. Take an arbitrary $P \in \mathbf{K}$, and let $F := \text{Hom}_{\mathbf{K}}(P, -)$. We get a commutative diagram

$$\begin{array}{ccccccccc}
 F(L) & \xrightarrow{F(\alpha)} & F(M) & \xrightarrow{F(\beta)} & F(N) & \xrightarrow{F(\gamma)} & F(\mathbf{T}(L)) & \xrightarrow{F(\mathbf{T}(\alpha))} & F(\mathbf{T}(M)) \\
 F(\phi) \downarrow & & F(\psi) \downarrow & & F(\chi) \downarrow & & F(\mathbf{T}(\phi)) \downarrow & & F(\mathbf{T}(\psi)) \downarrow \\
 F(L') & \xrightarrow{F(\alpha')} & F(M') & \xrightarrow{F(\beta')} & F(N') & \xrightarrow{F(\gamma')} & F(\mathbf{T}(L')) & \xrightarrow{F(\mathbf{T}(\alpha'))} & F(\mathbf{T}(M'))
 \end{array}$$

in \mathbf{Ab} . By Proposition 6.3.4(2) the rows in the diagram are exact sequences. Since the other vertical arrows are isomorphisms, it follows that

$$F(\chi) : \text{Hom}_{\mathbf{K}}(P, N) \rightarrow \text{Hom}_{\mathbf{K}}(P, N')$$

is an isomorphism of abelian groups. By forgetting structure, we see that $F(\chi)$ is an isomorphism of sets.

We now use the Yoneda Lemma. Let us write $Y_N := \text{Hom}_{\mathbf{K}}(-, N)$ and $Y_{N'} := \text{Hom}_{\mathbf{K}}(-, N')$, viewed as functors $\mathbf{K}^{\text{op}} \rightarrow \mathbf{Set}$. For any object $P \in \mathbf{K}$ we have isomorphisms of sets $Y_N(P) \cong F(N)$ and $Y_{N'}(P) \cong F(N')$. The calculation above shows that the morphism of functors $Y(\chi) : Y_N \rightarrow Y_{N'}$ is an isomorphism. According to Proposition 1.7.1(2), the morphism $\chi : N \rightarrow N'$ in \mathbf{K} is an isomorphism. \square

Proposition 6.3.6. *Let \mathbf{K} be a triangulated category, and let*

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

be a distinguished triangle in it. The two conditions below are equivalent:

- (i) $\alpha : L \rightarrow M$ is an isomorphism.
- (ii) $N \cong 0$.

Proof. Exercise. (Hint: use Proposition 6.3.5.) \square

Question 6.3.7. Let \mathbf{K} and \mathbf{L} be triangulated categories, and let $F : \mathbf{K} \rightarrow \mathbf{L}$ be an additive functor. Is it true that there is at most one isomorphism of functors $\tau : F \circ \mathbf{T}_{\mathbf{K}} \xrightarrow{\cong} \mathbf{T}_{\mathbf{L}} \circ F$ such that the pair (F, τ) is a triangulated functor?

We end this subsection with a discussion of the contravariant case. Contravariant \mathbf{T} -additive functors were introduced in Definition 6.1.6.

Definition 6.3.8. Let \mathbf{K} and \mathbf{L} be triangulated categories. A *contravariant triangulated functor*

$$(F, \tau) : \mathbf{K} \rightarrow \mathbf{L}$$

is a contravariant \mathbf{T} -additive functor, such that for every distinguished triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

in \mathbf{K} , the triangle

$$F(N) \xrightarrow{F(\beta)} F(M) \xrightarrow{F(\alpha)} F(L) \xrightarrow{\tau_N \circ F(-\mathbf{T}_{\mathbf{K}}^{-1}(\gamma))} \mathbf{T}_{\mathbf{L}}(F(N))$$

\mathbf{L} is distinguished.

According to Proposition 6.2.8, the opposite category \mathbf{K}^{op} is triangulated.

Proposition 6.3.9. *Let \mathbf{K} and \mathbf{L} be triangulated categories.*

(1) *The contravariant T -additive functor*

$$(\text{op}, \text{id}) : \mathbf{K} \rightarrow \mathbf{K}^{\text{op}}$$

is a contravariant triangulated functor.

(2) *If*

$$(F, \tau) : \mathbf{K} \rightarrow \mathbf{L}$$

is a contravariant triangulated functor, then

$$(F \circ \text{op}, \tau) : \mathbf{K}^{\text{op}} \rightarrow \mathbf{L}$$

is a triangulated functor; and vice-versa.

Proof. Both assertions are immediate from comparing Definition 6.3.8 to Proposition 6.2.8. \square

6.4. The Homotopy Category is Triangulated. In this subsection we consider an abelian category \mathbf{M} and a DG ring A (everything central over the commutative base ring \mathbb{K}). These ingredients give rise to the \mathbb{K} -linear DG category $\mathbf{C}(A, \mathbf{M})$ of DG A -module in \mathbf{M} , as in Subsection 3.7.

The strict category $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ and the homotopy category $\mathbf{K}(A, \mathbf{M})$ were introduced in Definition 3.7.5. Recall that these \mathbb{K} -linear categories have the same objects as $\mathbf{C}(A, \mathbf{M})$. The morphisms \mathbb{K} -modules are

$$\text{Hom}_{\mathbf{C}_{\text{str}}(A, \mathbf{M})}(M_0, M_1) = Z^0(\text{Hom}_{\mathbf{C}(A, \mathbf{M})}(M_0, M_1))$$

and

$$\text{Hom}_{\mathbf{K}(A, \mathbf{M})}(M_0, M_1) = H^0(\text{Hom}_{\mathbf{C}(A, \mathbf{M})}(M_0, M_1)).$$

Thus the morphisms $M_0 \rightarrow M_1$ in $\mathbf{K}(A, \mathbf{M})$ are the homotopy classes $\bar{\phi} : M_0 \rightarrow M_1$ of the morphisms $\phi : M_0 \rightarrow M_1$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

Recall the full additive functor

$$(6.4.1) \quad P : \mathbf{C}_{\text{str}}(A, \mathbf{M}) \rightarrow \mathbf{K}(A, \mathbf{M})$$

from Definition 3.4.4, that is the identity on objects, and on morphisms it is $P(\phi) := \bar{\phi}$.

Consider the translation functor T from Definition 4.1.8. Since T is a DG functor from $\mathbf{C}(A, \mathbf{M})$ to itself (see Corollary 4.1.9), it restricts to a linear functor from $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ to itself, and it induces a linear functor \bar{T} from $\mathbf{K}(A, \mathbf{M})$ to itself, such that $P \circ T = \bar{T} \circ P$.

Proposition 6.4.2.

- (1) *The category $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, equipped with the translation functor T , is a T -additive category.*
- (2) *The category $\mathbf{K}(A, \mathbf{M})$, equipped with the translation functor \bar{T} , is a T -additive category.*
- (3) *Let $\tau : P \circ T \xrightarrow{\cong} \bar{T} \circ P$ be equality. Then the pair*

$$(P, \tau) : \mathbf{C}_{\text{str}}(A, \mathbf{M}) \rightarrow \mathbf{K}(A, \mathbf{M})$$

is a T -additive functor.

Proof. (1) We need to prove that $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ is additive. Of course the zero complex is a zero object. Next we consider finite direct sums. Let M_1, \dots, M_r be a finite collection of objects in $\mathbf{C}(A, \mathbf{M})$. Each M_i is a DG A -module in \mathbf{M} , and we write it as $M_i = \{M_i^j\}_{j \in \mathbb{Z}}$. In each degree j the direct sum $M^j := \bigoplus_{i=1}^r M_i^j$ exists

in \mathbf{M} . Let $M := \{M^j\}_{j \in \mathbb{Z}}$ be the resulting graded object in \mathbf{M} . The differential $d_M : M^j \rightarrow M^{j+1}$ exists by the universal property of direct sums; so we obtain a complex $M \in \mathbf{C}(\mathbf{M})$. The DG A -module structure on M is defined similarly: for $a \in A^k$, there is an induced degree k morphism $f(a) : M \rightarrow M$ in $\mathbf{C}(\mathbf{M})$. Thus M becomes an object of $\mathbf{C}(A, \mathbf{M})$. But the embeddings $e_i : M_i \rightarrow M$ are strict morphisms, so $(M, \{e_i\})$ is a coproduct of the collection $\{M_i\}$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

(2) Now consider the category $\mathbf{K}(A, \mathbf{M})$. Because the functor $P : \mathbf{C}_{\text{str}}(A, \mathbf{M}) \rightarrow \mathbf{K}(A, \mathbf{M})$ is additive, and is bijective on objects, part (1) above and Proposition 2.4.2 say that $\mathbf{K}(A, \mathbf{M})$ is an additive category.

(3) Clear. \square

From now on we denote by T , instead of by \bar{T} , the translation functor of $\mathbf{K}(A, \mathbf{M})$.

Definition 6.4.3. A triangle

$$L \xrightarrow{\bar{\alpha}} M \xrightarrow{\bar{\beta}} N \xrightarrow{\bar{\gamma}} T(L)$$

in $\mathbf{K}(A, \mathbf{M})$ is said to be a *distinguished triangle* if there is a standard triangle

$$L' \xrightarrow{\alpha'} M' \xrightarrow{\beta'} N' \xrightarrow{\gamma'} T(L')$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, as in Definition 4.2.5, and an isomorphism of triangles

$$\begin{array}{ccccccc} L' & \xrightarrow{P(\alpha')} & M' & \xrightarrow{P(\beta')} & N' & \xrightarrow{P(\gamma')} & T(L') \\ \bar{\phi} \downarrow & & \bar{\psi} \downarrow & & \bar{\chi} \downarrow & & T(\bar{\phi}) \downarrow \\ L & \xrightarrow{\bar{\alpha}} & M & \xrightarrow{\bar{\beta}} & N & \xrightarrow{\bar{\gamma}} & T(L) \end{array} .$$

in $\mathbf{K}(A, \mathbf{M})$.

Theorem 6.4.4. *The T -additive category $\mathbf{K}(A, \mathbf{M})$, with the set of distinguished triangles defined above, is a triangulated category.*

The proof is after three lemmas.

Lemma 6.4.5. *Let $M \in \mathbf{C}(A, \mathbf{M})$, and consider the cone $N := \text{Cone}(1_M)$. Then the DG module N is null-homotopic, i.e. $0 \rightarrow N$ is an isomorphism in $\mathbf{K}(A, \mathbf{M})$.*

Proof. We shall exhibit a homotopy θ from 0_N to 1_N . Recall from Subsection 4.2 that

$$N = \text{Cone}(1_M) = M \oplus T(M) = \begin{bmatrix} M \\ T(M) \end{bmatrix}$$

as graded modules, with differential whose matrix presentation is

$$d_N = \begin{bmatrix} d_M & t_M^{-1} \\ 0 & d_{T(M)} \end{bmatrix} .$$

And by the definition in Subsection 4.1 we have

$$d_{T(M)} = -t_M \circ d_M \circ t_M^{-1} .$$

Define $\theta : N \rightarrow N$ to be the degree -1 morphism with matrix presentation

$$\theta := \begin{bmatrix} 0 & 0 \\ t_M & 0 \end{bmatrix} .$$

Then, using the formulas above for d_N and $d_{T(M)}$, we get

$$d_N \circ \theta + \theta \circ d_N = \begin{bmatrix} 1_M & 0 \\ 0 & 1_{T(M)} \end{bmatrix} = 1_N.$$

□

Exercise 6.4.6. Here is a generalization of Lemma 6.4.5. Consider a morphism $\phi : M_0 \rightarrow M_1$ in $\mathbf{C}_{\text{str}}(A, M)$. Show that the three conditions below are equivalent:

- (i) ϕ is a homotopy equivalence.
- (ii) $\bar{\phi}$ is an isomorphism in $\mathbf{K}(A, M)$.
- (iii) The DG module $\text{Cone}(\phi)$ is null-homotopic.

Try to do this directly, not using Proposition 6.3.4(2) and Theorem 6.4.4.

The next lemma is based on [KaSc1, Lemma 1.4.2].

Lemma 6.4.7. Consider a morphism $\alpha : L \rightarrow M$ in $\mathbf{C}_{\text{str}}(A, M)$, the standard triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

associated to α , and the standard triangle

$$M \xrightarrow{\beta} N \xrightarrow{\phi} P \xrightarrow{\psi} T(M)$$

associated to β , all in $\mathbf{C}_{\text{str}}(A, M)$. So $N = \text{Cone}(\alpha)$ and $P = \text{Cone}(\beta)$. There is a morphism $\rho : T(L) \rightarrow P$ in $\mathbf{C}_{\text{str}}(A, M)$ s.t. $\bar{\rho}$ is an isomorphism in $\mathbf{K}(A, M)$, and the diagram

$$\begin{array}{ccccccc} M & \xrightarrow{\bar{\beta}} & N & \xrightarrow{\bar{\gamma}} & T(L) & \xrightarrow{-T(\bar{\alpha})} & T(M) \\ \bar{\iota}_M \downarrow & & \bar{\iota}_N \downarrow & & \bar{\rho} \downarrow & & \bar{\iota}_{T(M)} \downarrow \\ M & \xrightarrow{\bar{\beta}} & N & \xrightarrow{\bar{\phi}} & P & \xrightarrow{\bar{\psi}} & T(M) \end{array}$$

commutes in $\mathbf{K}(A, M)$.

Proof. Note that $N = M \oplus T(L)$ and $P = N \oplus T(M) = M \oplus T(L) \oplus T(M)$ as graded module. Thus P and d_P have the following matrix presentations:

$$P = \begin{bmatrix} M \\ T(L) \\ T(M) \end{bmatrix}, \quad d_P = \begin{bmatrix} d_M & \alpha \circ t_L^{-1} & t_M^{-1} \\ 0 & d_{T(L)} & 0 \\ 0 & 0 & d_{T(M)} \end{bmatrix}.$$

Define morphisms $\rho : T(L) \rightarrow P$ and $\chi : P \rightarrow T(L)$ in $\mathbf{C}_{\text{str}}(A, M)$ by the matrix presentations

$$\rho := \begin{bmatrix} 0 \\ 1_{T(L)} \\ -T(\alpha) \end{bmatrix}, \quad \chi := \begin{bmatrix} 0 & 1_{T(L)} & 0 \end{bmatrix}.$$

Direct calculations show that:

- $\chi \circ \rho = 1_{T(L)}$.
- $\rho \circ \gamma = \rho \circ \chi \circ \phi$.
- $\psi \circ \rho = -T(\alpha)$.

It remains to prove that $\rho \circ \chi$ is homotopic to 1_P . Define a degree -1 morphism $\theta : P \rightarrow P$ by the matrix

$$\theta := \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \mathfrak{t}_M & 0 & 0 \end{bmatrix}.$$

Then a direct calculation, using the equalities

$$\mathfrak{t}_M \circ \mathfrak{d}_M + \mathfrak{d}_{\mathbf{T}(M)} \circ \mathfrak{t}_M = 0$$

and

$$\mathbf{T}(\alpha) = \mathfrak{t}_M \circ \alpha \circ \mathfrak{t}_L^{-1}$$

gives

$$\theta \circ \mathfrak{d}_P + \mathfrak{d}_P \circ \theta = 1_P - \rho \circ \chi.$$

□

Lemma 6.4.8. *Consider a standard triangle*

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. For any integer k , the triangle

$$\mathbf{T}^k(L) \xrightarrow{\mathbf{T}^k(\alpha)} \mathbf{T}^k(M) \xrightarrow{\mathbf{T}^k(\beta)} \mathbf{T}^k(N) \xrightarrow{(-1)^k \cdot \mathbf{T}^k(\gamma)} \mathbf{T}^{k+1}(L)$$

is isomorphic, in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, to a standard triangle.

Proof. Combine Corollary 4.1.9, Corollary 5.3.8 with $F = \mathbf{T}$, and Proposition 5.2.4. □

Proof of Theorem 6.4.4. We essentially follow the proof of [KaSc1, Proposition 1.4.4], adding some details.

(TR1): By definition the set of distinguished triangles in $\mathbf{K}(A, \mathbf{M})$ is closed under isomorphisms. This establishes item (a).

As for item (b): consider any morphism $\bar{\alpha} : L \rightarrow M$ in $\mathbf{K}(A, \mathbf{M})$. It is represented by a morphism $\alpha : L \rightarrow M$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Take the standard triangle on α in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Its image in $\mathbf{K}(A, \mathbf{M})$ has the desired property.

Finally, Lemma 6.4.5 shows that the triangle

$$M \xrightarrow{\bar{1}_M} M \rightarrow 0 \rightarrow \mathbf{T}(M)$$

is isomorphic in $\mathbf{K}(A, \mathbf{M})$ to the triangle

$$M \xrightarrow{\bar{1}_M} M \xrightarrow{\bar{e}} \text{Cone}(1_M) \xrightarrow{\bar{p}} \mathbf{T}(M).$$

The latter is the image of a standard triangle, and so it is distinguished.

(TR2): Consider the triangles

$$(6.4.9) \quad L \xrightarrow{\bar{\alpha}} M \xrightarrow{\bar{\beta}} N \xrightarrow{\bar{\gamma}} \mathbf{T}(L)$$

and

$$(6.4.10) \quad M \xrightarrow{\bar{\beta}} N \xrightarrow{\bar{\gamma}} \mathbf{T}(L) \xrightarrow{-\mathbf{T}(\bar{\alpha})} \mathbf{T}(M)$$

in $\mathbf{K}(A, \mathbf{M})$. If (6.4.9) is distinguished, then by Lemma 6.4.7 so is (6.4.10).

Conversely, if (6.4.10) is distinguished, then by turning it 5 times, and using the previous step (namely by Lemma 6.4.7), we see that the triangle

$$\mathbf{T}^2(L) \xrightarrow{\mathbf{T}^2(\bar{\alpha})} \mathbf{T}^2(M) \xrightarrow{\mathbf{T}^2(\bar{\beta})} \mathbf{T}^2(N) \xrightarrow{\mathbf{T}^2(\bar{\gamma})} \mathbf{T}^3(L)$$

is distinguished. According to Lemma 6.4.8 (with $k = -2$), the triangle gotten by applying \mathbf{T}^{-2} to this is distinguished. But this is just the triangle (6.4.9).

(TR3): Consider a commutative diagram in $\mathbf{K}(A, \mathbf{M})$:

$$(6.4.11) \quad \begin{array}{ccccccc} \bar{L} & \xrightarrow{\bar{\alpha}} & \bar{M} & \xrightarrow{\bar{\beta}} & \bar{N} & \xrightarrow{\bar{\gamma}} & \mathbf{T}(\bar{L}) \\ \bar{\phi} \downarrow & & \bar{\psi} \downarrow & & & & \\ \bar{L}' & \xrightarrow{\bar{\alpha}'} & \bar{M}' & \xrightarrow{\bar{\beta}'} & \bar{N}' & \xrightarrow{\bar{\gamma}'} & \mathbf{T}(\bar{L}') \end{array}$$

where the horizontal triangles are distinguished. By definition the rows in (6.4.11) are isomorphic in $\mathbf{K}(A, \mathbf{M})$ to the images under the functor \mathbf{P} of standard triangles in $\mathbf{C}(A, \mathbf{M})$. These are the rows in diagram (6.4.12) below. The vertical morphisms in (6.4.11) are also induced from morphisms in $\mathbf{C}(A, \mathbf{M})$, i.e. $\bar{\phi} = \mathbf{P}(\phi)$ and $\bar{\psi} = \mathbf{P}(\psi)$. Thus (6.4.11) is isomorphic to the image under \mathbf{P} of the following diagram:

$$(6.4.12) \quad \begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbf{T}(L) \\ \phi \downarrow & & \psi \downarrow & & & & \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array}$$

Warning: the diagram (6.4.12) is only commutative up to homotopy in $\mathbf{C}(A, \mathbf{M})$.

Since the rows in (6.4.12) are standard triangles (see Definition 4.2.5), the objects N and N' are cones: $N = \text{Cone}(\alpha)$ and $N' = \text{Cone}(\alpha')$. The commutativity up to homotopy of this diagram means that there is a degree -1 morphism $\theta : L \rightarrow M'$ in $\mathbf{C}(A, \mathbf{M})$ such that

$$\alpha' \circ \phi = \psi \circ \alpha + \mathbf{d}(\theta).$$

Define the morphism

$$\chi : N = \begin{bmatrix} M \\ \mathbf{T}(L) \end{bmatrix} \rightarrow N' = \begin{bmatrix} M' \\ \mathbf{T}(L') \end{bmatrix}$$

by the matrix presentation

$$\chi := \begin{bmatrix} \psi & \theta \circ \mathbf{t}_L^{-1} \\ 0 & \mathbf{T}(\phi) \end{bmatrix}.$$

An easy calculation shows that χ is a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, and that there are equalities $\mathbf{T}(\phi) \circ \gamma = \gamma' \circ \chi$ and $\chi \circ \beta = \beta' \circ \psi$. Therefore, when we apply the functor \mathbf{P} , and conjugate by the original isomorphism between (6.4.11) and the image of (6.4.12), we obtain a commutative diagram

$$\begin{array}{ccccccc} \bar{L} & \xrightarrow{\bar{\alpha}} & \bar{M} & \xrightarrow{\bar{\beta}} & \bar{N} & \xrightarrow{\bar{\gamma}} & \mathbf{T}(\bar{L}) \\ \bar{\phi} \downarrow & & \bar{\psi} \downarrow & & \bar{\chi} \downarrow & & \mathbf{T}(\bar{\phi}) \downarrow \\ \bar{L}' & \xrightarrow{\bar{\alpha}'} & \bar{M}' & \xrightarrow{\bar{\beta}'} & \bar{N}' & \xrightarrow{\bar{\gamma}'} & \mathbf{T}(\bar{L}') \end{array}$$

in $\mathbf{K}(A, \mathbf{M})$, where $\bar{\chi}$ is conjugate to $P(\chi)$.

(TR4): We may assume that the three given distinguished triangles are standard triangles in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Namely, we can assume that $\alpha : L \rightarrow M$ and $\beta : M \rightarrow N$ are morphisms in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$; the DG modules P, Q, R are $P = \text{Cone}(\alpha)$, $Q = \text{Cone}(\beta \circ \alpha)$ and $R = \text{Cone}(\beta)$; and the morphisms γ, δ, ϵ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ are $\gamma = e_\alpha$, $\delta = e_{\beta \circ \alpha}$ and $\epsilon = e_\beta$. All this in the notation of Subsection 4.2.

In matrix notation we have

$$P = \begin{bmatrix} M \\ \mathbf{T}(L) \end{bmatrix}, \quad Q = \begin{bmatrix} N \\ \mathbf{T}(L) \end{bmatrix}, \quad R = \begin{bmatrix} N \\ \mathbf{T}(M) \end{bmatrix}.$$

We define the morphisms $\phi : P \rightarrow Q$ and $\psi : Q \rightarrow R$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ by the matrix presentations

$$\phi := \begin{bmatrix} \beta & 0 \\ 0 & \text{id}_{\mathbf{T}(L)} \end{bmatrix}, \quad \psi := \begin{bmatrix} \text{id}_N & 0 \\ 0 & \mathbf{T}(\alpha) \end{bmatrix}.$$

(We leave to the reader to verify that ϕ and ψ commute with the differentials d_P, d_Q and d_R ; this is just linear algebra, using the matrix presentations of the differentials of the cones from Definition 4.2.1.) Define the morphism $\rho : R \rightarrow \mathbf{T}(Q)$ in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ to be the composition of the morphisms $R \rightarrow \mathbf{T}(M) \xrightarrow{\mathbf{T}(\gamma)} \mathbf{T}(Q)$. Then the big diagram in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ is commutative.

It remains to prove that the triangle

$$(6.4.13) \quad P \xrightarrow{\bar{\phi}} Q \xrightarrow{\bar{\psi}} R \xrightarrow{\bar{\rho}} \mathbf{T}(P)$$

in $\mathbf{K}(A, \mathbf{M})$ is distinguished. Let $C := \text{Cone}(\phi)$; so we have a standard triangle

$$(6.4.14) \quad P \xrightarrow{\phi} Q \xrightarrow{e_\phi} C \xrightarrow{p_\phi} \mathbf{T}(P)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. We are going to prove that the triangles (6.4.13) and (6.4.14) are isomorphic in $\mathbf{K}(A, \mathbf{M})$, by producing an isomorphism $\bar{\chi} : C \xrightarrow{\cong} R$ in $\mathbf{K}(A, \mathbf{M})$ that makes the diagram

$$\begin{array}{ccccccc} P & \xrightarrow{\bar{\phi}} & Q & \xrightarrow{\bar{e}_\phi} & C & \xrightarrow{\bar{p}_\phi} & \mathbf{T}(P) \\ \downarrow \text{id} & & \downarrow \text{id} & & \downarrow \bar{\chi} & & \downarrow \text{id} \\ P & \xrightarrow{\phi} & Q & \xrightarrow{\psi} & R & \xrightarrow{\bar{\rho}} & \mathbf{T}(P) \end{array}$$

commutative.

Here are the matrices for the object C , the morphism $\chi : C \rightarrow R$, and another morphism $\omega : R \rightarrow C$, both in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

$$C = \begin{bmatrix} N \\ \mathbf{T}(L) \\ \mathbf{T}(M) \\ \mathbf{T}^2(L) \end{bmatrix}, \quad \chi := \begin{bmatrix} \text{id}_N & 0 & 0 & 0 \\ 0 & \mathbf{T}(\alpha) & \text{id}_{\mathbf{T}(M)} & 0 \end{bmatrix}, \quad \omega := \begin{bmatrix} \text{id}_N & 0 \\ 0 & 0 \\ 0 & \text{id}_{\mathbf{T}(M)} \\ 0 & 0 \end{bmatrix}.$$

Again, we leave it to the reader to check that χ and ω commute with the differentials. It is easy to see that $\omega \circ \psi = e_\phi$, $\rho \circ \chi = p_\phi$ and $\chi \circ \omega = \text{id}_R$.

Finally we must find a homotopy between $\omega \circ \chi$ and id_C . Consider the degree -1 endomorphisms θ of C :

$$\theta := \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \text{t}_{\mathbf{T}(L)} & 0 & 0 \end{bmatrix}.$$

Then

$$d_C \circ \theta + \theta \circ d_C = \text{id}_C - \omega \circ \chi.$$

□

We now add a second DG ring B , and a second additive category \mathbf{N} . DG functors were introduced in Subsection 3.5.

Consider a DG functor

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N}).$$

From Theorem 5.2.3 we know that the translation isomorphism is an isomorphism of DG functors

$$\tau_F : F \circ \mathbf{T}_{A, \mathbf{M}} \xrightarrow{\cong} \mathbf{T}_{B, \mathbf{N}} \circ F.$$

Therefore, when we pass to the homotopy categories, and writing $\bar{F} := \text{Ho}(F)$, we get a \mathbf{T} -additive functor

$$(\bar{F}, \bar{\tau}_F) : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{K}(B, \mathbf{N}).$$

Theorem 6.4.15. *Let*

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N})$$

be a DG functor, with translation isomorphism τ_F . Then the \mathbf{T} -additive functor

$$(\bar{F}, \bar{\tau}_F) : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{K}(B, \mathbf{N})$$

is a triangulated functor.

Proof. Take a distinguished triangle

$$L \xrightarrow{\bar{\alpha}} M \xrightarrow{\bar{\beta}} N \xrightarrow{\bar{\gamma}} \mathbf{T}(L)$$

in $\mathbf{K}(A, \mathbf{M})$. Since we are only interested in triangles up to isomorphism, we can assume that this is the image under the functor \mathbf{P} of a standard triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. According to Theorem 5.3.7 and Corollary 5.3.8, there is a standard triangle

$$L' \xrightarrow{\alpha'} M' \xrightarrow{\beta'} N' \xrightarrow{\gamma'} \mathbf{T}(L')$$

in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$, and a commutative diagram

$$\begin{array}{ccccccc} F(L) & \xrightarrow{F(\alpha)} & F(M) & \xrightarrow{F(\beta)} & F(N) & \xrightarrow{\tau_{F,L} \circ F(\gamma)} & \mathbf{T}(F(L)) \\ \phi \downarrow & & \psi \downarrow & & \chi \downarrow & & \mathbf{T}(\phi) \downarrow \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array}$$

in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$, in which the vertical arrows are isomorphisms. (Actually, we can take $L' = F(L)$, $\phi = \text{id}_{F(L)}$, etc.) After applying the functor P to this diagram, we see that the condition in Definition 6.3.1(1) is satisfied. \square

Corollary 6.4.16. *For any integer k , the pair $(\mathbb{T}^k, (-1)^k \cdot \text{id}_{\mathbb{T}^{k+1}})$ is a triangulated functor from $\mathbf{K}(A, \mathbf{M})$ to itself.*

Proof. Combine Theorems 6.4.15 and Proposition 5.2.4. \square

Remark 6.4.17. In [BoKa], Bondal and Kapranov introduce the concept of *pretriangulated DG category*. This is a DG category \mathbf{C} for which the homotopy category $\text{Ho}(\mathbf{C})$ is canonically triangulated (the details of the definition are too complicated to mention here). Our DG categories $\mathbf{C}(A, \mathbf{M})$ are pretriangulated in the sense of [BoKa]; but they have a lot more structure (e.g. the objects have cohomologies too).

Suppose \mathbf{C} and \mathbf{C}' are pretriangulated DG categories. In [BoKa] there is a (rather complicated) definition of *pre-exact DG functor* $F : \mathbf{C} \rightarrow \mathbf{C}'$. It is stated there that if F is a pre-exact DG functor, then $\text{Ho}(F) : \text{Ho}(\mathbf{C}) \rightarrow \text{Ho}(\mathbf{C}')$ is a triangulated functor. This is analogous to our Theorem 6.4.15. Presumably, Theorems 5.2.3 and 5.3.7 imply that any DG functor $F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(A', \mathbf{M}')$ is pre-exact in the sense of [BoKa]; but we did not verify this.

7. LOCALIZATION OF CATEGORIES

Most of this section is devoted to the general theory of *Ore localization of categories*. In the last subsection we talk about localization of a pretriangulated category \mathbf{K} with respect to a denominator set of cohomological origin $\mathbf{S} \subseteq \mathbf{K}$.

7.1. The Formalism of Localization. We will start with a category \mathbf{A} , without even assuming it is linear. Still we use the notation \mathbf{A} , because it will be suggestive to think about a linear category \mathbf{A} with a single object, which is just a ring A . The reason is that our localization procedure is the same as that in noncommutative ring theory (the only change being that we allow multiple objects).

The emphasis will be on morphisms rather than on objects. Thus it will be convenient to write

$$\mathbf{A}(M, N) := \text{Hom}_{\mathbf{A}}(M, N)$$

for $M, N \in \text{Ob}(\mathbf{A})$. We sometimes use the notation $a \in \mathbf{A}$ for a morphism $a \in \mathbf{A}(M, N)$, leaving the objects implicit. When we write $b \circ a$ for $a, b \in \mathbf{A}$, we implicitly mean that these morphisms are composable.

For heuristic purposes, we can think of \mathbf{A} as a linear category (e.g. living inside some category of modules), with objects M, N, \dots . For any given object M , we then have a genuine ring $\mathbf{A}(M) := \mathbf{A}(M, M)$.

Definition 7.1.1. Let \mathbf{A} be a category. A *multiplicatively closed set of morphisms* in \mathbf{A} is a subcategory $\mathbf{S} \subseteq \mathbf{A}$ such that $\text{Ob}(\mathbf{S}) = \text{Ob}(\mathbf{A})$.

In other words, for any pair of objects $M, N \in \mathbf{A}$ there is a subset $\mathbf{S}(M, N) \subseteq \mathbf{A}(M, N)$, such that $1_M \in \mathbf{S}(M, M)$, and such that for any $s \in \mathbf{S}(L, M)$ and $t \in \mathbf{S}(M, N)$, the composition $t \circ s \in \mathbf{S}(L, N)$.

Using our shorthand, we can write the definition like this: $1_M \in \mathbf{S}$, and $s, t \in \mathbf{S}$ implies $t \circ s \in \mathbf{S}$.

If $\mathbf{A} = \mathbf{A}$ is a single object linear category, namely a ring, then $\mathbf{S} = \mathbf{S}$ is a multiplicatively closed set in the sense of ring theory.

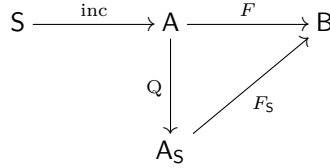
There are various notions of localization in the literature. We restrict attention to two of them.

Definition 7.1.2. Let \mathbf{S} be a multiplicatively closed set of morphisms in a category \mathbf{A} . A *localization* of \mathbf{A} with respect to \mathbf{S} is a pair $(\mathbf{A}_{\mathbf{S}}, \mathbf{Q})$, consisting of a category $\mathbf{A}_{\mathbf{S}}$ and a functor $\mathbf{Q} : \mathbf{A} \rightarrow \mathbf{A}_{\mathbf{S}}$, called the localization functor, having the following properties:

- (L1) There is equality $\text{Ob}(\mathbf{A}_{\mathbf{S}}) = \text{Ob}(\mathbf{A})$, and \mathbf{Q} is the identity on objects.
- (L2) For every $s \in \mathbf{S}$, the morphism $\mathbf{Q}(s) \in \mathbf{A}_{\mathbf{S}}$ is invertible (i.e. it is an isomorphism).
- (L3) Suppose \mathbf{B} is a category, and $F : \mathbf{A} \rightarrow \mathbf{B}$ is a functor such that $F(s)$ is invertible for every $s \in \mathbf{S}$. Then there is a unique functor $F_{\mathbf{S}} : \mathbf{A}_{\mathbf{S}} \rightarrow \mathbf{B}$ such that $F_{\mathbf{S}} \circ \mathbf{Q} = F$ as functors $\mathbf{A} \rightarrow \mathbf{B}$.

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In a commutative diagram:



In the ring case, $F : A \rightarrow B$ is a ring homomorphism, etc.

Proposition 7.1.3. *A localization (in the sense of Definition 7.1.2) is unique up to a unique isomorphism. Namely if (A'_S, Q') is another localization, then there is a unique functor $G : A_S \rightarrow A'_S$ which is the identity on objects, bijective on morphisms, and $G \circ Q = Q'$.*

Proof. Exercise. □

A localization in this general sense always exists, but often it is of little value, because there is no practical way to describe the morphisms in it.

7.2. Ore Localization. There is a better notion of localization. The references here are [RD], [GaZi], [We], [KaSc1], [Ste] and [Row]. The first four references talk about localization of categories; and the last two talk about noncommutative rings. It seems that historically, this *noncommutative calculus of fractions* was discovered by Ore and Asano in ring theory, around 1930. There was progress in the categorical side, notably by Gabriel around 1960.

In this subsection we mostly follow the treatment of [Ste]; but we sometimes use diagrams instead of formulas involving letters – this is the only way the author was able to understand the proofs!

Definition 7.2.1. Let S be a multiplicatively closed set of morphisms in a category A . A *right Ore localization* of A with respect to S is a pair (A_S, Q) , consisting of a category A_S and a functor $Q : A \rightarrow A_S$, having the following properties:

- (RO1) There is equality $\text{Ob}(A_S) = \text{Ob}(A)$, and Q is the identity on objects.
- (RO2) For every $s \in S$, the morphism $Q(s) \in A_S$ is an isomorphism.
- (RO3) Every morphism $q \in A_S$ can be written as $q = Q(a) \circ Q(s)^{-1}$ for some $a \in A$ and $s \in S$.
- (RO4) Suppose $a, b \in A$ satisfy $Q(a) = Q(b)$. Then $a \circ s = b \circ s$ for some $s \in S$.

The letters “RO” stand for “right Ore”. We refer to the expression $q = Q(a) \circ Q(s)^{-1}$ as a *right fraction representation* of q .

Remark 7.2.2. There is an obvious notion of *left Ore localization*, with properties (LO1)-(LO4) that are identical to (RO1)-(RO4) respectively, except that in the last two the compositions are reversed: $q = Q(s)^{-1} \circ Q(a)$ and $s \circ a = s \circ b$. The results to follow in this section all have “left” versions, with identical proofs (just a matter of reversing some arrows or compositions), and so they will be omitted.

To reinforce the last remark, we give:

Proposition 7.2.3. *Let S be a multiplicatively closed set in a category A , and let $Q : A \rightarrow A_S$ be a functor. Prove that $Q : A \rightarrow A_S$ is a right Ore localization of A with respect to S if and only if $Q^{\text{op}} : A^{\text{op}} \rightarrow (A^{\text{op}})_{S^{\text{op}}}$ is a left Ore localization of A^{op} with respect to S^{op} .*

Exercise 7.2.4. Prove Proposition 7.2.3.

Lemma 7.2.5. *Let (A_S, Q) be a right Ore localization, let $a_1, a_2 \in A$ and $s_1, s_2 \in S$. The following conditions are equivalent:*

- (i) $Q(a_1) \circ Q(s_1)^{-1} = Q(a_2) \circ Q(s_2)^{-1}$ in A_S .
- (ii) There are $b_1, b_2 \in A$ s.t. $a_1 \circ b_1 = a_2 \circ b_2$, and $s_1 \circ b_1 = s_2 \circ b_2 \in S$.

Proof. (ii) \Rightarrow (i): Since $Q(s_i)$ and $Q(s_i \circ b_i)$ are invertible, it follows that $Q(b_i)$ are invertible. So

$$\begin{aligned} Q(a_1) \circ Q(s_1)^{-1} &= Q(a_1) \circ Q(b_1) \circ Q(b_1)^{-1} \circ Q(s_1)^{-1} \\ &= Q(a_2) \circ Q(b_2) \circ Q(b_2)^{-1} \circ Q(s_2)^{-1} = Q(a_2) \circ Q(s_2)^{-1}. \end{aligned}$$

(i) \Rightarrow (ii): By property (RO3) there are $c \in A$ and $u \in S$ s.t.

$$(7.2.6) \quad Q(s_2)^{-1} \circ Q(s_1) = Q(c) \circ Q(u)^{-1}.$$

Rewriting this equation we get

$$(7.2.7) \quad Q(s_1 \circ u) = Q(s_2 \circ c).$$

It is given that

$$Q(a_1) = Q(a_2) \circ Q(s_2)^{-1} \circ Q(s_1).$$

Plugging (7.2.6) into it we obtain

$$Q(a_1) = Q(a_2) \circ Q(c) \circ Q(u)^{-1}.$$

Rearranging this equation we get

$$(7.2.8) \quad Q(a_1 \circ u) = Q(a_2 \circ c).$$

By property (RO4) there is $v \in S$ s.t.

$$a_1 \circ u \circ v = a_2 \circ c \circ v.$$

Likewise, from equation (7.2.7) and property (RO4), there is $v' \in S$ s.t.

$$s_1 \circ u \circ v' = s_2 \circ c \circ v'.$$

Again using property (RO3), there are $d \in A$ and $w \in S$ s.t.

$$Q(v)^{-1} \circ Q(v') = Q(d) \circ Q(w)^{-1}.$$

Rearranging we get

$$Q(v' \circ w) = Q(v \circ d).$$

By property (RO4) there is $w' \in S$ s.t.

$$v' \circ w \circ w' = v \circ d \circ w'.$$

Define

$$b_1 := u \circ v \circ d \circ w', \quad b_2 := c \circ v \circ d \circ w'.$$

Then

$$\begin{aligned} s_1 \circ b_1 &= s_1 \circ u \circ v \circ d \circ w' = s_1 \circ u \circ v' \circ w \circ w' \\ &= s_2 \circ c \circ v' \circ w \circ w' = s_2 \circ b_2, \end{aligned}$$

and it is in S . Also

$$a_1 \circ b_1 = a_1 \circ u \circ v \circ d \circ w' = a_2 \circ c \circ v \circ d \circ w' = a_2 \circ b_2.$$

□

Proposition 7.2.9. *A right Ore localization $(\mathbf{A}_S, \mathbf{Q})$ is a localization in the sense of Definition 7.1.2.*

Proof. Say \mathbf{B} is a category, and $F : \mathbf{A} \rightarrow \mathbf{B}$ is a functor such that $F(s)$ is an isomorphism for every $s \in \mathbf{S}$.

The uniqueness of a functor $F_S : \mathbf{A}_S \rightarrow \mathbf{B}$ satisfying $F_S \circ \mathbf{Q} = F$ is clear from property (RO3). We have to prove existence.

Define F_S to be F on objects, and

$$F_S(q) := F(a_1) \circ F(s_1)^{-1},$$

where

$$q = \mathbf{Q}(a_1) \circ \mathbf{Q}(s_1)^{-1} \in \mathbf{A}_S, \quad a_1 \in \mathbf{A}, \quad s_1 \in \mathbf{S}$$

is any presentation of q as a right fraction, that exists by (RO3). We have to prove that this is well defined. So suppose that $q = \mathbf{Q}(a_2) \circ \mathbf{Q}(s_2)^{-1}$ is another presentation of q . Let $b_1, b_2 \in \mathbf{A}$ be as in Lemma 7.2.5. Since $F(s_i)$ and $F(s_i \circ b_i)$ are invertible, then so is $F(b_i)$. We get

$$F(a_2) = F(a_1) \circ F(b_1) \circ F(b_2)^{-1}$$

and

$$F(s_2) = F(s_1) \circ F(b_1) \circ F(b_2)^{-1}.$$

Hence

$$F(a_2) \circ F(s_2)^{-1} = F(a_1) \circ F(s_1)^{-1}.$$

It remains to prove that F_S is a functor. Since the identity 1_M of the object M in \mathbf{A}_S can be presented as $1_M = \mathbf{Q}(1_M) \circ \mathbf{Q}(1_M)^{-1}$, we see that $F_S(1_M) = 1_{F(M)}$.

Next let q_1 and q_2 be morphisms in \mathbf{A}_S , such that composition $q_2 \circ q_1$ exists (i.e. the target of q_1 is the source of q_2). We have to show that $F_S(q_2 \circ q_1)$ equals $F_S(q_2) \circ F_S(q_1)$. Choose presentations $q_i = \mathbf{Q}(a_i) \circ \mathbf{Q}(s_i)^{-1}$, so that

$$(7.2.10) \quad F_S(q_2) \circ F_S(q_1) = F(a_2) \circ F(s_2)^{-1} \circ F(a_1) \circ F(s_1)^{-1}.$$

By property (RO3) there is a right fraction presentation

$$(7.2.11) \quad \mathbf{Q}(s_2)^{-1} \circ \mathbf{Q}(a_1) = \mathbf{Q}(b) \circ \mathbf{Q}(t)^{-1}$$

for some $b \in \mathbf{A}$ and $t \in \mathbf{S}$. Because

$$\mathbf{Q}(a_1 \circ t) = \mathbf{Q}(s_2 \circ b),$$

by (RO4) there is some $r \in \mathbf{S}$ such that

$$a_1 \circ t \circ r = s_2 \circ b \circ r.$$

Therefore

$$F(a_1 \circ t \circ r) = F(s_2 \circ b \circ r),$$

which implies, by canceling the invertible morphism $F(r)$ and rearranging, that

$$(7.2.12) \quad F(s_2)^{-1} \circ F(a_1) = F(b) \circ F(t)^{-1}$$

in \mathbf{B} .

Let us continue. Using equation (7.2.11) we have

$$\begin{aligned} q_2 \circ q_1 &= \mathbf{Q}(a_2) \circ \mathbf{Q}(s_2)^{-1} \circ \mathbf{Q}(a_1) \circ \mathbf{Q}(s_1)^{-1} \\ &= \mathbf{Q}(a_2) \circ \mathbf{Q}(b) \circ \mathbf{Q}(t)^{-1} \circ \mathbf{Q}(s_1)^{-1} = \mathbf{Q}(a_2 \circ b) \circ \mathbf{Q}(s_1 \circ t)^{-1}. \end{aligned}$$

Using this presentation of $q_2 \circ q_1$, and the equality (7.2.12), we obtain

$$\begin{aligned} F_S(q_2 \circ q_1) &= F(a_2 \circ b) \circ F(s_1 \circ t)^{-1} = F(a_2) \circ F(b) \circ F(t)^{-1} \circ F(s_1)^{-1} \\ &= F(a_2) \circ F(s_2)^{-1} \circ F(a_1) \circ F(s_1)^{-1}. \end{aligned}$$

This is the same as (7.2.10). □

Corollary 7.2.13. *Let S be a multiplicatively closed set of morphisms in a category \mathbf{A} . Assume that $(\mathbf{A}_S, \mathbf{Q})$ and $(\mathbf{A}'_S, \mathbf{Q}')$ are either right Ore localizations or left Ore localizations of \mathbf{A} with respect to S . Then there is a unique isomorphism of localizations*

$$(\mathbf{A}_S, \mathbf{Q}) \cong (\mathbf{A}'_S, \mathbf{Q}'),$$

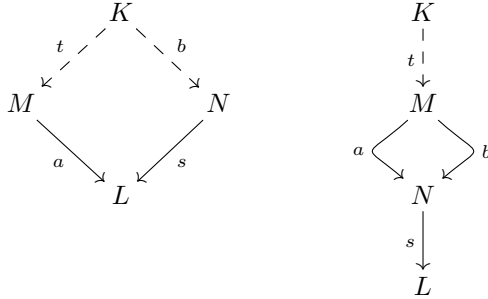
as in Proposition 7.1.3.

Proof. By Proposition 7.2.9 (in its right or left versions, as the case may be), both $(\mathbf{A}_S, \mathbf{Q})$ and $(\mathbf{A}'_S, \mathbf{Q}')$ are localizations in the sense of Definition 7.1.2. Hence, by Proposition 7.1.3, there is a unique isomorphism $(\mathbf{A}_S, \mathbf{Q}) \cong (\mathbf{A}'_S, \mathbf{Q}')$. □

Definition 7.2.14. Let S be multiplicatively closed set of morphisms in a category \mathbf{A} . We say that S is a *right denominator set* if it satisfies these two conditions:

- (RD1) (Right Ore condition) Given $a \in \mathbf{A}$ and $s \in S$, there exist $b \in \mathbf{A}$ and $t \in S$ such that $a \circ t = s \circ b$.
- (RD2) (Right Cancellation condition) Given $a, b \in \mathbf{A}$ and $s \in S$ such that $s \circ a = s \circ b$, there exists $t \in S$ such that $a \circ t = b \circ t$.

In commutative diagrams:



There is a similar left version of this definition, with conditions (LD1) and (LD2). Here is the main theorem regarding Ore localization.

Theorem 7.2.15. *The following conditions are equivalent for a category \mathbf{A} and a multiplicatively closed set of morphisms $S \subseteq \mathbf{A}$.*

- (i) *The right Ore localization $(\mathbf{A}_S, \mathbf{Q})$ exists.*
- (ii) *S is a right denominator set.*

The proof of Theorem 7.2.15 is after some preparation. The hard part is proving that (ii) \Rightarrow (i). The general idea is the same as in commutative localization: we consider the set of pairs of morphisms $\mathbf{A} \times S$, and define a relation \sim on it, with the hope that this is an equivalence relation, and that the quotient set \mathbf{A}_S will be a category, and it will have the desired properties.

Let's assume that \mathbf{S} is a right denominator set. For any $M, N \in \text{Ob}(A)$ consider the set

$$(\mathbf{A} \times \mathbf{S})(M, N) := \coprod_{L \in \text{Ob}(A)} \mathbf{A}(L, N) \times \mathbf{S}(L, M).$$

Remark 7.2.16. The set $(\mathbf{A} \times \mathbf{S})(M, N)$ could be big, namely not an element of the initial universe \mathbf{U} . This would require the introduction of a larger universe, say \mathbf{V} , in which \mathbf{U} is an element. And the resulting category $\mathbf{A}_{\mathbf{S}}$ will be a \mathbf{V} -category.

We will ignore this issue. Moreover, in many cases of interest (derived categories where there are DG enhancements, such as the \mathbf{K} -injective enhancement), there will be an alternative presentation of $\mathbf{A}_{\mathbf{S}}$ as a \mathbf{U} -category. We will refer to this when we get to it.

An element $(a, s) \in (\mathbf{A} \times \mathbf{S})(M, N)$ can be pictured as a diagram

$$(7.2.17) \quad \begin{array}{ccc} & L & \\ s \swarrow & & \searrow a \\ M & & N \end{array}$$

in \mathbf{A} . This diagram will eventually represent the right fraction

$$Q(a) \circ Q(s)^{-1} : M \rightarrow N.$$

Definition 7.2.18. We define a relation \sim on the set $\mathbf{A} \times \mathbf{S}$ like this:

$$(a_1, s_1) \sim (a_2, s_2)$$

if there exist $b_1, b_2 \in \mathbf{A}$ s.t.

$$a_1 \circ b_1 = a_2 \circ b_2 \text{ and } s_1 \circ b_1 = s_2 \circ b_2 \in \mathbf{S}.$$

Note that the relation \sim imposes condition (ii) of Lemma 7.2.5.

Here it is in a commutative diagram, in which we have made the objects explicit:

$$(7.2.19) \quad \begin{array}{ccccc} & & K & & \\ & b_1 \swarrow & & \searrow b_2 & \\ & L_1 & & & L_2 \\ & \downarrow s_1 & & & \downarrow a_2 \\ & M & & & N \\ & \swarrow s_2 & & \nwarrow a_1 & \end{array}$$

The arrows ending at M are in \mathbf{S} .

Lemma 7.2.20. *If the right Ore condition holds then the relation \sim is an equivalence.*

Proof. Reflexivity: take $K := L$ and $b_i := 1_L : L \rightarrow L$. Symmetry is trivial.

Now to prove transitivity. Suppose we are given $(a_1, s_1) \sim (a_2, s_2)$ and $(a_2, s_2) \sim (a_3, s_3)$. So we have the solid part of the first diagram in Figure 2, and it is commutative. The arrows ending at M are in \mathbf{S} .

By condition (RD1) applied to $K \rightarrow M \leftarrow J$ there are $t \in \mathbf{S}$ and $d \in \mathbf{A}$ s.t.

$$(s_3 \circ c_3) \circ d = (s_1 \circ b_1) \circ t.$$

Comparing arrows $I \rightarrow M$ in this diagram, we see that

$$s_2 \circ (b_2 \circ t) = s_1 \circ b_1 \circ t = s_3 \circ c_3 \circ d = s_2 \circ (c_2 \circ d).$$

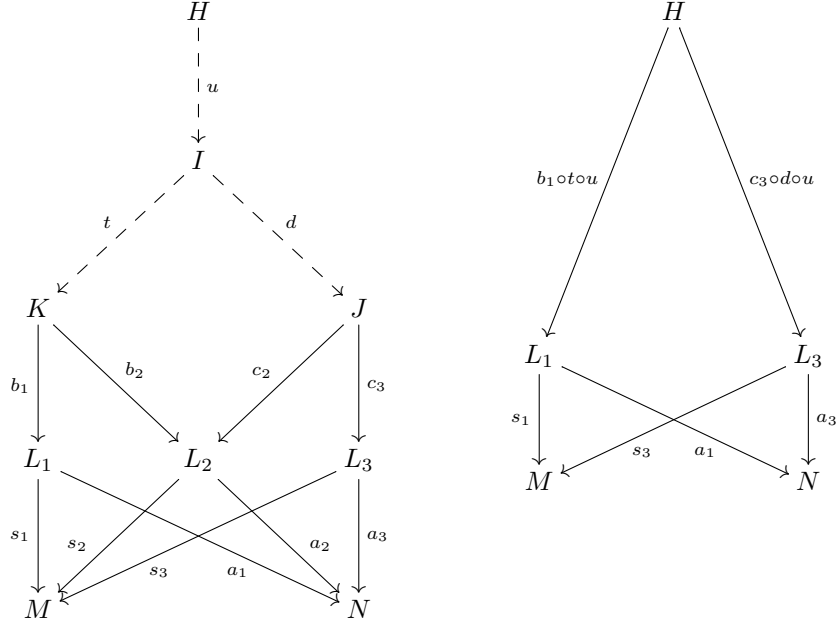


FIGURE 2.

By (RD2) there is $u \in \mathbf{S}$ s.t.

$$(b_2 \circ t) \circ u = (c_2 \circ d) \circ u.$$

So all paths $H \rightarrow M$ are equal and belong to \mathbf{S} , and all paths $H \rightarrow N$ are equal. Now delete the object L_2 and the arrows going through it. Then delete the objects I, J, K , but keep the paths going through them. We get the second diagram in Figure 2. It is commutative, and all arrows ending at M are in \mathbf{S} . This is evidence for $(a_1, s_1) \sim (a_3, s_3)$. \square

Proof of Theorem 7.2.15.

Step 1. In this step we prove (i) \Rightarrow (ii). Take $a \in \mathbf{A}$ and $s \in \mathbf{S}$. Consider $q := Q(s)^{-1} \circ Q(a)$. By (RO3) there are $b \in \mathbf{A}$ and $t \in \mathbf{S}$ s.t. $q = Q(b) \circ Q(t)^{-1}$. So

$$Q(s \circ b) = Q(a \circ t).$$

By (RO4) there is $u \in \mathbf{S}$ s.t.

$$(s \circ b) \circ u = (a \circ t) \circ u.$$

We read this as

$$s \circ (b \circ u) = a \circ (t \circ u),$$

and note that $t \circ u \in \mathbf{S}$. So (RD1) holds.

Next $a, b \in \mathbf{A}$ and $s \in \mathbf{S}$ s.t. $s \circ a = s \circ b$. Then $Q(s \circ a) = Q(s \circ b)$. But $Q(s)$ is invertible, so $Q(a) = Q(b)$. By (RO4) there is $t \in \mathbf{S}$ s.t. $a \circ t = b \circ t$. We have proved (RD2).

Step 2. Now we assume that condition (ii) holds, and we define the morphism sets $\mathbf{A}_{\mathbf{S}}(M, N)$, composition between them, and the identity morphisms.

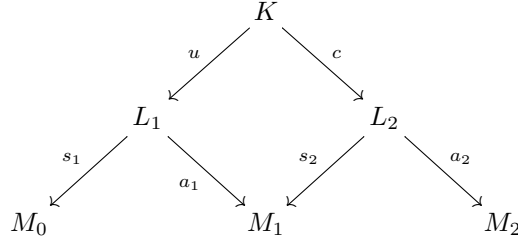


FIGURE 3.

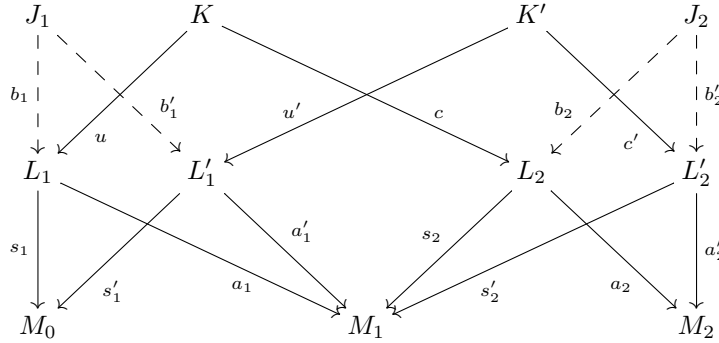


FIGURE 4.

For any $M, N \in \text{Ob}(\mathcal{A})$ let

$$\mathcal{A}_{\mathcal{S}}(M, N) := \frac{(\mathcal{A} \times \mathcal{S})(M, N)}{\sim},$$

where \sim is the relation from Definition 7.2.18, which is an equivalence relation by Lemma 7.2.20.

We define composition like this. Given $q_1 \in \mathcal{A}_{\mathcal{S}}(M_0, M_1)$ and $q_2 \in \mathcal{A}_{\mathcal{S}}(M_1, M_2)$, choose representatives $(a_i, s_i) \in (\mathcal{A} \times \mathcal{S})(M_{i-1}, M_i)$. We use the notation $q_i = \overline{(a_i, s_i)}$ to indicate this. By (RD1) there are $c \in \mathcal{A}$ and $u \in \mathcal{S}$ s.t. $s_2 \circ c = a_1 \circ u$. The composition

$$q_2 \circ q_1 \in \mathcal{A}_{\mathcal{S}}(M_0, M_2)$$

is defined to be

$$q_2 \circ q_1 := \overline{(a_2 \circ c, s_1 \circ u)} \in (\mathcal{A} \times \mathcal{S})(M_0, M_2).$$

The idea behind the formula can be seen in the diagram in Figure 3.

We have to verify that this definition is independent of the representatives. So suppose we take other representatives $q_i = \overline{(a'_i, s'_i)}$, and we choose morphisms u', c' to construct the composition. This is the solid part of the diagram in Figure 4, and it is a commutative diagram. We must prove that

$$\overline{(a_2 \circ c, s_1 \circ u)} = \overline{(a'_2 \circ c', s'_1 \circ u')}.$$

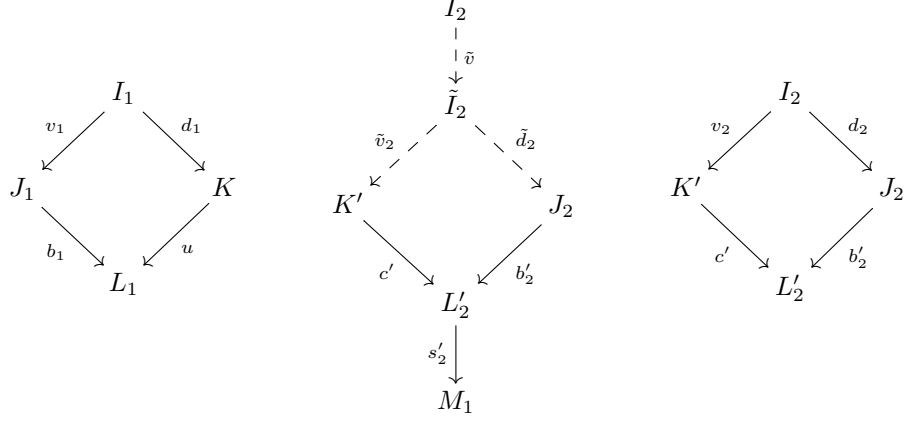


FIGURE 5.

There are morphisms b_i, b'_i the are evidence for $(a_i, s_i) \sim (a'_i, s'_i)$. They are depicted as the dashed arrows in Figure 4. That whole diagram is commutative. The morphisms $J_1 \rightarrow M_0$, $K \rightarrow M_0$, $K' \rightarrow M_0$ and $J_2 \rightarrow M_1$ are all in \mathcal{S} .

Choose $v_1 \in \mathcal{S}$ and $d_1 \in \mathcal{A}$ s.t. the first diagram in Figure 5 is commutative. This can be done by (RD1).

Consider the solid part of the middle diagram in Figure 5. Since $J_2 \rightarrow M_1$ is in \mathcal{S} , by (RD1) there are $\tilde{v}_2 \in \mathcal{S}$ and $\tilde{d}_2 \in \mathcal{A}$ s.t. the two paths $\tilde{I}_2 \rightarrow M_1$ are equal. By (RD2) there is $\tilde{v} \in \mathcal{S}$ s.t. the two paths $I_2 \rightarrow L'_2$ are equal. We get the commutative diagram in the middle of Figure 5. Next, defining $d_2 := \tilde{d}_2 \circ \tilde{v}$ and $v_2 := \tilde{v}_2 \circ \tilde{v} \in \mathcal{S}$, we obtain the third commutative diagram in Figure 5.

We now embed the first and third diagrams from Figure 5 into the diagram in Figure 4. This gives us the solid diagram in Figure 6, and it is commutative. The morphisms $I_1 \rightarrow M_0$ belong to \mathcal{S} .

Choose $w \in \mathcal{S}$ and $e \in \mathcal{A}$, starting at an object H , to fill the diagram $I_1 \rightarrow M_0 \leftarrow I_2$, using (RD1). The path $H \rightarrow I_1 \rightarrow M_0$ is in \mathcal{S} , and all the paths $H \rightarrow M_0$ are equal. But we could have failure of commutativity in the paths $H \rightarrow L'_1$ and $H \rightarrow L_2$.

The two paths $H \rightarrow L'_1$ in Figure 6 satisfy

$$s'_1 \circ (b'_1 \circ v_1 \circ w) = s'_1 \circ (u' \circ v_2 \circ e).$$

Therefore there is $w' \in \mathcal{S}$ s.t.

$$(b'_1 \circ v_1 \circ w) \circ w' = (u' \circ v_2 \circ e) \circ w'.$$

Next, the two paths $H' \rightarrow L_2$ satisfy

$$s_2 \circ (c \circ d_1 \circ w \circ w') = s_2 \circ (b_2 \circ d_2 \circ e \circ w');$$

this is because we can take a detour through L'_1 . Therefore there is $w'' \in \mathcal{S}$ s.t.

$$(c \circ d_1 \circ w \circ w') \circ w'' = (b_2 \circ d_2 \circ e \circ w') \circ w''.$$

Now all paths $H'' \rightarrow M_2$ in Figure 6 are equal. All paths $H'' \rightarrow M_0$ are equal and are in \mathcal{S} .

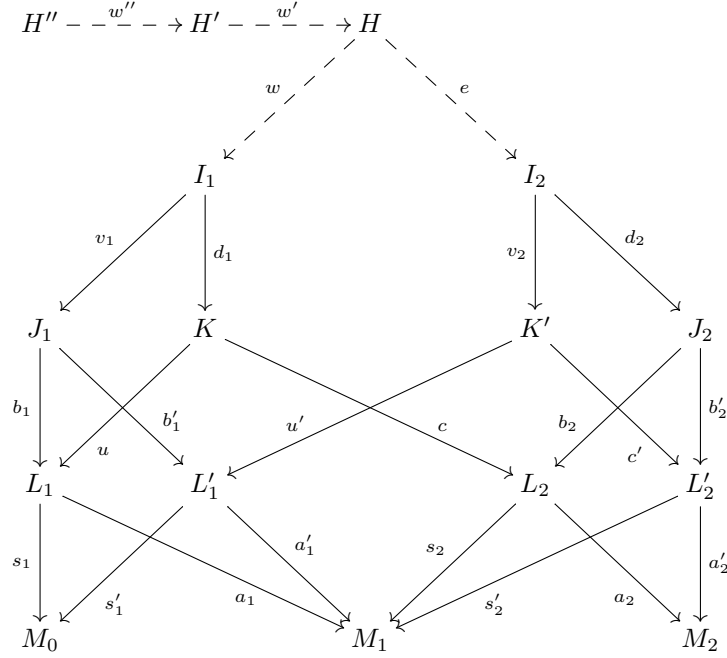


FIGURE 6.

Erase the objects M_1, J_1, J_2 and all arrows touching them from Figure 6. Then erase H, H' , but keep the paths through them. We obtain the commutative diagram in Figure 7. This is evidence for

$$(a_2 \circ c, s_1 \circ u) \sim (a'_2 \circ c', s'_1 \circ u').$$

The proof that composition is well-defined is done.

The identity morphism 1_M of an object M is $\overline{(1_M, 1_M)}$.

Step 3. We have to verify the associativity and the identity properties of composition in \mathcal{A}_5 . Namely that \mathcal{A}_5 is a category. This seems to be not too hard, given Step 2, and we leave it as an exercise!

Step 4. The functor $Q : \mathcal{A} \rightarrow \mathcal{A}_5$ is defined to be $Q(M) := M$ on objects, and $Q(a) := \overline{(a, 1_M)}$ for $a : M \rightarrow N$ in \mathcal{A} . We have to verify this is a functor... Again, an exercise.

Step 5. Finally we verify properties (RO1)-(RO4). (RO1) is clear. The inverse of $Q(s)$ is $\overline{(1, s)}$, so (RO2) holds.

It is not hard to see that

$$\overline{(a, s)} = \overline{(a, 1)} \circ \overline{(1, s)};$$

this is (RO3).

If $Q(a_1) = Q(a_2)$, then $(a_1, 1_M) \sim (a_2, 1_M)$; so there are $b_1, b_2 \in \mathcal{A}$ s.t. $a_1 \circ b_1 = a_2 \circ b_2$ and $1 \circ b_1 = 1 \circ b_2 \in \mathcal{S}$. Writing $s := b_1 \in \mathcal{S}$, we get $a_1 \circ s = a_2 \circ s$. This proves (RO4). \square

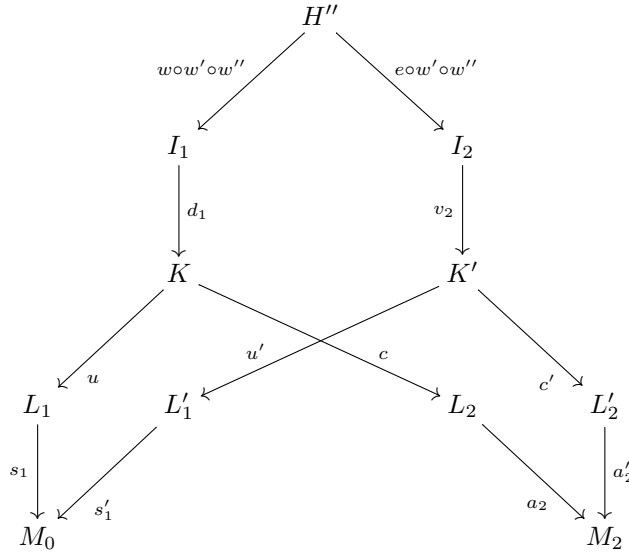


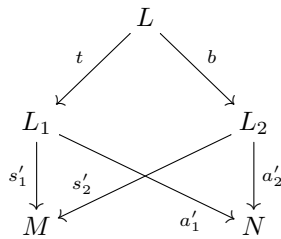
FIGURE 7.

Proposition 7.2.21. *Let \mathcal{A} be a category, let S be a right denominator set in \mathcal{A} , and let $(\mathcal{A}_S, \mathcal{Q})$ be the right Ore localization. For any two morphisms $q_1, q_2 : M \rightarrow N$ in \mathcal{A}_S there is a common denominator. Namely we can write*

$$q_i = \mathcal{Q}(a_i) \circ \mathcal{Q}(s)^{-1}$$

for suitable $a_i \in \mathcal{A}$ and $s \in S$.

Proof. Choose representatives $q_i = \mathcal{Q}(a'_i) \circ \mathcal{Q}(s'_i)^{-1}$. By (RD1) applied to $L_1 \rightarrow M \leftarrow L_2$, there are $b \in \mathcal{A}$ and $t \in S$ s.t. the diagram above M commutes:



Write $s := s'_1 \circ t = s'_2 \circ b$, $a_1 := a'_1 \circ t$ and $a_2 := a'_2 \circ b$. By Lemma 7.2.5 we get $q_i = \mathcal{Q}(a_i) \circ \mathcal{Q}(s)^{-1}$. □

Exercise 7.2.22. Let \mathcal{A} be a category, let S be a right denominator set in \mathcal{A} . Let Y be a subset of $\text{Ob}(\mathcal{A})$, and let \mathcal{B} and \mathcal{T} be the full subcategories of \mathcal{A} and S respectively on the set of objects Y .

- (1) Is \mathcal{T} a right denominator set in \mathcal{B} ?
- (2) Show that if \mathcal{T} is a right denominator set in \mathcal{B} , then the inclusion functor $F : \mathcal{B} \rightarrow \mathcal{A}$ extends uniquely to a functor $F_{\mathcal{T}} : \mathcal{B}_{\mathcal{T}} \rightarrow \mathcal{A}_S$.
- (3) Assume that \mathcal{T} is a right denominator set in \mathcal{B} . Is the functor $F_{\mathcal{T}}$ full or faithful?

We will return to these questions later.

7.3. Localization of Linear Categories. Until now in this section we dealt with arbitrary categories. In this and the subsequent subsection, our categories will be linear over some commutative base ring \mathbb{K} (that will be implicit in everything). This includes the case $\mathbb{K} = \mathbb{Z}$ of course.

For convenience we only talk about right denominator sets here. All the statements hold equally for left denominator sets; cf. Remark 7.2.2 and Proposition 7.2.3.

Theorem 7.3.1. *Let \mathcal{A} be a \mathbb{K} -linear category, let \mathcal{S} be a right denominator set in \mathcal{A} , and let $(\mathcal{A}_{\mathcal{S}}, \mathcal{Q})$ be the right Ore localization.*

- (1) *The category $\mathcal{A}_{\mathcal{S}}$ has a unique \mathbb{K} -linear structure, such that $\mathcal{Q} : \mathcal{A} \rightarrow \mathcal{A}_{\mathcal{S}}$ is a \mathbb{K} -linear functor.*
- (2) *Suppose \mathcal{B} is another \mathbb{K} -linear category, and $F : \mathcal{A} \rightarrow \mathcal{B}$ is a \mathbb{K} -linear functor s.t. $F(s)$ is invertible for every $s \in \mathcal{S}$. Let $F_{\mathcal{S}} : \mathcal{A}_{\mathcal{S}} \rightarrow \mathcal{B}$ be the localization of F . Then $F_{\mathcal{S}}$ is a \mathbb{K} -linear functor.*
- (3) *If \mathcal{A} is an additive category, then so is $\mathcal{A}_{\mathcal{S}}$.*

Proof. (1) Let $q_i : M \rightarrow N$ be morphisms in $\mathcal{A}_{\mathcal{S}}$. Choose common denominator presentations $q_i = \mathcal{Q}(a_i) \circ \mathcal{Q}(s)^{-1}$. Since \mathcal{Q} must be an additive functor, we have to define

$$(7.3.2) \quad \mathcal{Q}(a_1) + \mathcal{Q}(a_2) := \mathcal{Q}(a_1 + a_2).$$

By the distributive law (bilinearity of composition) we must define

$$q_1 + q_2 := \mathcal{Q}(a_1 + a_2) \circ \mathcal{Q}(s)^{-1}.$$

For $\lambda \in \mathbb{K}$ we must define

$$\lambda \cdot q_i := \mathcal{Q}(\lambda \cdot a_i) \circ \mathcal{Q}(s)^{-1}.$$

The usual tricks are then used to prove independence of representatives. For instance, to prove that (7.3.2) is independent of choices, suppose that $\mathcal{Q}(a_1) = \mathcal{Q}(a'_1)$ and $\mathcal{Q}(a_2) = \mathcal{Q}(a'_2)$. Then, by (RO4), there are $t_1, t_2 \in \mathcal{S}$ such that $a_1 \circ t_1 = a'_1 \circ t_1$ and $a_2 \circ t_2 = a'_2 \circ t_2$. By (RD1) there exist $b \in \mathcal{A}$ and $v \in \mathcal{S}$ s.t. $t_1 \circ b = t_2 \circ v$. Let $t_3 := t_2 \circ v \in \mathcal{S}$. Then

$$(a_1 + a_2) \circ t_3 = (a'_1 + a'_2) \circ t_3,$$

and hence

$$\mathcal{Q}(a_1 + a_2) = \mathcal{Q}(a'_1 + a'_2).$$

In this way $\mathcal{A}_{\mathcal{S}}$ is a \mathbb{K} -linear category, and \mathcal{Q} is a \mathbb{K} -linear functor.

(2) The only option for $F_{\mathcal{S}}$ is $F_{\mathcal{S}}(q_i) := F(a_i) \circ F(s)^{-1}$. The usual tricks are used to prove independence of representatives.

(3) Clear from Propositions 2.4.2 and 2.4.5. □

Example 7.3.3. Let A be a ring, which we can think of as a one object linear category \mathcal{A} . In this context, Theorem 7.3.1 is one of the most important results in ring theory. See [Row, Ste].

Example 7.3.4. Suppose A is a commutative ring, and S is a multiplicatively closed set in it. Because A is commutative, the denominator conditions hold automatically. The localized category A_S is the single object category, with endomorphism set A_S . This is simply the usual commutative localization.

Note that if S contains a nilpotent element, then the ring A_S is trivial.

The observation above should serve as a warning: localization can sometimes kill everything. This is the singularity effect: dividing by zero!

Fortunately, the localization procedure (8.0.1), that gives rise to the derived category, does not cause any catastrophe, as we shall see in Proposition 7.4.10.

Remark 7.3.5. Suppose A is a ring and S is a right denominator set in it. Then the right Ore localization A_S is *flat* as left A -module. See [Row, Theorem 3.1.20]. I have no idea if something like this is true for linear categories with more than one object.

Proposition 7.3.6. *Let (\mathbb{K}, T) be a T -additive \mathbb{K} -linear category, let S be a right denominator set in \mathbb{K} such that $T(S) = S$, and let $Q : \mathbb{K} \rightarrow \mathbb{K}_S$ be the localization functor.*

- (1) *There is a unique \mathbb{K} -linear automorphism T_S of the category \mathbb{K}_S , such that*

$$T_S \circ Q = Q \circ T$$

as functors $\mathbb{K} \rightarrow \mathbb{K}_S$.

- (2) *Let τ be the identity automorphism of the functor $Q \circ T$. Then*

$$(Q, \tau) : (\mathbb{K}, T) \rightarrow (\mathbb{K}_S, T_S)$$

is a T -additive functor.

Proof. (1) By the assumption the functor $Q \circ T : \mathbb{K} \rightarrow \mathbb{K}_S$ sends the morphisms in S to isomorphism. By the property (L3) of localization in Definition 7.1.2, the functor $T_S : \mathbb{K}_S \rightarrow \mathbb{K}_S$ satisfying $T_S \circ Q = Q \circ T$ exists and is unique. Similarly, there is a unique functor $T_S^{-1} : \mathbb{K}_S \rightarrow \mathbb{K}_S$ satisfying $T_S^{-1} \circ Q = Q \circ T^{-1}$. An easy calculation shows that

$$T_S^{-1} \circ T_S = \text{Id} = T_S \circ T_S^{-1}.$$

Hence T_S is an automorphism of \mathbb{K}_S .

- (2) This is clear. □

The composition of T -additive functors was defined in Definition 6.1.4.

Proposition 7.3.7. *In the situation of Proposition 7.3.6, suppose (\mathbb{K}', T') is another T -additive \mathbb{K} -linear category, and*

$$(F, \nu) : (\mathbb{K}, T) \rightarrow (\mathbb{K}', T')$$

is a T -additive \mathbb{K} -linear functor, such that $F(s)$ is invertible for any $s \in S$. Let $F_S : \mathbb{K}_S \rightarrow \mathbb{K}'$ be the localized functor. Then there is a unique isomorphism

$$\nu_S : F_S \circ T_S \xrightarrow{\cong} T' \circ F_S$$

of functors $\mathbb{K}_S \rightarrow \mathbb{K}'$, such that

$$(F, \nu) = (F_S, \nu_S) \circ (Q, \tau)$$

as T -additive functors $(\mathbb{K}, T) \rightarrow (\mathbb{K}', T')$.

Exercise 7.3.8. Prove Proposition 7.3.7.

7.4. Localization of Pretriangulated Categories. Let \mathbf{K} be a pretriangulated category, with translation functor \mathbf{T} .

Proposition 7.4.1. *Suppose $H : \mathbf{K} \rightarrow \mathbf{M}$ is a cohomological functor, where \mathbf{M} is some abelian category. Let*

$$\mathbf{S} := \{s \in \mathbf{K} \mid H(\mathbf{T}^i(s)) \text{ is invertible for all } i \in \mathbb{Z}\}.$$

Then \mathbf{S} is a left and right denominator set in \mathbf{K} .

Proof. It is clear that \mathbf{S} is closed under composition and contains the identity morphisms. So it is a multiplicatively closed set.

Let's prove that condition (RD1) of Definition 7.2.14 holds. Suppose we are given morphisms $L \xrightarrow{a} N \xleftarrow{s} M$ with $s \in \mathbf{S}$. We need to find morphisms $L \xleftarrow{t} K \xrightarrow{b} M$ with $t \in \mathbf{S}$ and such that $a \circ t = s \circ b$.

Consider the solid commutative diagram

$$\begin{array}{ccccccc} K & \xrightarrow{t} & L & \xrightarrow{coa} & P & \longrightarrow & \mathbf{T}(K) \\ \downarrow b & & \downarrow a & & \downarrow = & & \downarrow \mathbf{T}(b) \\ M & \xrightarrow{s} & N & \xrightarrow{c} & P & \longrightarrow & \mathbf{T}(M) \end{array}$$

where the bottom row is a distinguished triangle built on $M \xrightarrow{s} N$, and the top row is a distinguished triangle built on $L \xrightarrow{coa} P$, then turned 120° to the right. By axiom (TR3) there is a morphism b making the diagram commutative. Thus $a \circ t = s \circ b$. Since $H(\mathbf{T}^i(s))$ are invertible for all $i \in \mathbb{Z}$, it follows that $H(\mathbf{T}^i(P)) = 0$. But then $H(\mathbf{T}^i(t))$ are invertible for all $i \in \mathbb{Z}$, so $t \in \mathbf{S}$.

Next we prove condition (RD2) of Definition 7.2.14. Because we are in an additive category, this condition is simplified: given $a \in \mathbf{K}$ and $s \in \mathbf{S}$ satisfying $s \circ a = 0$, we have to find $t \in \mathbf{S}$ satisfying $a \circ t = 0$.

Say the objects involved are $L \xrightarrow{a} M \xrightarrow{s} N$. Take a distinguished triangle built on s and then turned:

$$P \xrightarrow{b} M \xrightarrow{s} N \rightarrow \mathbf{T}(P).$$

We get an exact sequence

$$\mathrm{Hom}_{\mathbf{K}}(L, P) \xrightarrow{b \circ -} \mathrm{Hom}_{\mathbf{K}}(L, M) \xrightarrow{s \circ -} \mathrm{Hom}_{\mathbf{K}}(L, N).$$

Since $s \circ a = 0$, there is $c : L \rightarrow P$ s.t. $a = b \circ c$. Now look at a distinguished triangle built on c , and then turned:

$$K \xrightarrow{t} L \xrightarrow{c} P \rightarrow \mathbf{T}(K).$$

We know that $c \circ t = 0$; hence $a \circ t = b \circ c \circ t = 0$. But $(s \in \mathbf{S}) \Rightarrow (H(\mathbf{T}^i(P)) = 0 \text{ for all } i) \Rightarrow (t \in \mathbf{S})$.

The left versions (LD1) and (LD2) are proved the same way. \square

Definition 7.4.2. A *denominator set of cohomological origin* in \mathbf{K} is a denominator set $\mathbf{S} \subseteq \mathbf{K}$ that arises from a cohomological functor H , as in Proposition 7.4.1. The morphisms in \mathbf{S} are called *quasi-isomorphisms relative to H* .

Theorem 7.4.3. *Let (\mathbf{K}, \mathbf{T}) be a pretriangulated category, let \mathbf{S} be a denominator set of cohomological origin in \mathbf{K} , and let*

$$(\mathbf{Q}, \tau) : (\mathbf{K}, \mathbf{T}) \rightarrow (\mathbf{K}_{\mathbf{S}}, \mathbf{T}_{\mathbf{S}})$$

be the T -additive functor from Proposition 7.3.6. The T -additive category $(\mathbf{K}_S, \mathbf{T}_S)$ has a unique pretriangulated structure such that these two properties hold:

- (i) The pair (Q, τ) is a triangulated functor.
- (ii) Suppose $(\mathbf{K}', \mathbf{T}')$ is another pretriangulated category, and

$$(F, \nu) : (\mathbf{K}, \mathbf{T}) \rightarrow (\mathbf{K}', \mathbf{T}')$$

is a triangulated functor, such that $F(s)$ is invertible for every $s \in S$. Let

$$(F_S, \nu_S) : (\mathbf{K}_S, \mathbf{T}_S) \rightarrow (\mathbf{K}', \mathbf{T}')$$

be the T -additive functor from Proposition 7.3.7. Then (F_S, ν_S) is a triangulated functor.

Proof. Since S is of cohomological origin we have $\mathbf{T}(S) = S$. Recall that the translation isomorphism τ is the identity automorphism of the functor $Q \circ T$; see Proposition 7.3.6. So we will ignore it.

Step 1. The distinguished triangles in \mathbf{K}_S are defined to be those triangles that are isomorphic to the images under Q of distinguished triangles in \mathbf{K} . Let us verify the axioms of pretriangulated category.

(TR1). By definition every triangle that's isomorphic to a distinguished triangle is distinguished; and the triangle

$$M \xrightarrow{1_M} M \rightarrow 0 \rightarrow T(M)$$

in \mathbf{K}_S is clearly distinguished.

Suppose we are given a morphism $\alpha : L \rightarrow M$ in \mathbf{K}_S . We have to build a distinguished triangle on it. Choose a fraction presentation $\alpha = Q(a) \circ Q(s)^{-1}$. Using condition (LD1) we can find $b \in \mathbf{K}$ and $t \in S$ such that $t \circ a = b \circ s$. These fit into the solid commutative diagram

$$\begin{array}{ccccc}
 & & \alpha & & \\
 & & \text{---} & & \\
 L & \xleftarrow{s} & K & \xrightarrow{a} & M \\
 & \searrow b & & & \swarrow t \\
 & & \tilde{K} & &
 \end{array}$$

in \mathbf{K} . (The dashed arrow α is in \mathbf{K}_S .)

Consider the solid commutative diagram below, where the rows are distinguished triangles built on a and b respectively.

$$(7.4.4) \quad \begin{array}{ccccccc}
 K & \xrightarrow{a} & M & \xrightarrow{e} & N & \xrightarrow{c} & T(K) \\
 \downarrow s & & \downarrow t & & \downarrow u & & \downarrow T(s) \\
 L & \xrightarrow{b} & \tilde{K} & \longrightarrow & P & \xrightarrow{d} & T(L)
 \end{array}$$

By (TR3) there is a morphism u that makes the whole diagram commutative. Since $s, t \in S$ and H is a cohomological functor, it follows that $u \in S$. Applying the functor Q to (7.4.4), and using the isomorphism $Q(t) : M \rightarrow \tilde{K}$ to replace \tilde{K} with

M , we get the commutative diagram

$$\begin{array}{ccccccc}
 K & \xrightarrow{Q(a)} & M & \xrightarrow{Q(e)} & N & \xrightarrow{Q(c)} & T(K) \\
 Q(s) \downarrow & & \downarrow Q(1_M) & & \downarrow Q(u) & & \downarrow T(Q(s)) \\
 L & \xrightarrow{\alpha} & M & \xrightarrow{Q(u \circ e)} & P & \xrightarrow{Q(d)} & T(L)
 \end{array}$$

in \mathcal{K}_S . The top row is a distinguished triangle, and the vertical arrows are isomorphisms. So the bottom row is a distinguished triangle. This is the triangle we were looking for.

(TR2). Turning: this is trivial.

(TR3). We are given the solid commutative diagram in \mathcal{K}_S , where the rows are distinguished triangles:

$$(7.4.5) \quad \begin{array}{ccccccc}
 L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & T(L) \\
 \phi \downarrow & & \downarrow \psi & & \downarrow \chi & & \downarrow T(\phi) \\
 L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & T(L')
 \end{array}$$

and we have to find χ to complete the diagram.

By replacing the rows with isomorphic triangles, we can assume they come from \mathcal{K} . Thus we can replace (7.4.5) with this diagram:

$$(7.4.6) \quad \begin{array}{ccccccc}
 L & \xrightarrow{Q(\alpha)} & M & \xrightarrow{Q(\beta)} & N & \xrightarrow{Q(\gamma)} & T(L) \\
 \phi \downarrow & & \downarrow \psi & & \downarrow \chi & & \downarrow T(\phi) \\
 L' & \xrightarrow{Q(\alpha')} & M' & \xrightarrow{Q(\beta')} & N' & \xrightarrow{Q(\gamma')} & T(L')
 \end{array}$$

in which $\alpha, \beta, \gamma, \alpha', \beta', \gamma'$ are morphisms in \mathcal{K} . It is a commutative diagram. Let us choose fraction presentations $\phi = Q(a) \circ Q(s)^{-1}$ and $\psi = Q(b) \circ Q(t)^{-1}$. Then the solid diagram (7.4.6) comes from applying Q to the diagram

$$(7.4.7) \quad \begin{array}{ccccccc}
 L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & T(L) \\
 s \uparrow & & \uparrow t & & & & \uparrow T(s) \\
 \tilde{L} & & \tilde{M} & & & & T(\tilde{L}) \\
 a \downarrow & & \downarrow b & & & & \downarrow T(a) \\
 L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & T(L')
 \end{array}$$

in \mathcal{K} . Here the rows are distinguished triangles in \mathcal{K} ; but the diagram might fail to be commutative.

By axiom (RO3) we can find $c \in \mathcal{K}$ and $u \in S$ s.t.

$$Q(t)^{-1} \circ Q(\alpha) \circ Q(s) = Q(c) \circ Q(u)^{-1}.$$

This is the solid diagram:

$$\begin{array}{ccccc}
 & & L & \xrightarrow{\alpha} & M \\
 & & \uparrow & & \uparrow \\
 & & s & & t \\
 \tilde{L}'' & \xrightarrow{u'} & \tilde{L}' & \xrightarrow{u} & \tilde{L} & \xrightarrow{a} & \tilde{M} \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & L' & \xrightarrow{\alpha'} & M'
 \end{array}$$

Thus

$$Q(\alpha \circ s \circ u) = Q(t \circ c).$$

By (RO4) there is $u' \in \mathcal{S}$ s.t.

$$(\alpha \circ s \circ u) \circ u' = (t \circ c) \circ u'.$$

We get

$$\phi = Q(a) \circ Q(s)^{-1} = Q(a \circ u \circ u') \circ Q(s \circ u \circ u')^{-1}$$

in $\mathcal{K}_{\mathcal{S}}$. Thus, after substituting $\tilde{L} := \tilde{L}'$, $s := s \circ u \circ u'$, $a := a \circ u \circ u'$ and $c := c \circ u'$, we get a new diagram

$$(7.4.8) \quad
 \begin{array}{ccccccc}
 L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & T(L) \\
 \uparrow & & \uparrow & & & & T(s) \uparrow \\
 s & & t & & & & T(\tilde{L}) \\
 \tilde{L} & \xrightarrow{c} & \tilde{M} & & & & \\
 \downarrow & & \downarrow & & & & T(a) \downarrow \\
 a & & b & & & & T(L') \\
 L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & T(L')
 \end{array}$$

in \mathcal{K} instead of (7.4.7). In this new diagram the top left square is commutative; but maybe the bottom left square is not commutative.

When we apply Q to the diagram (7.4.8), the whole diagram, including the bottom left square, becomes commutative, since (7.4.6) is commutative. Again using condition (RO4), there is $v \in \mathcal{S}$ s.t.

$$(\alpha' \circ a) \circ v = (b \circ c) \circ v.$$

In a diagram:

$$\begin{array}{ccccc}
 & & L & \xrightarrow{\alpha} & M \\
 & & \uparrow & & \uparrow \\
 & & s & & t \\
 \tilde{L}' & \xrightarrow{v} & \tilde{L} & \xrightarrow{c} & \tilde{M} \\
 & & \downarrow & & \downarrow \\
 & & a & & b \\
 & & L' & \xrightarrow{\alpha'} & M'
 \end{array}$$

Performing the replacements $\tilde{L} := \tilde{L}'$, $s := s \circ v$, $c := c \circ v$ and $a := a \circ v$ we now have a commutative square also at the bottom left of (7.4.8). Since $\gamma \circ \beta = 0$ and $\gamma' \circ \beta' = 0$, in fact the whole diagram (7.4.8) in \mathcal{K} is now commutative.

Now by (TR1) we can embed the morphism c in a distinguished triangle. We get the solid diagram

$$(7.4.9) \quad \begin{array}{ccccccc} L & \xrightarrow{\alpha} & M & \xrightarrow{\beta} & N & \xrightarrow{\gamma} & \mathbf{T}(L) \\ \uparrow s & & \uparrow t & & \uparrow w & & \uparrow \mathbf{T}(s) \\ \tilde{L} & \xrightarrow{c} & \tilde{M} & \xrightarrow{\tilde{\beta}} & \tilde{N} & \xrightarrow{\tilde{\gamma}} & \mathbf{T}(\tilde{L}) \\ \downarrow a & & \downarrow b & & \downarrow d & & \downarrow \mathbf{T}(a) \\ L' & \xrightarrow{\alpha'} & M' & \xrightarrow{\beta'} & N' & \xrightarrow{\gamma'} & \mathbf{T}(L') \end{array}$$

in \mathbf{K} . The rows are distinguished triangles. Since $\tilde{\gamma} \circ \tilde{\beta} = 0$, the solid diagram is commutative. By (TR3) there are morphisms w and d that make the whole diagram commutative. Now the morphism $w \in \mathbf{S}$ by the usual long exact sequence argument. The morphism

$$\chi := \mathbf{Q}(d) \circ \mathbf{Q}(w)^{-1} : N \rightarrow N'$$

solves the problem.

Step 2. Suppose (F, ν) is a triangulated functor as in condition (ii). By Proposition 7.3.7 this extends uniquely to a \mathbf{T} -additive functor $(F_{\mathbf{S}}, \nu_{\mathbf{S}})$. The construction of the pretriangulated structure on $(\mathbf{K}_{\mathbf{S}}, \mathbf{T}_{\mathbf{S}})$ in the previous steps, and the defining property of the translation isomorphism $\nu_{\mathbf{S}}$ in Proposition 7.3.7, show that $(F_{\mathbf{S}}, \nu_{\mathbf{S}})$ is a triangulated functor.

Step 3. At this point $(\mathbf{K}_{\mathbf{S}}, \mathbf{T}_{\mathbf{S}})$ is a pretriangulated category, and conditions (i)-(ii) of the theorem are satisfied. We need to prove the uniqueness of the pretriangulated structure on $(\mathbf{K}_{\mathbf{S}}, \mathbf{T}_{\mathbf{S}})$. Condition (i) says that we can't have less distinguished triangles than those we declared. We can't have more distinguished triangles, because of condition (ii). \square

Proposition 7.4.10. *Consider the situation of Proposition 7.4.1 and Theorem 7.4.3.*

- (1) *The cohomological functor $H : \mathbf{K} \rightarrow \mathbf{M}$ factors into $H = H_{\mathbf{S}} \circ \mathbf{Q}$, where $H_{\mathbf{S}} : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{M}$ is a cohomological functor.*
- (2) *Let M be an object of \mathbf{K} . The object $\mathbf{Q}(M)$ is zero in $\mathbf{K}_{\mathbf{S}}$ iff the objects $H(\mathbf{T}^i(M))$ are zero in \mathbf{M} for all i .*

Proof. (1) The existence and uniqueness of the functor $H_{\mathbf{S}}$ are by the universal property (L3) in Definition 7.1.2. We leave it as an exercise to show that $H_{\mathbf{S}}$ is a cohomological functor.

(2) Since $H_{\mathbf{S}}$ is an additive functor, if $\mathbf{Q}(M) = 0$, then so is $H(M) = H_{\mathbf{S}}(\mathbf{Q}(M))$. And of course $\mathbf{Q}(M) = 0$ iff $\mathbf{Q}(\mathbf{T}^i(M)) = 0$ for all i .

For the converse, let $\phi : 0 \rightarrow M$ be the zero morphism in \mathbf{K} . If $H(\mathbf{T}^i(M)) = 0$ for all i , then $H(\mathbf{T}^i(\phi)) : 0 \rightarrow H(\mathbf{T}^i(M))$ are isomorphisms for all i . Then $\phi \in \mathbf{S}$, and so $\mathbf{Q}(\phi) : 0 \rightarrow \mathbf{Q}(M)$ is an isomorphism in $\mathbf{K}_{\mathbf{S}}$. \square

8. THE DERIVED CATEGORY $\mathbf{D}(A, \mathbf{M})$

In this section there is a commutative base ring \mathbb{K} , that shall remain implicit most of the time. We fix a central DG \mathbb{K} -ring A , and a \mathbb{K} -linear abelian category \mathbf{M} . The DG category $\mathbf{C}(A, \mathbf{M})$ was introduced in Subsection 3.7, and the pretriangulated category $\mathbf{K}(A, \mathbf{M})$ was introduced in Subsection 6.4.

The functor $H^0 : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{M}$ is a cohomological functor, in the sense of Definition 6.3.2. The resulting denominator set is denoted by $\mathbf{S}(A, \mathbf{M})$, and its elements are called *quasi-isomorphisms*. The *derived category* of (A, \mathbf{M}) is the pretriangulated category

$$(8.0.1) \quad \mathbf{D}(A, \mathbf{M}) := \mathbf{K}(A, \mathbf{M})_{\mathbf{S}(A, \mathbf{M})}.$$

8.1. Definition of the Derived Category.

Proposition 8.1.1. *Let \mathbf{M} be an abelian category and let A be a DG ring. The functor*

$$H^0 : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{M}$$

is cohomological.

Proof. Clearly H^0 is additive. Consider a distinguished triangle

$$(8.1.2) \quad L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T(L)$$

in $\mathbf{K}(A, \mathbf{M})$. We can assume that it is the image of a standard triangle in $\mathbf{C}(A, \mathbf{M})$, namely that N is the cone associated to α , as in Definition 4.2.5, $\beta = e_\alpha$ and $\gamma = p_\alpha$. By construction, the cone N sits in an exact sequence of complexes

$$(8.1.3) \quad 0 \rightarrow M \xrightarrow{e_\alpha} N \xrightarrow{p_\alpha} T(L) \rightarrow 0.$$

Consider the diagram

$$\begin{array}{ccccc} H^{-1}(T(L)) & \xrightarrow{\text{conn}} & H^0(M) & \xrightarrow{H^0(e_\alpha)} & H^0(N) \\ \downarrow H(t_L^{-1}) & & \downarrow = & & \downarrow = \\ H^0(L) & \xrightarrow{H^0(\alpha)} & H^0(M) & \xrightarrow{H^0(\beta)} & H^0(N) \end{array}$$

in \mathbf{M} , where the first row is part of the long exact cohomology sequence for (8.1.3), and the second row comes from (8.1.2). The first square is commutative because any lifting represents the connecting homomorphism (cf. [Rot, Theorem 6.2]). The second square is also commutative. It follows that the diagram is commutative, and that the bottom row is exact. \square

Definition 8.1.4. A morphism ϕ in $\mathbf{K}(A, \mathbf{M})$ is called a *quasi-isomorphism* if the morphisms $H^i(\phi)$ in \mathbf{M} are isomorphisms for all i .

The set of quasi-isomorphisms in $\mathbf{K}(A, \mathbf{M})$ is denoted by $\mathbf{S}(A, \mathbf{M})$.

Note that $H^i = H^0 \circ T^i$. By Proposition 8.1.1 the functor H^0 is cohomological. Therefore $\mathbf{S}(A, \mathbf{M})$ is a denominator set of cohomological origin, Theorem 7.4.3 applies to it, and the next definition makes sense.

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Definition 8.1.5. Let \mathbf{M} be a \mathbb{K} -linear abelian category and A a central DG \mathbb{K} -ring. The *derived category* of (A, \mathbf{M}) is the \mathbb{K} -linear pretriangulated category

$$\mathbf{D}(A, \mathbf{M}) := \mathbf{K}(A, \mathbf{M})_{\mathbf{S}(A, \mathbf{M})}.$$

In our situation we have additive functors

$$\mathbf{C}_{\text{str}}(A, \mathbf{M}) \xrightarrow{\mathbf{P}} \mathbf{K}(A, \mathbf{M}) \xrightarrow{\mathbf{Q}} \mathbf{D}(A, \mathbf{M}),$$

that are the identity on objects. Recall that the functor \mathbf{P} sends a strict morphism of DG modules to its homotopy class; and \mathbf{Q} is the localization functor with respect to quasi-isomorphisms.

Definition 8.1.6. Let \mathbf{M} be an abelian category and let A be a DG ring. Define the functor

$$\tilde{\mathbf{Q}} := \mathbf{Q} \circ \mathbf{P} : \mathbf{C}_{\text{str}}(A, \mathbf{M}) \rightarrow \mathbf{D}(A, \mathbf{M}).$$

This definition will only be used in the present section.

It is sometimes convenient to describe morphisms in $\mathbf{D}(A, \mathbf{M})$ in terms of the functor $\tilde{\mathbf{Q}}$. A morphism $s \in \mathbf{C}_{\text{str}}(A, \mathbf{M})$ is called a quasi-isomorphism if $\mathbf{P}(s)$ is a quasi-isomorphism in $\mathbf{K}(A, \mathbf{M})$; i.e. if all the $\mathbf{H}^i(s)$ are isomorphisms.

Proposition 8.1.7.

(1) Any morphism ϕ in $\mathbf{D}(A, \mathbf{M})$ can be written as a right fraction

$$\phi = \tilde{\mathbf{Q}}(a) \circ \tilde{\mathbf{Q}}(s)^{-1}$$

where $a, s \in \mathbf{C}_{\text{str}}(A, \mathbf{M})$ and s is a quasi-isomorphism.

(2) The kernel of $\tilde{\mathbf{Q}}$ is this: $\tilde{\mathbf{Q}}(a) = 0$ in $\mathbf{D}(A, \mathbf{M})$ iff there exists a quasi-isomorphism s in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ such that $a \circ s$ is a coboundary in $\mathbf{C}(A, \mathbf{M})$.

Proof. (1) This is because of property (RO3) of Definition 7.2.1 and the fact that \mathbf{P} is full.

(2) Property (RO4) of Definition 7.2.1 tells us what the kernel of \mathbf{Q} is; and by definition the kernel of \mathbf{P} is the 0-coboundaries. \square

Of course there is a left version of this proposition.

Recall that $\mathbf{G}(\mathbf{M})$ is the category of graded objects of \mathbf{M} . For any DG module $M \in \mathbf{D}(A, \mathbf{M})$, its cohomology $\mathbf{H}(M)$ is an object of $\mathbf{G}(\mathbf{M})$, and this is a functor.

Corollary 8.1.8. *The functor*

$$\mathbf{H} : \mathbf{D}(A, \mathbf{M}) \rightarrow \mathbf{G}(\mathbf{M})$$

is conservative. Namely a morphism $\phi : M \rightarrow N$ in $\mathbf{D}(A, \mathbf{M})$ is an isomorphism if and only if the morphism

$$\mathbf{H}(\phi) : \mathbf{H}(M) \rightarrow \mathbf{H}(N)$$

in $\mathbf{G}(\mathbf{M})$ is an isomorphism.

Proof. One implication is trivial. For the other direction, assume that $\mathbf{H}(\phi)$ is an isomorphism. We can write ϕ as a right fraction: $\phi = \mathbf{Q}(a) \circ \mathbf{Q}(s)^{-1}$ where $a \in \mathbf{K}(A, \mathbf{M})$ and $s \in \mathbf{S}(A, \mathbf{M})$. Then

$$\mathbf{H}(\phi) = \mathbf{H}(\mathbf{Q}(a)) \circ \mathbf{H}(\mathbf{Q}(s))^{-1}.$$

By definition $\mathbf{H}(\mathbf{Q}(s))$ is an isomorphism. Hence $\mathbf{H}(\mathbf{Q}(a))$ is an isomorphism. But then $a \in \mathbf{S}(A, \mathbf{M})$ too, and therefore $\mathbf{Q}(a)$ is an isomorphism in $\mathbf{D}(A, \mathbf{M})$. It follows that ϕ is an isomorphism in $\mathbf{D}(A, \mathbf{M})$. \square

Exercise 8.1.9. Here $M = \text{Mod } \mathbb{K}$, so $\mathbf{K}(A, M) = \mathbf{K}(A)$. Show that the functor $H^0 : \mathbf{K}(A) \rightarrow \text{Mod } \mathbb{K}$ is corepresentable by the object $A \in \mathbf{K}(A)$ (see Subsection 1.7).

8.2. Localization of Subcategories of $\mathbf{K}(A, M)$.

Definition 8.2.1. Let \mathbf{K} be a pretriangulated category. A *full pretriangulated subcategory* of \mathbf{K} is a subcategory $\mathbf{L} \subseteq \mathbf{K}$ satisfying these conditions:

- (a) \mathbf{L} is a full additive subcategory (see Definition 2.2.6).
- (b) \mathbf{L} is closed under translations, i.e. $L \in \mathbf{L}$ iff $T(L) \in \mathbf{L}$.
- (c) \mathbf{L} is closed under distinguished triangles, i.e. if

$$L' \rightarrow L \rightarrow L'' \rightarrow T(L)$$

is a distinguished triangle in \mathbf{K} s.t. $L', L \in \mathbf{L}$, then also $L'' \in \mathbf{L}$.

Observe that \mathbf{L} itself is pretriangulated, and the inclusion $\mathbf{L} \rightarrow \mathbf{K}$ is a triangulated functor.

Denominator sets of cohomological origin were introduced in Definition 7.4.2. By Theorem 7.4.3, if $\mathbf{S} \subseteq \mathbf{K}$ is a denominator set of cohomological origin, then the localization $\mathbf{K}_{\mathbf{S}}$ is a pretriangulated category.

Example 8.2.2. This is the most important example for us: $\mathbf{K} = \mathbf{K}(A, M)$, $H = H^0 : \mathbf{K}(A, M) \rightarrow M$ and $\mathbf{S} = \mathbf{S}(A, M)$. Here $\mathbf{K}_{\mathbf{S}} = \mathbf{D}(A, M)$, the derived category.

Proposition 8.2.3. *Let \mathbf{K} be a pretriangulated category, let \mathbf{S} be a denominator set of cohomological origin in \mathbf{K} , and let \mathbf{K}' be a full pretriangulated subcategory of \mathbf{K} . Then $\mathbf{S}' := \mathbf{K}' \cap \mathbf{S}$ is a denominator set of cohomological origin in \mathbf{K}' , the Ore localization $\mathbf{K}'_{\mathbf{S}'}$ exists, and $\mathbf{K}'_{\mathbf{S}'}$ is a pretriangulated category.*

Proof. Let $H : \mathbf{K} \rightarrow M$ be a cohomological functor that determines \mathbf{S} . The functor $H|_{\mathbf{K}'} : \mathbf{K}' \rightarrow M$ is also cohomological, and the set of morphisms \mathbf{S}' satisfies

$$\mathbf{S}' = \{s \in \mathbf{K}' \mid H|_{\mathbf{K}'}(T^i(s)) \text{ is an isomorphism for all } i\}.$$

Hence Proposition 7.4.1 and Theorem 7.4.3 apply. \square

In the situation of the proposition, the localization functor is denoted by $Q' : \mathbf{K}' \rightarrow \mathbf{K}'_{\mathbf{S}'}$.

Proposition 8.2.4. *In the situation of Proposition 8.2.3, let $F : \mathbf{K}' \rightarrow \mathbf{E}$ be a triangulated functor into some pretriangulated category \mathbf{E} . Assume that for every $s \in \mathbf{S}'$, the morphism $F(s)$ is an isomorphism in \mathbf{E} . Then there is a unique triangulated functor $F_{\mathbf{S}'} : \mathbf{K}'_{\mathbf{S}'} \rightarrow \mathbf{E}$ that extends F ; Namely $F_{\mathbf{S}'} \circ Q' = F$ as functors $\mathbf{K}' \rightarrow \mathbf{E}$.*

Proof. This is part of Theorem 7.4.3. \square

In particular we can look at the functor $F : \mathbf{K}' \xrightarrow{\text{inc}} \mathbf{K} \xrightarrow{Q} \mathbf{K}_{\mathbf{S}}$, and its extension $F_{\mathbf{S}'} : \mathbf{K}'_{\mathbf{S}'} \rightarrow \mathbf{K}_{\mathbf{S}}$. We are interested in sufficient conditions for the functor $F_{\mathbf{S}'}$ to be fully faithful.

Proposition 8.2.5. *Let \mathbf{K} be a pretriangulated category, let \mathbf{S} be a denominator set of cohomological origin in \mathbf{K} , and let $\mathbf{K}' \subseteq \mathbf{K}$ be a full pretriangulated subcategory. Define $\mathbf{S}' := \mathbf{K}' \cap \mathbf{S}$. Assume either of these conditions holds:*

(r) Let $M \in \text{Ob}(\mathbf{K})$. If there exists a morphism $s : M \rightarrow L$ in \mathbf{S} with $L \in \text{Ob}(\mathbf{K}')$, there exists a morphism $t : K \rightarrow M$ in \mathbf{S} with $K \in \text{Ob}(\mathbf{K}')$.

(1) The same, but with arrows reversed.

Then the functor $F_{\mathbf{S}'} : \mathbf{K}'_{\mathbf{S}'} \rightarrow \mathbf{K}_{\mathbf{S}}$ is fully faithful.

Proof. We will prove the proposition under condition (r); the other condition is done the same way.

Let $L_1, L_2 \in \text{Ob}(\mathbf{K}')$, and let $q : L_1 \rightarrow L_2$ be a morphism in $\mathbf{K}_{\mathbf{S}}$. Choose a presentation $q = Q(a) \circ Q(s)^{-1}$ with $s : M \rightarrow L_1$ a morphism in \mathbf{S} and $a : M \rightarrow L_2$ a morphism in \mathbf{K} . By condition (r) we can find a morphism $t : K \rightarrow M$ in \mathbf{S} with $K \in \text{Ob}(\mathbf{K}')$.

$$\begin{array}{ccc}
 & K & \\
 & \downarrow t & \\
 & M & \\
 \swarrow s & & \searrow a \\
 L_1 & \overset{q}{\dashrightarrow} & L_2
 \end{array}$$

Then $q = Q(a \circ t) \circ Q(s \circ t)^{-1}$. But $s \circ t \in \mathbf{S}'$ and $a \circ t \in \mathbf{K}'$, so q is in the image of the functor $F_{\mathbf{S}'}$. We see that $F_{\mathbf{S}'}$ is full.

Now let $q' : L_1 \rightarrow L_2$ be a morphism in $\mathbf{K}'_{\mathbf{S}'}$ such that $F_{\mathbf{S}'}(q') = 0$. Let us denote the localization functor $\mathbf{K}' \rightarrow \mathbf{K}'_{\mathbf{S}'}$ by Q' . Choose a presentation $q' = Q'(a) \circ Q'(s)^{-1}$, with $s : N \rightarrow L_1$ a morphism in \mathbf{S}' and $a : N \rightarrow L_2$ a morphism in \mathbf{K}' . Because $F_{\mathbf{S}'}(q') = 0$, and using Lemma 7.2.5, there is a morphism $u : M \rightarrow N$ in \mathbf{K} such that $a \circ u = 0$ and $s \circ u \in \mathbf{S}$. Note that $u \in \mathbf{S}$. By condition (r), applied to $u : M \rightarrow N$, there is a morphism $t : K \rightarrow M$ in \mathbf{S} such that $K \in \text{Ob}(\mathbf{K}')$.

$$\begin{array}{ccc}
 & K & \\
 & \downarrow t & \\
 & M & \\
 & \downarrow u & \\
 & N & \\
 \swarrow s & & \searrow a \\
 L_1 & \overset{q'}{\dashrightarrow} & L_2
 \end{array}$$

Then we have

$$q' = Q'(a \circ u \circ t) \circ Q'(s \circ u \circ t)^{-1} = 0.$$

This proves that $F_{\mathbf{S}'}$ is faithful. \square

8.3. Boundedness Conditions. A graded object $M = \{M^i\}_{i \in \mathbb{Z}}$ of \mathbf{M} is said to be *bounded above* if the set $\{i \mid M^i \neq 0\}$ is bounded above. Likewise we define *bounded below* and *bounded* graded objects.

Definition 8.3.1. We define $\mathbf{C}^-(A, \mathbf{M})$, $\mathbf{C}^+(A, \mathbf{M})$ and $\mathbf{C}^b(A, \mathbf{M})$ to be full subcategories of $\mathbf{C}(A, \mathbf{M})$ consisting of bounded above, bounded below and bounded complexes respectively.

Likewise we define $\mathbf{K}^-(A, M)$, $\mathbf{K}^+(A, M)$ and $\mathbf{K}^b(A, M)$ to be the corresponding full subcategories of $\mathbf{K}(A, M)$.

Of course

$$\mathbf{C}^b(A, M) = \mathbf{C}^-(A, M) \cap \mathbf{C}^+(A, M),$$

and the same for $\mathbf{K}^b(A, M)$. The subcategories $\mathbf{K}^\star(A, M)$, for $\star \in \{-, +, b\}$, are full pretriangulated subcategory of $\mathbf{K}(A, M)$; this is because the operations of translation and cone preserve the various boundedness conditions.

As the next example shows, sometimes the category $\mathbf{K}^\star(A, M)$ can be very degenerate.

Example 8.3.2. Let A be the DG ring $\mathbb{K}[t, t^{-1}]$, the ring of Laurent polynomials in the variable t of degree 1, with the zero differential. If $M = \{M^i\}_{i \in \mathbb{Z}}$ is a nonzero object of $\mathbf{C}(A, M)$, then $M^i \neq 0$ for all i . Therefore the categories $\mathbf{C}^\star(A, M)$ and $\mathbf{K}^\star(A, M)$ are zero for $\star \in \{-, +, b\}$.

Let

$$\mathbf{S}^\star(A, M) := \mathbf{K}^\star(A, M) \cap \mathbf{S}(A, M),$$

the category of quasi-isomorphisms in $\mathbf{K}^\star(A, M)$. As already mentioned, Theorem 7.4.3 applies here, so we can localize.

Definition 8.3.3. For $\star \in \{-, +, b\}$ we define

$$\mathbf{D}^\star(A, M) := \mathbf{K}^\star(A, M)_{\mathbf{S}^\star(A, M)},$$

the Ore localization of $\mathbf{K}^\star(A, M)$ with respect to $\mathbf{S}^\star(A, M)$.

Here is another kind of boundedness condition.

Definition 8.3.4. For $\star \in \{-, +, b\}$ we define $\mathbf{D}(A, M)^\star$ to be the full subcategory of $\mathbf{D}(A, M)$ on the complexes M whose cohomology $H(M)$ is of boundedness type \star .

Of course $\mathbf{D}(A, M)^\star$ is a full pretriangulated subcategory of $\mathbf{D}(A, M)$.

The next proposition refers to the abelian case only – namely to $\mathbf{D}(M) = \mathbf{D}(\mathbb{K}, M)$. See Exercise 8.3.12 for a generalization to $\mathbf{D}(A, M)$ for a special sort of DG ring A .

Proposition 8.3.5. For $\star \in \{-, +, b\}$ the canonical functor $\mathbf{D}^\star(M) \rightarrow \mathbf{D}(M)^\star$ is an equivalence of pretriangulated categories.

Proof. Step 1. Here we prove that $F^- : \mathbf{D}^-(M) \rightarrow \mathbf{D}(M)$ is fully faithful. Let $s : M \rightarrow L$ be a quasi-isomorphism with $L \in \mathbf{K}^-(M)$. Say L is concentrated in degrees $\leq i$. Then $H^j(M) = H^j(L) = 0$ for all $j > i$. Consider the *smart truncation* of M at i :

$$(8.3.6) \quad \text{smt}^{\leq i}(M) := (\cdots \rightarrow M^{i-2} \xrightarrow{d} M^{i-1} \xrightarrow{d} Z^i(M) \rightarrow 0 \rightarrow \cdots)$$

where $Z^i(M) := \text{Ker}(d : M^i \rightarrow M^{i+1})$, the object of i -cocycles, is in degree i . Then $\text{smt}^{\leq i}(M)$ is a subcomplex of M , $\text{smt}^{\leq i}(M) \in \mathbf{K}^-(M)$, and the inclusion $t : \text{smt}^{\leq i}(M) \rightarrow M$ is a quasi-isomorphism. According to Proposition 8.2.5, with $\mathbf{K} = \mathbf{K}(M)$ and $\mathbf{K}' = \mathbf{K}^-(M)$, and with condition (r), we see that $F^- : \mathbf{D}^-(M) \rightarrow \mathbf{D}(M)$ is fully faithful.

Step 2. Here we prove that $F^+ : \mathbf{D}^+(M) \rightarrow \mathbf{D}(M)$ is fully faithful. Let $s : L \rightarrow M$ be a quasi-isomorphism with $L \in \mathbf{K}^+(M)$. Say L is concentrated in degrees $\geq i$.

Then $H^j(M) = H^j(L) = 0$ for all $j < i$. Consider the other smart truncation of M at i :

$$(8.3.7) \quad \text{smt}^{\geq i}(M) := (\cdots \rightarrow 0 \rightarrow Y^i(M) \xrightarrow{d} M^{i+1} \xrightarrow{d} M^{i+2} \rightarrow \cdots)$$

where

$$(8.3.8) \quad Y^i(M) := \text{Coker}(d : M^{i-1} \rightarrow M^i)$$

is in degree i . Then $\text{smt}^{\geq i}(M)$ is a quotient complex of M , $\text{smt}^{\geq i}(M) \in \mathbf{K}^+(M)$, and the projection $t : M \rightarrow \text{smt}^{\geq i}(M)$ is a quasi-isomorphism. According to Proposition 8.2.5, with condition (1), we see that $F^+ : \mathbf{D}^+(M) \rightarrow \mathbf{D}(M)$ is fully faithful.

Step 3. The arguments in step 1 we show that $\mathbf{D}^b(M) \rightarrow \mathbf{D}^+(M)$ is fully faithful. And by step 2, $\mathbf{D}^+(M) \rightarrow \mathbf{D}(M)$ is fully faithful. Therefore $\mathbf{D}^b(M) \rightarrow \mathbf{D}(M)$ is fully faithful.

Step 4. Smart truncation shows that the functor $\mathbf{D}^*(M) \rightarrow \mathbf{D}(M)^*$ is essentially surjective on objects. \square

Remark 8.3.9. Most advanced texts write $\mathbf{D}^*(M)$ instead of $\mathbf{D}(M)^*$, and do not use the notation $\mathbf{D}(M)^*$ at all. This is harmless by Proposition 8.3.5.

Remark 8.3.10. The object $Y^p(M) = \text{Coker}(d_M^{p-1})$ that appears in formula (8.3.8) does not have a name. The naming conventions would indicate that it should be called the “object of cococycles”, because it plays a role that’s dual to the role of the object of cocycles $Z^p(M) = \text{Ker}(d_M^p)$, and it can’t be called “cycles”. But the name “cococycles” sounds a bit strange.

Definition 8.3.11. A DG ring A is called *nonpositive* if $A^i = 0$ for all $i > 0$.

Exercise 8.3.12. Let A be a nonpositive DG ring and let M be an abelian category.

- (1) Prove that differential on any $M \in \mathbf{C}_{\text{str}}(A, M)$ is A^0 -linear.
- (2) Prove that the smart truncations from formulas (8.3.6) and (8.3.8) are functors from $\mathbf{C}_{\text{str}}(A, M)$ to itself.
- (3) Prove Proposition 8.3.5 for $\mathbf{C}_{\text{str}}(A, M)$.

8.4. Thick Subcategories of M . Let M be an abelian category. A *thick abelian subcategory* of M is a full abelian subcategory N that is closed under extensions. Namely if

$$0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$$

is a short exact sequence in M with $M', M'' \in N$, then $M \in N$ too.

Let $\mathbf{D}_N(M)$ be the full subcategory of $\mathbf{D}(M)$ consisting of complexes M such that $H^i(M) \in N$ for every i .

Proposition 8.4.1. *If N is a thick abelian subcategory of M then $\mathbf{D}_N(M)$ is a full pretriangulated subcategory of $\mathbf{D}(M)$.*

Proof. Clearly $\mathbf{D}_N(M)$ is closed under translations. Now suppose

$$M' \rightarrow M \rightarrow M'' \rightarrow M[1]$$

is a distinguished triangle in $\mathbf{D}(M)$ such that $M', M \in \mathbf{D}_N(M)$; we have to show that M'' is also in $\mathbf{D}_N(M)$. Consider the exact sequence

$$H^i(M') \rightarrow H^i(M) \rightarrow H^i(M'') \rightarrow H^{i+1}(M') \rightarrow H^{i+1}(M).$$

The four outer objects belong to N . Since N is a thick abelian subcategory of M it follows that $H^i(M'') \in N$. \square

Example 8.4.2. Let A be a noetherian commutative ring. The category $\text{Mod}_f A$ of finitely generated modules is a thick abelian subcategory of $\text{Mod } A$.

Example 8.4.3. Consider $\text{Mod } \mathbb{Z} = \text{Ab}$. As above we have the thick abelian subcategory $\text{Ab}_{\text{fgen}} = \text{Mod}_f \mathbb{Z}$ of finitely generated abelian groups. There is also the thick abelian subcategory Ab_{tors} of torsion abelian groups (every element has a finite order). The intersection of Ab_{tors} and Ab_{fgen} is the category Ab_{fin} of finite abelian groups. This is also thick.

Example 8.4.4. Let X be a noetherian scheme (e.g. an algebraic variety over an algebraically closed field). Consider the abelian category $\text{Mod } \mathcal{O}_X$ of \mathcal{O}_X -modules. In it there is the thick abelian subcategory $\text{QCoh } \mathcal{O}_X$ of quasi-coherent sheaves, and in that there is the thick abelian subcategory $\text{Coh } \mathcal{O}_X$ of coherent sheaves.

For a left noetherian ring A we write

$$\mathbf{D}_f(\text{Mod } A) := \mathbf{D}_{\text{Mod}_f A}(\text{Mod } A).$$

Proposition 8.4.5. *Let A be a left noetherian ring and $\star \in \{-, \text{b}\}$. Then the canonical functor*

$$\mathbf{D}^\star(\text{Mod}_f A) \rightarrow \mathbf{D}_f(\text{Mod } A)^\star$$

is an equivalence of pretriangulated categories.

Proof. Consider the functor

$$F : \mathbf{D}^-(\text{Mod}_f A) \rightarrow \mathbf{D}(\text{Mod } A).$$

Suppose $s : M \rightarrow L$ is a quasi-isomorphism in $\mathbf{K}(\text{Mod } A)$, such that $L \in \mathbf{K}^-(\text{Mod}_f A)$. Then $M \in \mathbf{D}_f(\text{Mod}_f A)^-$. A bit later (in Corollary 11.3.32) we will prove that M admits a free resolution $P \rightarrow M$, where P is a bounded above complex of finitely generated free modules. Thus we get a quasi-isomorphism $t : P \rightarrow M$ with $P \in \mathbf{K}^-(\text{Mod}_f A)$. By Proposition 8.2.5 with condition (r) we conclude that F is fully faithful. This also shows that the essential image of F is $\mathbf{D}_f(\text{Mod}_f A)^-$.

Next consider the functor

$$G : \mathbf{D}^{\text{b}}(\text{Mod}_f A) \rightarrow \mathbf{D}^-(\text{Mod}_f A).$$

Suppose $s : L \rightarrow M$ is a quasi-isomorphism in $\mathbf{K}^-(\text{Mod}_f A)$ with $L \in \mathbf{K}^{\text{b}}(\text{Mod}_f A)$. Say $\text{H}(L)$ is concentrated in the integer interval $[d_0, d_1]$. Then $t : M \rightarrow \text{smt}^{\geq d_0}(M)$ is a quasi-isomorphism, and $\text{smt}^{\geq d_0}(M) \in \mathbf{K}^{\text{b}}(\text{Mod}_f A)$. By Proposition 8.2.5 with condition (l) we conclude that G is fully faithful. Therefore the composition

$$F \circ G : \mathbf{D}^{\text{b}}(\text{Mod}_f A) \rightarrow \mathbf{D}(\text{Mod } A)$$

is fully faithful. Suitable truncations ($\text{smt}^{\geq d_0}$ and $\text{smt}^{\leq d_1}$) show that the essential image of $F \circ G$ is $\mathbf{D}_f(\text{Mod}_f A)^{\text{b}}$. \square

8.5. The Embedding of \mathbf{M} in $\mathbf{D}(\mathbf{M})$. Here again we only consider an abelian category \mathbf{M} .

For $M, N \in \mathbf{M}$ there is no difference between $\text{Hom}_{\mathbf{M}}(M, N)$, $\text{Hom}_{\mathbf{C}(\mathbf{M})}(M, N)$ and $\text{Hom}_{\mathbf{K}(\mathbf{M})}(M, N)$. Thus the canonical functors $\mathbf{M} \rightarrow \mathbf{C}(\mathbf{M})$ and $\mathbf{M} \rightarrow \mathbf{K}(\mathbf{M})$ are fully faithful. The same is true for $\mathbf{D}(\mathbf{M})$, but this requires a proof.

Let $\mathbf{D}(\mathbf{M})^0$ be the full subcategory of $\mathbf{D}(\mathbf{M})$ consisting of complexes whose cohomology is concentrated in degree 0. This is an additive subcategory of $\mathbf{D}(\mathbf{M})$.

Proposition 8.5.1. *The canonical functor $\mathbf{M} \rightarrow \mathbf{D}(\mathbf{M})^0$ is an equivalence.*

Proof. Let's denote the canonical functor $\mathbf{M} \rightarrow \mathbf{D}(\mathbf{M})^0$ by F . Under the fully faithful embedding $\mathbf{M} \subseteq \mathbf{C}_{\text{str}}(\mathbf{M})$, F is just the restriction of \tilde{Q} .

Since the functor $H^0 : \mathbf{D}(\mathbf{M}) \rightarrow \mathbf{M}$ satisfies $H^0 \circ F = \text{Id}_{\mathbf{M}}$. This implies that F is faithful.

Next we prove that F is full. Take any objects $M, N \in \mathbf{M}$ and a morphism $q : M \rightarrow N$ in $\mathbf{D}(\mathbf{M})$. By Proposition 8.1.7 we know that $q = \tilde{Q}(a) \circ \tilde{Q}(s)^{-1}$ for some morphisms $a : L \rightarrow N$ and $s : L \rightarrow M$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$, with s a quasi-isomorphism. Let $L' := \text{smt}^{\leq 0}(L)$, as in (8.3.6); so there is a quasi-isomorphism $u : L' \rightarrow L$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$. Writing $a' := a \circ u$ and $s' := s \circ u$, we see that s' is a quasi-isomorphism, and $q = \tilde{Q}(a') \circ \tilde{Q}(s')^{-1}$.

Next let $L'' := \text{smt}^{\geq 0}(L')$, as in (8.3.8); so there is a surjective quasi-isomorphism $v : L' \rightarrow L''$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$. Because L'' is a complex concentrated in degree 0, we can view it as an object of \mathbf{M} . The morphisms a' and s' factor as $a' = a'' \circ v$ and $s' = s'' \circ v$, where $a'' : L'' \rightarrow N$ and $s'' : L'' \rightarrow M$ are morphisms in \mathbf{M} . But s'' is a quasi-isomorphism in $\mathbf{C}_{\text{str}}(\mathbf{M})$, and so it is actually an isomorphism in \mathbf{M} . Therefore we have a morphism $a'' \circ (s'')^{-1}$ in \mathbf{M} , and

$$\tilde{Q}(a'' \circ (s'')^{-1}) = \tilde{Q}(a'') \circ \tilde{Q}(s'')^{-1} = \tilde{Q}(a') \circ \tilde{Q}(s')^{-1} = q.$$

Finally we have to prove that any $L \in \mathbf{D}(\mathbf{M})^0$ is isomorphic, in $\mathbf{D}(\mathbf{M})$, to a complex L'' that's concentrated in degree 0. But we already showed it in the previous paragraphs. \square

Proposition 8.5.2. *Let \mathbf{M} be an abelian category. Let*

$$0 \rightarrow L \xrightarrow{\phi} M \xrightarrow{\psi} N \rightarrow 0$$

be a diagram in \mathbf{M} . The following conditions are equivalent:

- (i) *The diagram is an exact sequence.*
- (ii) *There is a distinguished triangle*

$$L \xrightarrow{\tilde{Q}(\phi)} M \xrightarrow{\tilde{Q}(\psi)} N \xrightarrow{\theta} \mathbf{T}(L)$$

in $\mathbf{D}(\mathbf{M})$.

Exercise 8.5.3. Prove Proposition 8.5.2. (Hint: for the implication (i) \Rightarrow (ii) you can take $\theta = 0$.)

The last two propositions say that the abelian category \mathbf{M} can be recovered from the pretriangulated category $\mathbf{D}(\mathbf{M})$.

9. DERIVED FUNCTORS

As before, \mathbb{K} is a commutative base ring, that shall remain implicit. Let A be a central DG \mathbb{K} -ring, and \mathbf{M} a \mathbb{K} -linear abelian category. The category $\mathbf{C}(A, \mathbf{M})$ of DG A -modules in \mathbf{M} was introduced in Subsection 3.7. It is a DG category. The pretriangulated categories $\mathbf{K}(A, \mathbf{M})$ and $\mathbf{D}(A, \mathbf{M})$ were introduced in Subsections 6.4 and 8.1 respectively. There is a triangulated localization functor

$$Q : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{D}(A, \mathbf{M}).$$

Let (B, \mathbf{N}) be another pair of DG ring and abelian category. Suppose we are given a DG functor

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N}).$$

Then, according to Theorem 6.4.15, there is an induced triangulated functor

$$(\bar{F}, \bar{\tau}_F) : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{K}(B, \mathbf{N})$$

Most triangulated functors that we shall encounter arise this way. For convenience of notation, let us suppress mentioning the translation isomorphism $\bar{\tau}_F$, and let us write F instead of \bar{F} .

By postcomposing with the localization functor of $\mathbf{K}(B, \mathbf{N})$ we obtain a triangulated functor

$$(9.0.1) \quad Q \circ F : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{D}(B, \mathbf{N}).$$

Again we denote this triangulated functor by F .

Our goal in this section is to extend F to triangulated functors

$$RF, LF : \mathbf{D}(A, \mathbf{M}) \rightarrow \mathbf{D}(B, \mathbf{N}).$$

These are the right and left derived functors of F , respectively.

It will be easier to state matters more generally. Thus we shall mostly work in the setup below.

Setup 9.0.2. The following are given:

- (1) Pretriangulated categories \mathbf{K} and \mathbf{E} .
- (2) A triangulated functor $F : \mathbf{K} \rightarrow \mathbf{E}$.
- (3) A denominator set of cohomological origin $S \subseteq \mathbf{K}$ (see Definition 7.4.2).

Recall that the morphisms in S are called quasi-isomorphisms.

By Proposition 7.4.1 and Theorem 7.4.3, the localization \mathbf{K}_S exists, and it is a pretriangulated category. The triangulated localization functor is $Q : \mathbf{K} \rightarrow \mathbf{K}_S$.

This setup specializes to (9.0.1) when we take $\mathbf{K} = \mathbf{K}(A, \mathbf{M})$, $S = \mathbf{S}(A, \mathbf{M})$ and $\mathbf{E} = \mathbf{D}(B, \mathbf{N})$.

Remark 9.0.3. As far as we know, all previous textbooks only consider the special case of the derived functors

$$RF, LF : \mathbf{D}(\mathbf{M}) \rightarrow \mathbf{D}(\mathbf{N})$$

of a triangulated functor

$$F : \mathbf{K}(\mathbf{M}) \rightarrow \mathbf{K}(\mathbf{N}),$$

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where M and N are abelian categories. The DG variant is not mentioned at all. However, the definitions and the main existence results, as stated in this section, are virtually the same.

Furthermore, previous textbooks avoid the 2-categorical notation, and that (in our opinion) is a cause for undue difficulties in the presentation.

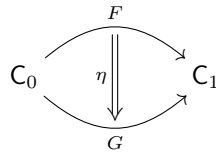
9.1. 2-Categorical Notation. In this section we are going to do a lot of work with morphisms of functors (i.e. natural transformations). The language and notation of ordinary category theory that we used so far is not adequate for this purpose. Therefore we will now introduce notation from the theory of *2-categories*. (We will not give a definition of a 2-category here; but it is basically the data mentioned below, satisfying a few conditions, most of which will be mentioned below too.) In the subsequent sections we will revert to the usual (i.e. 1-categorical) language. For more details on 2-categories the reader can look at [Mac2] or [Ye8, Section 1].

Consider the set **Cat** of all categories. The set theoretical aspects are neglected, as explained in Subsection 1.1. (Briefly, the precise solution is this: **Cat** is the set of all **U**-categories; so **Cat** is a subset of a bigger Grothendieck universe, say **V**, and it is a **V**-category.)

The set **Cat** is the set of objects of a 2-category. This means that in **Cat** there are two kinds of morphisms: *1-morphisms* between objects, and *2-morphisms* between 1-morphisms. There are several kinds of compositions, and these have several properties. All this will be explained below.

Suppose C_0, C_1, \dots are categories, namely objects of **Cat**. The 1-morphisms between them are the functors. The notation is as usual: $F : C_0 \rightarrow C_1$ denotes a functor.

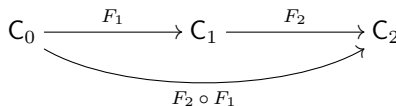
Suppose $F, G : C_0 \rightarrow C_1$ are functors (with the same source and target objects). The 2-morphisms from F to G are the morphisms of functors (i.e. the natural transformations), and the notation is $\eta : F \Rightarrow G$. The double arrow is the distinguishing notation for 2-morphisms. When specializing to an object $M \in C_0$ we revert to the single arrow notation, namely $\eta_M : F(M) \rightarrow G(M)$ is the corresponding morphism in C_1 . The diagram depicting this is



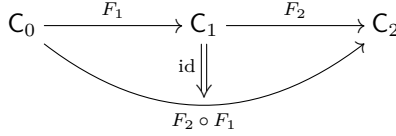
We shall refer to such a diagram as a *2-diagram*.

Each object (category) C has its identity 1-morphism (functor) $\text{Id}_C : C \rightarrow C$. Each 1-morphism F has its identity 2-morphism (natural transformation) $\text{id}_F : F \Rightarrow F$.

Now we consider compositions. For functors there is nothing new: given functors $F_i : C_{i-1} \rightarrow C_i$, the composition, that we now call *horizontal composition*, is the functor $F_2 \circ F_1 : C_0 \rightarrow C_2$. The diagram is

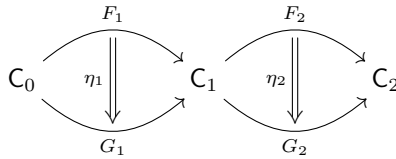


This can be viewed as a commutative 1-diagram, or as a shorthand for the 2-diagram



in which id is the identity 2-morphism of $F_2 \circ F_1$.

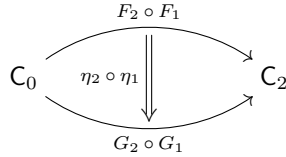
The complication begins with compositions of 2-morphisms. Suppose we are given 1-morphisms $F_i, G_i : C_{i-1} \rightarrow C_i$ and 2-morphisms $\eta_i : F_i \Rightarrow G_i$. In a diagram:



The *horizontal composition* is the morphism of functors

$$\eta_2 \circ \eta_1 : F_2 \circ F_1 \Rightarrow G_2 \circ G_1.$$

The diagram is

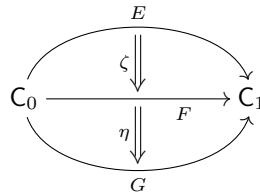


Exercise 9.1.1. For an object $M \in C_0$, give an explicit formula for the morphism

$$(\eta_2 \circ \eta_1)_M : (F_2 \circ F_1)(M) \rightarrow (G_2 \circ G_1)(M)$$

in the category C_2 .

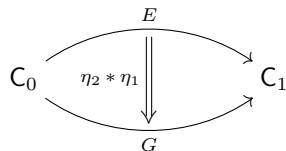
Suppose we are given 1-morphisms $E, F, G : C_0 \rightarrow C_1$, and 2-morphisms $\zeta : E \Rightarrow F$ and $\eta : F \Rightarrow G$. The diagram depicting this is



The *vertical composition* of ζ and η is the 2-morphism

$$\eta * \zeta : E \rightarrow G.$$

Notice the new symbol for this operation. The corresponding diagram is

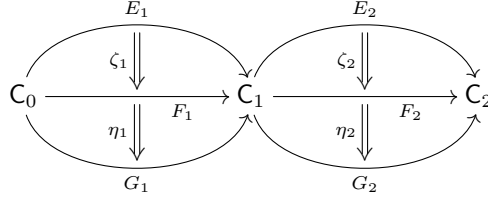


Exercise 9.1.2. For an object $M \in \mathbf{C}_0$, give an explicit formula for the morphism

$$(\eta * \zeta)_M : E(M) \rightarrow G(M)$$

in the category \mathbf{C}_1 .

Something intricate occurs in the situation shown in the next diagram.



It turns out that

$$(\eta_2 * \zeta_2) \circ (\eta_1 * \zeta_1) = (\eta_2 \circ \eta_1) * (\zeta_2 \circ \zeta_1)$$

as morphisms $E_2 \circ E_1 \Rightarrow G_2 \circ G_1$. This is called the *exchange property*.

Exercise 9.1.3. Prove the exchange property.

Just like general categories, we can talk about pretriangulated categories. There is the 2-category **PtrCat** of all pretriangulated categories (over \mathbb{K}). The objects here are the pretriangulated categories (\mathbf{K}, \mathbf{T}) ; the 1-morphisms are the triangulated functors (F, τ) ; and the 2-morphisms are the morphisms of triangulated functors η . This is what we are going to use.

9.2. Some Preliminaries on Triangulated Functors.

Proposition 9.2.1. *Let $(F, \tau) : \mathbf{K} \rightarrow \mathbf{L}$ be a triangulated functor between pretriangulated categories. Assume F is an equivalence (of abstract categories), with quasi-inverse $G : \mathbf{L} \rightarrow \mathbf{K}$, and with adjunction isomorphisms $\alpha : G \circ F \xrightarrow{\cong} \text{Id}_{\mathbf{K}}$ and $\beta : F \circ G \xrightarrow{\cong} \text{Id}_{\mathbf{L}}$.*

Then there is an isomorphism of functors

$$\nu : G \circ \mathbf{T}_{\mathbf{L}} \xrightarrow{\cong} \mathbf{T}_{\mathbf{K}} \circ G$$

such that $(G, \nu) : \mathbf{L} \rightarrow \mathbf{K}$ is a triangulated functor, and α and β are isomorphisms of triangulated functors.

Proof. It is well-known that G is additive (or in our case, \mathbb{K} -linear); but since the proof is so easy, we shall reproduce it. Take any pair of objects $M, N \in \mathbf{L}$. We have to prove that the bijection

$$G_{M,N} : \text{Hom}_{\mathbf{L}}(M, N) \rightarrow \text{Hom}_{\mathbf{K}}(G(M), G(N))$$

is linear. But

$$G_{M,N} = F_{G(M), G(N)}^{-1} \circ \text{Hom}_{\mathbf{L}}(\beta_M, \beta_N^{-1})$$

as bijections (of sets) between these modules. Since $\alpha_{M,N}^{-1}$ and $F_{G(M), G(N)}$ are \mathbb{K} -linear, then so is $G_{M,N}$.

We define the isomorphism of triangulated functors ν by the formula

$$\nu := (\alpha \circ \text{id}_{\mathbf{T}_{\mathbf{K}} \circ G}) * (\text{id}_G \circ \tau \circ \text{id}_G)^{-1} * (\text{id}_{G \circ \mathbf{T}_{\mathbf{L}}} \circ \beta)^{-1},$$

in terms of the 2-categorical notation. This gives rise to a commutative diagram of isomorphisms

$$\begin{array}{ccc}
 G \circ T_L \circ F \circ G & \xleftarrow{\text{id} \circ \tau \circ \text{id}} & G \circ F \circ T_K \circ G \\
 \text{id} \circ \beta \downarrow & & \downarrow \alpha \circ \text{id} \\
 G \circ T_L & \xrightarrow{\nu} & T_K \circ G
 \end{array}$$

of additive functors $L \rightarrow K$. So the pair (G, ν) is a T -additive functor.

The verification that (G, ν) preserves triangles (in the sense of Definition 6.3.1(1)) is done like the proof of the additivity of G , but now using axiom (TR1.a) from Definition 6.2.4 . We leave this as an exercise. \square

Exercise 9.2.2. Finish the proof above (the last assertion).

9.3. Right Derived Functors.

Definition 9.3.1. Assume Setup 9.0.2. A *right derived functor* of F is a triangulated functor

$$RF : K_S \rightarrow E,$$

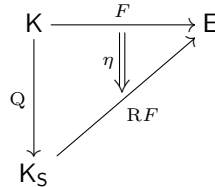
together with a morphism

$$\eta : F \Rightarrow RF \circ Q$$

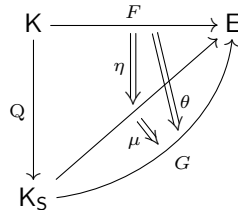
of triangulated functors $K \rightarrow E$. The pair (RF, η) must have this universal property:

- (\diamond) Given any pair (G, θ) , consisting of a triangulated functor $G : K_S \rightarrow E$ and a morphism of triangulated functors $\theta : F \Rightarrow G \circ Q$, there is a unique morphism of triangulated functors $\mu : RF \Rightarrow G$ such that $\theta = (\mu \circ \text{id}_Q) * \eta$.

Pictorially: there is a 2-diagram



For any other pair (G, θ) there is a unique morphism μ that sits in this 2-diagram:



The 1-morphisms in this 2-diagram do not (necessarily) commute; but the diagram of 2-morphisms (with $*$ composition)

$$\begin{array}{ccc}
 F & & \\
 \eta \downarrow & \searrow \theta & \\
 RF \circ Q & \xrightarrow{\mu \circ \text{id}_Q} & G \circ Q
 \end{array}$$

is commutative.

Proposition 9.3.2. *If a right derived functor $(\mathbf{R}F, \eta)$ exists, then it is unique, up to a unique isomorphism. Namely, if (G, θ) is another right derived functor of F , then there is a unique isomorphism of triangulated functors $\mu : \mathbf{R}F \xrightarrow{\cong} G$ such that $\theta = (\mu \circ \text{id}_Q) * \eta$.*

Proof. Despite the apparent complication of the situation, the usual argument for uniqueness of universals (here it is a universal 1-morphism) applies. It shows that the morphism μ from condition (\diamond) is an isomorphism. \square

Existence is much harder. Here is a sufficient condition. It is a rephrasing of [RD, Theorem I.5.1], and the proof is basically the same (but we give many more details).

Theorem 9.3.3. *Given Setup 9.0.2, assume there is a full pretriangulated subcategory $\mathbf{J} \subseteq \mathbf{K}$ with these two properties:*

- (a) *If $\phi : I \rightarrow I'$ is a quasi-isomorphism in \mathbf{J} , then $F(\phi) : F(I) \rightarrow F(I')$ is an isomorphism in \mathbf{E} .*
- (b) *Every object $M \in \mathbf{K}$ admits a quasi-isomorphism $\rho : M \rightarrow I$ to some object $I \in \mathbf{J}$.*

Then the right derived functor

$$(\mathbf{R}F, \eta) : \mathbf{K}_{\mathcal{S}} \rightarrow \mathbf{E}$$

exists. Moreover, for any object $I \in \mathbf{J}$ the morphism

$$\eta_I : F(I) \rightarrow (\mathbf{R}F \circ Q)(I)$$

in \mathbf{E} is an isomorphism.

Remark 9.3.4. A quasi-isomorphism $\rho : M \rightarrow I$ as in condition (b) is supposed to be viewed as a “generalized injective resolution” of M . See Example 9.3.22, where this is made concrete.

We use the letter \mathbf{J} for the category of “generalized injective complexes” because the letter \mathbf{I} , in this particular font, is too ambiguous.

The proof of the theorem follows some preparation. We will sometimes suppress the localization functors Q and Q' , for the sake of clarity. For instance, given a morphism $s \in \mathcal{S}$, we might say that s is invertible in $\mathbf{K}_{\mathcal{S}}$.

Definition 9.3.5. In the situation of Theorem 9.3.3, by a *system of right \mathbf{J} -resolutions* we mean a pair (I, ρ) , where $I : \text{Ob}(\mathbf{K}) \rightarrow \text{Ob}(\mathbf{J})$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(\mathbf{K})}$ is a collection of quasi-isomorphisms $\rho_M : M \rightarrow I(M)$ in \mathbf{K} . Moreover, if $M \in \text{Ob}(\mathbf{J})$, then $I(M) = M$ and $\rho_M = \text{id}_M$.

Property (b) of Theorem 9.3.3 guarantees that a system of right \mathbf{J} -resolutions (I, ρ) exists.

Suppose we made a choice of a system of right \mathbf{J} -resolutions. Let us denote by $U : \mathbf{J} \rightarrow \mathbf{K}$ the inclusion functor, so $I \circ U$ is the identity on the set $\text{Ob}(\mathbf{J})$. Let us define $F' := F \circ U : \mathbf{J} \rightarrow \mathbf{E}$ and $\mathcal{S}' := \mathbf{J} \cap \mathcal{S}$. The localization functor of \mathbf{J} is denoted by $Q' : \mathbf{J} \rightarrow \mathbf{J}_{\mathcal{S}'}$. There is a triangulated functor $U_{\mathcal{S}'} : \mathbf{J}_{\mathcal{S}'} \rightarrow \mathbf{K}_{\mathcal{S}}$ extending U , and

there is equality $Q \circ U = U_{S'} \circ Q'$. These sit in a commutative diagram

$$\begin{array}{ccc} J & \xrightarrow{U} & K \\ Q' \downarrow & & \downarrow Q \\ J_{S'} & \xrightarrow{U_{S'}} & K_S \end{array}$$

We know (from Theorem 7.4.3) that the functor F' extends uniquely to a triangulated functor $F'_{S'} : J_{S'} \rightarrow E$. Let $\eta' := \text{id}_{F'}$, which is a 2-morphism

$$(9.3.6) \quad \eta' : F' \Rightarrow F'_{S'} \circ Q'.$$

The 2-diagram is:

$$(9.3.7) \quad \begin{array}{ccc} J & \xrightarrow{F'} & E \\ Q' \downarrow & \eta' \Downarrow & \nearrow F'_{S'} \\ J_{S'} & & \end{array}$$

Lemma 9.3.8. *The pair $(F'_{S'}, \eta')$ is a right derived functor of F' .*

Proof. We need to verify condition (\diamond) of Definition 9.3.1. Say a triangulated functor $G' : J_{S'} \rightarrow E$ is given. Because Q' is the identity on objects, the data of a morphism of triangulated functors $\mu' : F'_{S'} \Rightarrow G'$, namely a collection of morphisms $\mu'_I : F'(I) \rightarrow G'(I)$ in E for all $I \in J$, is the same data as a morphism of triangulated functors

$$(9.3.9) \quad \theta' := \mu' \circ \text{id}_{Q'} = (\mu' \circ \text{id}_{Q'}) * \eta' : F' \Rightarrow G' \circ Q'.$$

This implies that the function $\mu' \mapsto \theta'$ is injective. Here is the relevant 2-diagram:

$$(9.3.10) \quad \begin{array}{ccc} J & \xrightarrow{F'} & E \\ Q' \downarrow & \eta' \Downarrow & \nearrow F'_{S'} \\ J_{S'} & \xrightarrow{\mu'} & G' \end{array}$$

We have to prove that the function $\mu' \mapsto \theta'$ is surjective. This amounts to showing that for any morphism $q : I \rightarrow J$ in $J_{S'}$ there is equality

$$\theta'_J \circ F'_{S'}(q) = G'(q) \circ \theta'_I$$

of morphisms in E . Let us choose a right fraction presentation $q = a \circ s^{-1}$, with $a : K \rightarrow J$ in J and $s : K \rightarrow I$ in S' . Because $\theta' : F' \Rightarrow G' \circ Q'$ is a morphism of

functors $\mathbf{J} \rightarrow \mathbf{E}$, the solid diagram below

$$\begin{array}{ccccc}
 & & F'_{S'}(q) & & \\
 & & \text{---} & & \\
 & & \text{---} & & \\
 F'(I) & \xleftarrow{F'(s)} & F'(K) & \xrightarrow{F'(a)} & F'(J) \\
 \theta'_I \downarrow & & \theta'_K \downarrow & & \theta'_J \downarrow \\
 G'(I) & \xleftarrow{G'(s)} & G'(K) & \xrightarrow{G'(a)} & G'(J) \\
 & & G'(q) & &
 \end{array}$$

is commutative. But then, since $F'(s)$ and $G'(s)$ are invertible in \mathbf{E} , the whole diagram is commutative. \square

Lemma 9.3.11. *The functor $U_{S'} : \mathbf{J}_{S'} \rightarrow \mathbf{K}_S$ is an equivalence of pretriangulated categories.*

Proof. By the proof of Proposition 8.2.5, with condition (1), together with Proposition 9.2.1. \square

Lemma 9.3.12. *Suppose a system of right \mathbf{J} -resolutions (I, ρ) has been chosen. Then the function I extends uniquely to a triangulated functor $I : \mathbf{K}_S \rightarrow \mathbf{J}_{S'}$, such that $\text{Id}_{\mathbf{J}_{S'}} = I \circ U_{S'}$, and $\rho : \text{Id}_{\mathbf{K}_S} \Rightarrow U_{S'} \circ I$ is an isomorphism of triangulated functors.*

In other words, the triangulated functor I is a quasi-inverse of $U_{S'}$. The relevant 2-diagram is this:

$$\begin{array}{ccccc}
 \mathbf{J} & \xrightarrow{Q'} & \mathbf{J}_{S'} & \xrightarrow{\text{Id}} & \mathbf{J}_{S'} \\
 \downarrow U & & \uparrow I & \searrow U_{S'} & \uparrow I \\
 \mathbf{K} & \xrightarrow{Q} & \mathbf{K}_S & \xrightarrow{\text{Id}} & \mathbf{K}_S \\
 & & \uparrow \rho & &
 \end{array}$$

Proof. By Lemma 9.3.11 the functor $U_{S'}$ is an equivalence. Take any pair of objects $M, N \in \mathbf{K}$. There is a bijection

$$U_{S'} : \text{Hom}_{\mathbf{J}_{S'}}(I(M), I(N)) \rightarrow \text{Hom}_{\mathbf{K}_S}(I(M), I(N)),$$

and another bijection

$$\text{Hom}(\rho_M^{-1}, \rho_N) : \text{Hom}_{\mathbf{K}_S}(M, N) \rightarrow \text{Hom}_{\mathbf{K}_S}(I(M), I(N)).$$

These bijections say that to any morphism $\psi : M \rightarrow N$ in \mathbf{K}_S there corresponds a unique morphism $I(\psi) : I(M) \rightarrow I(N)$ in $\mathbf{J}_{S'}$, such that

$$U_{S'}(I(\psi)) \circ \rho_M = \rho_N \circ \psi.$$

An easy calculation shows that $I : \mathbf{K}_S \rightarrow \mathbf{J}_{S'}$ is a functor. Moreover, there is equality of functors $I \circ U_{S'} = \text{Id}_{\mathbf{J}_{S'}}$, and an isomorphism of functors $\rho : \text{Id}_{\mathbf{K}_S} \xrightarrow{\cong} U_{S'} \circ I$. This says that I is a quasi-inverse of $U_{S'}$. Therefore, by Proposition 9.2.1, I is a triangulated functor, and ρ is an isomorphism of triangulated functors. \square

Lemma 9.3.13. *Under the assumptions of the theorem, let $G : \mathbf{K}_S \rightarrow \mathbf{E}$ be triangulated functor, and define $G' := G \circ U_{S'}$. Suppose $\eta' : F' \Rightarrow G' \circ Q'$ is a morphism of triangulated functors $\mathbf{J} \rightarrow \mathbf{E}$. Then there is a unique morphism $\eta : F \Rightarrow G \circ Q$ of triangulated functors $\mathbf{K} \rightarrow \mathbf{E}$ that extends η' , namely such that $\eta \circ \text{id}_U = \eta'$.*

Here are the corresponding 2-diagrams:

$$\begin{array}{ccc}
 \mathbf{J} & \xrightarrow{F'} & \mathbf{E} \\
 \downarrow Q' & \Downarrow \eta' & \nearrow G' \\
 \mathbf{J}_{S'} & &
 \end{array}
 \qquad
 \begin{array}{ccccc}
 \mathbf{J} & \xrightarrow{U} & \mathbf{K} & \xrightarrow{F} & \mathbf{E} \\
 \downarrow Q' & & \downarrow Q & \Downarrow \eta & \nearrow G \\
 \mathbf{J}_{S'} & \xrightarrow{U_{S'}} & \mathbf{K}_S & &
 \end{array}$$

Here is another way to state the lemma. Let us denote by $\text{Hom}_{\mathbf{PTrCat}}^2(-, -)$ the set of 2-morphisms (morphisms of triangulated functors). Then the operation $\eta \mapsto \eta \circ \text{id}_U$ is a function

$$- \circ \text{id}_U : \text{Hom}_{\mathbf{PTrCat}}^2(F, G \circ Q) \rightarrow \text{Hom}_{\mathbf{PTrCat}}^2(F', G' \circ Q'),$$

and the lemma asserts that this is a bijection.

Proof. Choose a system of right \mathbf{J} -resolutions (I, ρ) . For any object $M \in \mathbf{K}$ the morphism ρ_M is invertible in \mathbf{K}_S . Hence the morphism

$$G(\rho_M) : G(M) \rightarrow G(I(M))$$

is invertible in \mathbf{E} . We are given the morphism

$$\eta'_{I(M)} : F'(I(M)) \rightarrow G'(I(M))$$

in \mathbf{E} . Recall that $F'(I(M)) = F(I(M))$ and $G'(I(M)) = G(I(M))$. Let us define

$$(9.3.14) \quad \eta_M := G(\rho_M)^{-1} \circ \eta'_{I(M)} \circ F(\rho_M),$$

which is a morphism $F(M) \rightarrow G(M)$ in \mathbf{E} . We get a commutative diagram

$$(9.3.15) \quad
 \begin{array}{ccc}
 F(M) & \xrightarrow{\eta_M} & G(M) \\
 \downarrow F(\rho_M) & & \downarrow G(\rho_M) \\
 F'(I(M)) & \xrightarrow{\eta'_{I(M)}} & G'(I(M))
 \end{array}$$

in \mathbf{E} .

It is now routine to check that η is a morphism of triangulated functors $F \Rightarrow G \circ Q$. By construction η extends η' . The uniqueness of η follows from the fact that the diagram (9.3.15) must commute, and thus formula (9.3.14) must hold. \square

Proof of Theorem 9.3.3.

Step 1. We choose a system of right \mathbf{J} -resolutions (I, ρ) . For any object $M \in \mathbf{K}$ we define the object

$$(9.3.16) \quad \mathbf{R}F(M) := F(I(M)) \in \mathbf{E}$$

and the morphism

$$(9.3.17) \quad \eta_M := F(\rho_M) : F(M) \rightarrow \mathbf{R}F(M)$$

in \mathbf{E} . We still did not say what $\mathbf{R}F$ does to morphisms.

Step 2. For any object $M \in \mathbf{K}$ we have, by construction, $\mathbf{R}F(M) = F'(I(M))$. This means that $\mathbf{R}F = F'_{S'} \circ I$ on objects. The definition

$$(9.3.18) \quad \mathbf{R}F := F'_{S'} \circ I : \mathbf{K}_S \rightarrow \mathbf{E}.$$

upgrades $\mathbf{R}F$ to a triangulated functor. And there is a commutative diagram of triangulated functors

$$\begin{array}{ccc} & & \xrightarrow{F'} \\ \mathbf{J} & \xrightarrow{Q'} & \mathbf{J}_{S'} \xrightarrow{F'_{S'}} \mathbf{E} \\ \downarrow U & & \uparrow I \\ \mathbf{K} & \xrightarrow{Q} & \mathbf{K}_S \end{array} \quad \begin{array}{c} \nearrow \mathbf{R}F \\ \searrow \end{array}$$

Step 3. Recall that we already defined $\eta_M = F(\rho_M)$. In this step we prove that η is a morphism of triangulated functors $\eta : F \rightarrow \mathbf{R}F \circ Q$.

According to Lemma 9.3.13, the morphism of triangulated functors $\eta' : F' \Rightarrow F'_{S'} \circ Q'$ from (9.3.6) extends uniquely to a morphism of triangulated functors $\tilde{\eta} : F \Rightarrow \mathbf{R}F \circ Q$. The 2-diagram is

$$\begin{array}{ccc} \mathbf{K} & \xrightarrow{F} & \mathbf{E} \\ \downarrow Q & \searrow \tilde{\eta} & \nearrow \mathbf{R}F \\ \mathbf{K}_S & & \end{array}$$

We know that $\eta'_{I(M)} = \text{id}_{F(I(M))}$ and $\mathbf{R}F = F'_{S'} \circ I$. By construction of the functor I we have $I(\rho_M) = \text{id}_{I(M)}$ in $\mathbf{J}_{S'}$. Plugging this and $G = \mathbf{R}F$ into formula (9.3.14) we obtain

$$\begin{aligned} \tilde{\eta}_M &= (F'_{S'}(I(\rho_M)))^{-1} \circ \eta'_{I(M)} \circ F(\rho_M) \\ &= (\text{id}_{F(I(M))})^{-1} \circ \text{id}_{F(I(M))} \circ F(\rho_M) = F(\rho_M). \end{aligned}$$

So the morphism $\tilde{\eta}_M$ coincides with η_M . As M varies we get $\tilde{\eta} = \eta$.

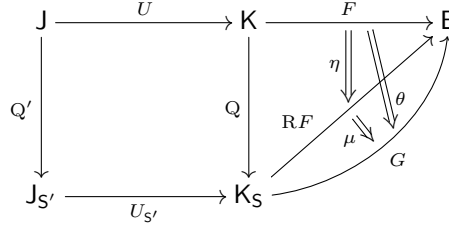
Step 4. It remains to verify condition (\diamond) of Definition 9.3.1. Say a pair (G, θ) is given. Define $G' := G \circ U_{S'}$ and $\theta' := \theta \circ \text{id}_U$. In Lemma 9.3.8 we proved that $(F'_{S'}, \eta')$ is the right derived functor of F' . Therefore there is a unique morphism $\mu' : F'_{S'} \Rightarrow G'$ of triangulated functors $\mathbf{J}_{S'} \rightarrow \mathbf{E}$ such that $\mu' \circ \text{id}_{Q'} = \theta'$. In terms of vertical composition, and using the equality $\eta' = \text{id}_{F'}$, this is

$$(9.3.19) \quad (\mu' \circ \text{id}_{Q'}) * \eta' = \theta'.$$

In a 2-diagram:

$$\begin{array}{ccc} \mathbf{J} & \xrightarrow{F'} & \mathbf{E} \\ \downarrow Q' & \searrow \eta' & \nearrow \theta' \\ \mathbf{J}_{S'} & \xrightarrow{F'_{S'}} & \mathbf{E} \end{array} \quad \begin{array}{c} \nearrow \mu' \\ \searrow G' \end{array}$$

Recall that $F'_{S'} = RF \circ U_{S'}$. The functor $U_{S'}$ is an equivalence. Hence (like Lemma 9.3.13 but much easier) there is a unique morphism $\mu : RF \rightarrow G$ such that $\mu \circ \text{id}_{U_{S'}} = \mu'$. We get this 2-diagram:



We know that

$$\text{id}_Q \circ \text{id}_U = \text{id}_{U_{S'}} \circ \text{id}_{Q'}.$$

Hence

$$(\mu \circ \text{id}_Q \circ \text{id}_U) * (\eta \circ \text{id}_U) = (\mu \circ \text{id}_{U_{S'}} \circ \text{id}_{Q'}) * \eta' = (\mu' \circ \text{id}'_Q) * \eta'$$

(this is the exchange condition). Taking this with formula (9.3.19), and using the exchange condition once more, we deduce that

$$((\mu \circ \text{id}_Q) * \eta) \circ \text{id}_U = \theta'.$$

The uniqueness in Lemma 9.3.13 now implies that

$$(9.3.20) \quad (\mu \circ \text{id}_Q) * \eta = \theta.$$

Finally we have to establish the uniqueness of μ . Suppose $\tilde{\mu}$ is another morphism $RF \Rightarrow G$ satisfying (9.3.20). Then $\tilde{\mu}' := \tilde{\mu} \circ \text{id}_{U_{S'}}$ satisfies (9.3.19). But then, by the uniqueness of μ' , we have $\tilde{\mu}' = \mu'$. Therefore (because $U_{S'}$ is an equivalence) we see that $\tilde{\mu} = \mu$. \square

Definition 9.3.21. The construction of the right derived functor (RF, η) in the proof of the theorem above, and specifically formulas (9.3.16) and (9.3.17), is called a *presentation of (RF, η) by the system of right J-resolutions (I, ρ)* .

Of course any other right derived functor of F (perhaps presented by another system of right J-resolutions) is uniquely isomorphic to (RF, η) . This is according to Proposition 9.3.2.

In Section 10 we shall give several existence results for the right derived functor

$$(RF, \eta) : \mathbf{D}^*(A, M) \rightarrow E$$

of a triangulated functor

$$F : \mathbf{K}^*(A, M) \rightarrow E,$$

under various assumptions on F, A, M and \star . These existence results will be based on Theorem 9.3.3: we will prove existence of suitable resolving subcategories $J \subseteq \mathbf{K}^*(A, M)$. The example below is one such case.

Example 9.3.22. Suppose we start from an additive functor $F : M \rightarrow N$. We know how to extend it to a DG functor $F : \mathbf{C}^+(M) \rightarrow \mathbf{C}^+(N)$, and then to a triangulated functor $F : \mathbf{K}^+(M) \rightarrow \mathbf{K}^+(N)$. By composing with Q we get a triangulated functor $Q \circ F : \mathbf{K}^+(M) \rightarrow \mathbf{D}^+(N)$, that we also denote by F for simplicity.

Assume that the abelian category M has enough injectives (this means that any object $M \in M$ admits an injective resolution). Define J to be the full subcategory of $\mathbf{K} := \mathbf{K}^+(M)$ on the bounded below complexes of injective objects; and let $E :=$

$\mathbf{D}^+(\mathbf{N})$. We will prove later that properties (a) and (b) of Theorem 9.3.3 hold in this situation. Therefore we have a right derived functor

$$RF : \mathbf{D}^+(\mathbf{M}) \rightarrow \mathbf{D}^+(\mathbf{N}).$$

In case the functor F is left exact, it has the classical right derived functors $R^qF : \mathbf{M} \rightarrow \mathbf{N}$, $q \geq 0$. Formula (9.3.16) shows that for any $M \in \mathbf{M}$ there is equality $R^qF(M) = H^q(RF(M))$ as objects of \mathbf{N} . We will prove that more is true:

$$R^qF = H^q \circ RF$$

as functors $\mathbf{M} \rightarrow \mathbf{N}$.

In the situation of Theorem 9.3.3, let \mathbf{K}^\dagger be a full pretriangulated subcategory of \mathbf{K} . Define $\mathbf{S}^\dagger := \mathbf{K}^\dagger \cap \mathbf{S}$ and $\mathbf{J}^\dagger := \mathbf{K}^\dagger \cap \mathbf{J}$. Denote by $V : \mathbf{K}^\dagger \rightarrow \mathbf{K}$ the inclusion functor, and by $V_{\mathbf{S}^\dagger} : \mathbf{K}_{\mathbf{S}^\dagger} \rightarrow \mathbf{K}_{\mathbf{S}}$ its localization. Warning: the functor $V_{\mathbf{S}^\dagger}$ is not necessarily fully faithful; cf. Proposition 8.2.5.

Proposition 9.3.23. *Assume that every $M \in \mathbf{K}^\dagger$ admits a quasi-isomorphism $M \rightarrow I$ where $I \in \mathbf{J}^\dagger$. Then the pair*

$$(RF \circ V_{\mathbf{S}^\dagger}, \eta \circ \text{id}_V)$$

is a right derived functor of $F \circ V : \mathbf{K}^\dagger \rightarrow \mathbf{E}$.

Loosely speaking, the proposition says that

$$R(F \circ V) = RF \circ V_{\mathbf{S}^\dagger}.$$

The proof is an exercise.

Exercise 9.3.24. Prove the last proposition. (Hint: Start by choosing a system of right \mathbf{J}^\dagger -resolutions of \mathbf{K}^\dagger . Then extend it to a system of right \mathbf{J} -resolutions of \mathbf{K} . Now follow the proof of the theorem.)

9.4. Left Derived Functors. Left derived functors behave just like right derived functors, except for a change of sides in the target category. Because of this our treatment will be brief: we will state the definitions and the main results, but won't give proofs, beyond a hint here and there.

Definition 9.4.1. Assume Setup 9.0.2. A *left derived functor* of F is a triangulated functor

$$LF : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E},$$

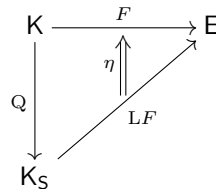
together with a morphism

$$\eta : LF \circ Q \Rightarrow F$$

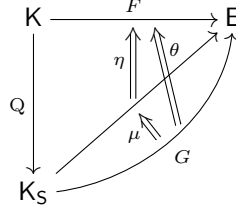
of triangulated functors $\mathbf{K} \rightarrow \mathbf{E}$. The pair (LF, η) must have this universal property:

- (\diamond) Given any pair (G, θ) , consisting of a triangulated functor $G : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}$ and a morphism of triangulated functors $\theta : G \circ Q \Rightarrow F$, there is a unique morphism of triangulated functors $\mu : G \Rightarrow LF$ such that $\theta = \eta * (\mu \circ \text{id}_Q)$.

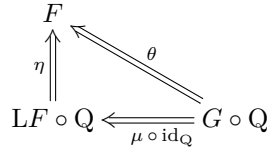
Pictorially: there is a 2-diagram



For any other pair (G, θ) there is a unique morphism μ that sits in this 2-diagram:



The 1-morphisms in this 2-diagram do not (necessarily) commute; but the diagram of 2-morphisms (with $*$ composition)



is commutative.

Proposition 9.4.2. *If a left derived functor (LF, η) exists, then it is unique, up to a unique isomorphism. Namely, if (G, θ) is another left derived functor of F , then there is a unique isomorphism of triangulated functors $\mu : G \xrightarrow{\cong} LF$ such that $\theta = \eta * (\mu \circ \text{id}_Q)$.*

The proof is the same as that of Proposition 9.3.2, with direction of arrows in E reversed.

Theorem 9.4.3. *Given Setup 9.0.2, assume there is a full pretriangulated subcategory $\mathcal{P} \subseteq K$ with these two properties:*

- (a) *If $\phi : P \rightarrow P'$ is a quasi-isomorphism in \mathcal{P} , then $F(\phi) : F(P) \rightarrow F(P')$ is an isomorphism in E .*
- (b) *Every object $M \in K$ admits a quasi-isomorphism $\rho : P \rightarrow M$ from some object $P \in \mathcal{P}$.*

Then the right derived functor

$$(LF, \eta) : K_S \rightarrow E$$

exists. Moreover, for any object $P \in \mathcal{P}$ the morphism

$$\eta_P : (LF \circ Q)(P) \rightarrow F(P)$$

in E is an isomorphism.

The category \mathcal{P} is a “generalized category of projectives”.

The proof is the same as that of Theorem 9.3.3, with direction of arrows in E reversed.

Definition 9.4.4. In the situation of Theorem 9.4.3, by a *system of left \mathcal{P} -resolutions* we mean a pair (P, ρ) , where $P : \text{Ob}(K) \rightarrow \text{Ob}(\mathcal{P})$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(K)}$ is a collection of quasi-isomorphisms $\rho_M : P(M) \rightarrow M$ in K . Moreover, if $M \in \text{Ob}(\mathcal{P})$, then $P(M) = M$ and $\rho_M = \text{id}_M$.

Property (b) of Theorem 9.4.3 guarantees that a system of left \mathcal{P} -resolutions (P, ρ) exists.

Definition 9.4.5. The construction of the left derived functor (LF, η) , when proving Theorem 9.4.3 along the lines of Theorem 9.3.3, and specifically the formulas

$$(9.4.6) \quad LF(M) := F(P(M))$$

and

$$\eta_M := F(\rho_M) : LF(M) \rightarrow F(M),$$

is called a *presentation of (LF, η) by the system of left \mathbf{P} -resolutions (P, ρ) .*

In Section 10 we shall give several existence results for the left derived functor

$$(LF, \eta) : \mathbf{D}^*(A, \mathbf{M}) \rightarrow \mathbf{E}$$

of a triangulated functor

$$F : \mathbf{K}^*(A, \mathbf{M}) \rightarrow \mathbf{E},$$

under various assumptions on F , A , \mathbf{M} and \star . These existence results will be based on Theorem 9.4.3: we will prove existence of suitable resolving subcategories $\mathbf{P} \subseteq \mathbf{K}^*(A, \mathbf{M})$. The example below is one such case.

Example 9.4.7. Suppose we start from an additive functor $F : \mathbf{M} \rightarrow \mathbf{N}$. We know how to extend it to a DG functor $F : \mathbf{C}^-(\mathbf{M}) \rightarrow \mathbf{C}^-(\mathbf{N})$, and then to a triangulated functor $F : \mathbf{K}^-(\mathbf{M}) \rightarrow \mathbf{K}^-(\mathbf{N})$. By composing with \mathbf{Q} we get a triangulated functor $\mathbf{Q} \circ F : \mathbf{K}^-(\mathbf{M}) \rightarrow \mathbf{D}^-(\mathbf{N})$, that we also denote by F for simplicity.

Assume that the abelian category \mathbf{M} has enough projectives (this means that any object $M \in \mathbf{M}$ admits a projective resolution). Define \mathbf{P} to be the full subcategory of $\mathbf{K} := \mathbf{K}^-(\mathbf{M})$ on the bounded above complexes of projective objects; and let $\mathbf{E} := \mathbf{D}^-(\mathbf{N})$. We will prove later that properties (a) and (b) of Theorem 9.4.3 hold in this situation. Therefore we have a left derived functor

$$LF : \mathbf{D}^-(\mathbf{M}) \rightarrow \mathbf{D}^-(\mathbf{N}).$$

In case the functor F is right exact, it has the classical left derived functors $L_q F : \mathbf{M} \rightarrow \mathbf{N}$, $q \geq 0$. Formula (9.4.6) shows that for any $M \in \mathbf{M}$ there is equality $L_q F(M) = H^{-q}(LF(M))$ as objects of \mathbf{N} . We will prove that more is true:

$$L_q F = H^{-q} \circ LF$$

as functors $\mathbf{M} \rightarrow \mathbf{N}$.

In the situation of Theorem 9.4.3, let \mathbf{K}^\dagger be a full pretriangulated subcategory of \mathbf{K} . Define $\mathbf{S}^\dagger := \mathbf{K}^\dagger \cap \mathbf{S}$ and $\mathbf{P}^\dagger := \mathbf{K}^\dagger \cap \mathbf{P}$. Denote by $V : \mathbf{K}^\dagger \rightarrow \mathbf{K}$ the inclusion functor, and by $V_{\mathbf{S}^\dagger} : \mathbf{K}_{\mathbf{S}^\dagger}^\dagger \rightarrow \mathbf{K}_{\mathbf{S}}$ its localization. Warning: the functor $V_{\mathbf{S}^\dagger}$ is not necessarily fully faithful; cf. Proposition 8.2.5.

Proposition 9.4.8. *Assume that every $M \in \mathbf{K}^\dagger$ admits a quasi-isomorphism $P \rightarrow M$ where $P \in \mathbf{P}^\dagger$. Then the pair*

$$(LF \circ V_{\mathbf{S}^\dagger}, \eta \circ \text{id}_V)$$

is a left derived functor of $F \circ V : \mathbf{K}^\dagger \rightarrow \mathbf{E}$.

The proof is just like that of Proposition 9.3.23 (which was an exercise...).

10. RESOLUTIONS OF DG MODULES

In this section we are back to the more concrete setting: A is a DG ring, and \mathbf{M} is an abelian category (both over a base ring \mathbb{K}). We will define *K-projective* and *K-injective* DG modules in $\mathbf{K}(A, \mathbf{M})$. These DG modules form full pretriangulated subcategories of $\mathbf{K}(A, \mathbf{M})$, and are concrete versions of the abstract categories \mathbf{J} and \mathbf{P} , that played important roles in Subsections 9.3 and 9.4 respectively. For $\mathbf{K}(A)$ we also define *K-flat DG modules*.

10.1. K-Injective DG Modules. For any i we have an additive functor

$$H^i : \mathbf{C}_{\text{str}}(A, \mathbf{M}) \rightarrow \mathbf{M}.$$

There is equality $H^i = H^0 \circ T^i$. The functors H^i pass to the homotopy category, and

$$H^0 : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{M}$$

is a cohomological functor in the sense of Definition 6.3.2.

Definition 10.1.1. A DG module $N \in \mathbf{C}(A, \mathbf{M})$ is called *acyclic* if $H^i(N) = 0$ for all i .

Definition 10.1.2. A DG module $I \in \mathbf{C}(A, \mathbf{M})$ is called *K-injective* if for every acyclic DG module $N \in \mathbf{C}(A, \mathbf{M})$, the DG \mathbb{K} -module $\text{Hom}_{A, \mathbf{M}}(N, I)$ is acyclic.

The definition above characterizes K-injectives as objects of $\mathbf{C}(A, \mathbf{M})$. The next proposition shows that being K-injective is intrinsic to the pretriangulated category $\mathbf{K}(A, \mathbf{M})$, with the cohomological functor H^0 (that tells us which are the acyclic objects).

Proposition 10.1.3. A DG module $I \in \mathbf{K}(A, \mathbf{M})$ is K-injective if and only if $\text{Hom}_{\mathbf{K}(A, \mathbf{M})}(N, I) = 0$ for every acyclic DG module $N \in \mathbf{K}(A, \mathbf{M})$.

Proof. This is because for any integer p we have

$$H^p(\text{Hom}_{A, \mathbf{M}}(N, I)) \cong H^0(\text{Hom}_{A, \mathbf{M}}(T^{-p}(N), I)) \cong \text{Hom}_{\mathbf{K}(A, \mathbf{M})}(T^{-p}(N), I),$$

and N is acyclic iff $T^{-p}(N)$ is acyclic. \square

The concept of K-injective complex (i.e. a K-injective object of $\mathbf{K}(\mathbf{M})$) was introduced by Spaltenstein [Sp] in 1988. At about the same time other authors (Keller [Kel], Bockstedt-Neeman [BoNe], Bernstein-Lunts [BeLu], ...) discovered this concept independently, with other names (such as *homotopically injective complex*). The texts [BeLu] and [Kel] already talk about DG modules over DG rings.

Remark 10.1.4. When the smart truncation functors exist (e.g. when A is a nonpositive DG ring), it is enough to check for K-injectivity of a DG module $I \in \mathbf{K}^*(A, \mathbf{M})$ against acyclic DG modules $N \in \mathbf{K}^*(A, \mathbf{M})$. Cf. Definition 8.3.11 and Exercise 8.3.12.

Definition 10.1.5. Let $M \in \mathbf{K}(A, \mathbf{M})$. A *K-injective resolution* of M is a quasi-isomorphism $\rho : M \rightarrow I$ in $\mathbf{K}(A, \mathbf{M})$, where I is a K-injective DG module.

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Remark 10.1.6. In some other texts (and in our Section 11) “resolution” refers to a quasi-isomorphism $\rho : M \rightarrow I$ in $\mathbf{C}_{\text{str}}(A, M)$. It usually makes no difference which meaning is used (as long as we know what we are talking about).

In the next section we will prove existence of K-injectives in several contexts. Here is an easy one.

Exercise 10.1.7. Let $I \in \mathbf{K}(M)$ be a complex of injective objects of M , with zero differential. Prove that I is K-injective.

Definition 10.1.8. Let \mathbf{K} be a full subcategory of $\mathbf{K}(A, M)$. The full subcategory of \mathbf{K} on the K-injective DG modules in it is denoted by \mathbf{K}_{inj} . In other words,

$$\mathbf{K}_{\text{inj}} = \mathbf{K}(A, M)_{\text{inj}} \cap \mathbf{K}.$$

Warning: the property of being K-injective is in general not intrinsic to the subcategory \mathbf{K} . Cf. Remark 10.1.4.

Proposition 10.1.9. *If \mathbf{K} is a full pretriangulated subcategory of $\mathbf{K}(A, M)$, then \mathbf{K}_{inj} is a full pretriangulated subcategory of \mathbf{K} .*

Proof. It suffices to prove that $\mathbf{K}(A, M)_{\text{inj}}$ is a pretriangulated subcategory of $\mathbf{K}(A, M)$. It is easy to see that $\mathbf{K}(A, M)_{\text{inj}}$ is closed under translations. Suppose

$$I \rightarrow J \rightarrow K \rightarrow T(I)$$

is a distinguished triangle in $\mathbf{K}(A, M)$, with I, J being K-injective DG modules. We have to show that K is also K-injective. Take any acyclic DG module $N \in \mathbf{K}(A, M)$. There is an exact sequence

$$\text{Hom}_{\mathbf{K}(A, M)}(N, J) \rightarrow \text{Hom}_{\mathbf{K}(A, M)}(N, K) \rightarrow \text{Hom}_{\mathbf{K}(A, M)}(N, T(I))$$

in $\text{Mod } \mathbb{K}$. Because J and $T(I)$ are K-injectives, Proposition 10.1.3 says that

$$\text{Hom}_{\mathbf{K}(A, M)}(N, J) = 0 = \text{Hom}_{\mathbf{K}(A, M)}(N, T(I)).$$

Therefore $\text{Hom}_{\mathbf{K}(A, M)}(N, K) = 0$. But N is an arbitrary acyclic DG module, so K is K-injective. \square

Example 10.1.10. Let \star be some boundedness condition (namely $b, +, -$ or nothing). We know that $\mathbf{K}^\star(A, M)$ is a full pretriangulated subcategory of $\mathbf{K}(A, M)$. Hence $\mathbf{K}^\star(A, M)_{\text{inj}}$ is a pretriangulated subcategory too.

Definition 10.1.11. Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, M)$. We say that \mathbf{K} has enough K-injectives if any DG module $M \in \mathbf{K}$ admits a K-injective resolution inside \mathbf{K} . I.e. there is a quasi-isomorphism $\rho : M \rightarrow I$ where $I \in \mathbf{K}_{\text{inj}}$.

Here is the crucial fact regarding K-injectives.

Lemma 10.1.12. *Let \mathbf{K} be a full subcategory of $\mathbf{K}(A, M)$. Let $s : I \rightarrow M$ be a quasi-isomorphism in \mathbf{K} , and assume I is K-injective. Then s has a left inverse, namely there is a morphism $t : M \rightarrow I$ in \mathbf{K} such that $t \circ s = \text{id}_I$.*

Proof. Since \mathbf{K} is a full subcategory of $\mathbf{K}(A, M)$, we can assume that $\mathbf{K} = \mathbf{K}(A, M)$. Consider a distinguished triangle

$$I \xrightarrow{s} M \rightarrow N \rightarrow T(I)$$

in $\mathbf{K}(A, \mathbf{M})$ that's built on s . The long exact cohomology sequence tells us that N is an acyclic DG module. So

$$\mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(\mathbf{T}^p(N), I) = 0$$

for all p . The exact sequence

$$\begin{aligned} \mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(N, I) &\rightarrow \mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(M, I) \\ &\rightarrow \mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(I, I) \rightarrow \mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(\mathbf{T}^{-1}(N), I) \end{aligned}$$

shows that $\phi \mapsto \phi \circ s$ is a bijection

$$\mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(M, I) \xrightarrow{\cong} \mathrm{Hom}_{\mathbf{K}(A, \mathbf{M})}(I, I).$$

We take $t : M \rightarrow I$ to be the unique morphism in $\mathbf{K}(A, \mathbf{M})$ such that $t \circ s = \mathrm{id}_I$. \square

Theorem 10.1.13. *Let A be a DG ring, let \mathbf{M} be an abelian category, and let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. Denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Then the localization functor*

$$\mathbf{Q} : \mathbf{K}_{\mathrm{inj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is fully faithful.

Proof. Consider any pair of objects $I, J \in \mathbf{K}_{\mathrm{inj}}$. We must prove that the \mathbb{K} -module homomorphism

$$(10.1.14) \quad \mathbf{Q} : \mathrm{Hom}_{\mathbf{K}}(I, J) \rightarrow \mathrm{Hom}_{\mathbf{K}_{\mathbf{S}}}(I, J)$$

is bijective.

Suppose $q : I \rightarrow J$ is a morphism in $\mathbf{K}_{\mathbf{S}}$. Let us present q as a left fraction: $q = \mathbf{Q}(s)^{-1} \circ \mathbf{Q}(a)$, where $a : I \rightarrow N$ and $s : J \rightarrow N$ are morphisms in \mathbf{K} , and s is a quasi-isomorphism. By Lemma 10.1.12 s has a left inverse t . We get a morphism $t \circ a : I \rightarrow J$ in \mathbf{K} , and an easy calculation shows that $\mathbf{Q}(t \circ a) = q$ in $\mathbf{K}_{\mathbf{S}}$. This proves surjectivity of (10.1.14).

Now let's prove injectivity of (10.1.14). If $a : I \rightarrow J$ is a morphism in \mathbf{K} such that $\mathbf{Q}(a) = 0$, then by axiom (LO4) of Ore localization (the left version of axiom (RO4) in Definition 7.2.1), there is a quasi-isomorphism $s : J \rightarrow L$ in \mathbf{K} such that $s \circ a = 0$ in \mathbf{K} . Let t be the left inverse of s . Then $a = t \circ s \circ a = 0$ in \mathbf{K} . \square

Corollary 10.1.15. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. If \mathbf{K} has enough K -injectives, then the localization functor*

$$\mathbf{Q} : \mathbf{K}_{\mathrm{inj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is an equivalence.

Proof. By the theorem the functor \mathbf{Q} is fully faithful. The extra condition guarantees that \mathbf{Q} is essentially surjective on objects. \square

Corollary 10.1.16. *Let \star be any boundedness condition. If $\mathbf{K}^{\star}(A, \mathbf{M})$ has enough K -injectives, then the triangulated functor*

$$\mathbf{Q} : \mathbf{K}^{\star}(A, \mathbf{M})_{\mathrm{inj}} \rightarrow \mathbf{D}^{\star}(A, \mathbf{M})$$

is an equivalence.

Proof. Since $\mathbf{K}^{\star}(A, \mathbf{M})$ is a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, this is a special case of the previous corollary. \square

Remark 10.1.17. This result is of tremendous importance, both theoretically and practically. In the theory, it shows that the localized category $\mathbf{D}^*(A, \mathbf{M})$, which is too big to lie inside the original universe \mathbf{U} (see Remark 7.2.16), is equivalent to a \mathbf{U} -category. On the practical side, it means that among \mathbf{K} -injective objects we do not need fractions to represent morphisms.

Corollary 10.1.18. *Let \star and \dagger be boundedness conditions such that*

$$\mathbf{K}^*(A, \mathbf{M}) \subseteq \mathbf{K}^\dagger(A, \mathbf{M}).$$

Assume these categories have enough \mathbf{K} -injectives. Then the canonical functor

$$\mathbf{D}^*(A, \mathbf{M}) \rightarrow \mathbf{D}^\dagger(A, \mathbf{M})$$

is fully faithful.

Proof. Combine Corollary 10.1.16 with the fact that $\mathbf{K}^*(A, \mathbf{M}) \rightarrow \mathbf{K}^\dagger(A, \mathbf{M})$ is fully faithful. \square

Remark 10.1.19. Earlier we only proved that $\mathbf{D}^*(A, \mathbf{M}) \rightarrow \mathbf{D}(A, \mathbf{M})$ is fully faithful in special cases (see Proposition 8.3.5 and Exercise 8.3.12).

Corollary 10.1.20. *Let $\phi : I \rightarrow J$ be a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ between \mathbf{K} -injective objects. Then ϕ is a homotopy equivalence if and only if it is a quasi-isomorphism.*

Proof. One implication is trivial. For the reverse implication, if ϕ is a quasi-isomorphism then it is an isomorphism in $\mathbf{D}(A, \mathbf{M})$, and by Theorem 10.1.13 for $\mathbf{K} = \mathbf{K}(A, \mathbf{M})$ we see that ϕ is an isomorphism in $\mathbf{K}(A, \mathbf{M})$. \square

Here is another useful definition. It is a variant of Definition 9.3.5.

Definition 10.1.21. Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and assume \mathbf{K} has enough \mathbf{K} -injectives. A *system of \mathbf{K} -injective resolutions* in \mathbf{K} is a pair (I, ρ) , where $I : \text{Ob}(\mathbf{K}) \rightarrow \text{Ob}(\mathbf{K}_{\text{inj}})$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(\mathbf{K})}$ is a collection of quasi-isomorphisms $\rho_M : M \rightarrow I(M)$ in \mathbf{K} . Moreover, if $M \in \text{Ob}(\mathbf{K}_{\text{inj}})$, then $I(M) = M$ and $\rho_M = \text{id}_M$.

The proposition below is a variant of Lemma 9.3.12.

Proposition 10.1.22. *Suppose a system of \mathbf{K} -injective resolutions (I, ρ) has been chosen. Then the function I extends uniquely to a triangulated functor $I : \mathbf{K}_S \rightarrow \mathbf{K}_{\text{inj}}$, such that $\text{Id}_{\mathbf{K}_{\text{inj}}} = I \circ \mathbf{Q}|_{\mathbf{K}_{\text{inj}}}$, and $\rho : \text{Id}_{\mathbf{K}_S} \Rightarrow \mathbf{Q} \circ I$ is an isomorphism of triangulated functors.*

Proof. The proof is the same as that of Lemma 9.3.12, except that here we use Corollary 10.1.15. \square

The next corollary is a categorical interpretation of the last proposition.

Corollary 10.1.23 (Functorial \mathbf{K} -Injective Resolutions). *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and assume \mathbf{K} has enough \mathbf{K} -injectives.*

- (1) *There are a triangulated functor $I : \mathbf{K} \rightarrow \mathbf{K}$ and a morphism of triangulated functors $\rho : \text{Id}_{\mathbf{K}} \rightarrow I$, such that for any object $M \in \mathbf{K}$ the object $I(M)$ is \mathbf{K} -injective, and the morphism $\rho_M : M \rightarrow I(M)$ is a quasi-isomorphism.*
- (2) *If (I', ρ') is another such pair, then there is a unique isomorphism of triangulated functors $\zeta : I \xrightarrow{\cong} I'$ such that $\rho' = \zeta \circ \rho$.*

Exercise 10.1.24. Prove Corollary 10.1.23.

Theorem 10.1.25. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Assume \mathbf{K} has enough K -injectives. Let \mathbf{E} be any pretriangulated category, and let*

$$F : \mathbf{K} \rightarrow \mathbf{E}$$

be any triangulated functor. Then F has a right derived functor

$$(RF, \eta) : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}.$$

Furthermore, for any $I \in \mathbf{K}_{\text{inj}}$ the morphism $\eta_I : F(I) \rightarrow RF(I)$ in \mathbf{E} is an isomorphism.

Proof. We will use Theorem 9.3.3. In the notation of that theorem, let $\mathbf{J} := \mathbf{K}_{\text{inj}}$. Condition (b) of that theorem holds (this is the “enough K -injectives” assertion). Next, Theorem 10.1.13 implies that any quasi-isomorphism $\phi : I \rightarrow J$ in \mathbf{K}_{inj} is actually an isomorphism. Therefore $F(\phi)$ is an isomorphism in \mathbf{E} , and this is condition (a) of Theorem 9.3.3. \square

Example 10.1.26. Let A be any DG ring. We will prove later that $\mathbf{K}(A)$ has enough K -injectives. Therefore, given any triangulated functor $F : \mathbf{K}(A) \rightarrow \mathbf{E}$ into any pretriangulated category \mathbf{E} , the right derived functor

$$(RF, \eta) : \mathbf{D}(A) \rightarrow \mathbf{E}$$

exists.

Suppose we choose a system of K -injective resolutions (I, ρ) in $\mathbf{K}(A)$. Then we get a presentation of (RF, η) as follows: $RF(M) = F(I(M))$ and $\eta_M = F(\rho_M)$.

10.2. K -Projective DG Modules. This subsection is dual to the previous one, and so we will be brief.

Definition 10.2.1. A DG module $P \in \mathbf{C}(A, \mathbf{M})$ is called *K -projective* if for every acyclic DG module $N \in \mathbf{C}(A, \mathbf{M})$, the DG \mathbb{K} -module $\text{Hom}_{A, \mathbf{M}}(P, N)$ is acyclic.

Proposition 10.2.2. *A DG module $P \in \mathbf{K}(A, \mathbf{M})$ is K -projective if and only if $\text{Hom}_{\mathbf{K}(A, \mathbf{M})}(P, N) = 0$ for every acyclic DG module $N \in \mathbf{K}(A, \mathbf{M})$.*

The proof is like that of Proposition 10.1.3.

Definition 10.2.3. Let $M \in \mathbf{K}(A, \mathbf{M})$. A *K -projective resolution* of M is a quasi-isomorphism $\rho : P \rightarrow M$ in $\mathbf{K}(A, \mathbf{M})$, where P is a K -projective DG module.

Definition 10.2.4. Let \mathbf{K} be a full subcategory of $\mathbf{K}(A, \mathbf{M})$. The full subcategory of \mathbf{K} on the K -projective DG modules in it is denoted by \mathbf{K}_{prj} . In other words,

$$\mathbf{K}_{\text{prj}} = \mathbf{K}(A, \mathbf{M})_{\text{prj}} \cap \mathbf{K}.$$

The same warning after Definition 10.1.8 applies here.

Proposition 10.2.5. *If \mathbf{K} is a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, then \mathbf{K}_{prj} is a full pretriangulated subcategory of \mathbf{K} .*

The proof is like that of Proposition 10.1.9.

Example 10.2.6. Let \star be some boundedness condition (namely b , $+$, $-$ or nothing). Since $\mathbf{K}^{\star}(A, \mathbf{M})$ is a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, we see that $\mathbf{K}^{\star}(A, \mathbf{M})_{\text{prj}}$ is a pretriangulated subcategory too.

Definition 10.2.7. Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. We say that \mathbf{K} *has enough K -projectives* if any DG module $M \in \mathbf{K}$ admits a \mathbf{K} -projective resolution inside \mathbf{K} . I.e. there is a quasi-isomorphism $\rho : P \rightarrow M$ where $P \in \mathbf{K}_{\text{prj}}$.

Lemma 10.2.8. *Let \mathbf{K} be a full subcategory of $\mathbf{K}(A, \mathbf{M})$. Let $s : M \rightarrow P$ be a quasi-isomorphism in \mathbf{K} , and assume P is K -projective. Then s has a right inverse; namely there is a morphism $t : P \rightarrow M$ in \mathbf{K} such that $s \circ t = \text{id}_P$.*

Same proof as that of Lemma 10.1.12.

Theorem 10.2.9. *Let A be a DG ring, let \mathbf{M} be an abelian category, and let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. Denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Then the localization functor*

$$Q : \mathbf{K}_{\text{prj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is fully faithful.

The proof is the same as that of Theorem 10.1.13, with reversed arrow. The next corollaries and proposition are also proved like their \mathbf{K} -injective counterparts.

Corollary 10.2.10. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. If \mathbf{K} has enough K -projectives, then the localization functor*

$$Q : \mathbf{K}_{\text{prj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is an equivalence.

Corollary 10.2.11. *Let \star and \dagger be boundedness conditions such that*

$$\mathbf{K}^{\star}(A, \mathbf{M}) \subseteq \mathbf{K}^{\dagger}(A, \mathbf{M}).$$

Assume these categories have enough K -projectives. Then the canonical functor

$$\mathbf{D}^{\star}(A, \mathbf{M}) \rightarrow \mathbf{D}^{\dagger}(A, \mathbf{M})$$

is fully faithful.

Corollary 10.2.12. *Let $\phi : P \rightarrow Q$ be a morphism in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ between K -projective objects. Then ϕ is a homotopy equivalence if and only if it is a quasi-isomorphism.*

Definition 10.2.13. Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and assume \mathbf{K} has enough K -projectives. A *system of K -projective resolutions* in \mathbf{K} is a pair (P, ρ) , where $P : \text{Ob}(\mathbf{K}) \rightarrow \text{Ob}(\mathbf{K}_{\text{prj}})$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(\mathbf{K})}$ is a collection of quasi-isomorphisms $\rho_M : P(M) \rightarrow M$ in \mathbf{K} . Moreover, if $M \in \text{Ob}(\mathbf{K}_{\text{prj}})$, then $P(M) = M$ and $\rho_M = \text{id}_M$.

Proposition 10.2.14. *Suppose a system of K -projective resolutions (P, ρ) has been chosen. Then the function P extends uniquely to a triangulated functor $P : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{K}_{\text{prj}}$, such that $\text{Id}_{\mathbf{K}_{\text{prj}}} = P \circ Q|_{\mathbf{K}_{\text{prj}}}$, and $\rho : Q \circ P \Rightarrow \text{Id}_{\mathbf{K}_{\mathbf{S}}}$ is an isomorphism of triangulated functors.*

Corollary 10.2.15 (Functorial K -Projective Resolutions). *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and assume \mathbf{K} has enough K -projectives.*

- (1) *There are a triangulated functor $P : \mathbf{K} \rightarrow \mathbf{K}$ and a morphism of triangulated functors $\rho : P \rightarrow \text{Id}_{\mathbf{K}}$, such that for any object $M \in \mathbf{K}$ the object $P(M)$ is K -projective, and the morphism $\rho_M : P(M) \rightarrow M$ is a quasi-isomorphism.*

- (2) If (P', ρ') is another such pair, then there is a unique isomorphism of triangulated functors $\zeta : P' \xrightarrow{\cong} P$ such that $\rho' = \rho \circ \zeta$.

Theorem 10.2.16. Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Assume \mathbf{K} has enough K -projectives. Let \mathbf{E} be any pretriangulated category, and let

$$F : \mathbf{K} \rightarrow \mathbf{E}$$

be any triangulated functor. Then F has a left derived functor

$$(LF, \eta) : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}.$$

Furthermore, for any $P \in \mathbf{K}_{\text{prj}}$ the morphism $\eta_P : LF(P) \rightarrow F(P)$ in \mathbf{E} is an isomorphism.

The proof is like that of Theorem 10.1.25.

Example 10.2.17. Let A be any DG ring. We will prove later that $\mathbf{K}(A)$ has enough K -projectives. Therefore, given any triangulated functor $F : \mathbf{K}(A) \rightarrow \mathbf{E}$ into any pretriangulated category \mathbf{E} , the left derived functor

$$(LF, \eta) : \mathbf{D}(A) \rightarrow \mathbf{E}$$

exists.

Suppose we choose a system of K -projective resolutions (P, ρ) in $\mathbf{K}(A)$. Then we get a presentation of (LF, η) as follows: $LF(M) = F(P(M))$ and $\eta_M = F(\rho_M)$.

10.3. \mathbf{K} -Flat DG Modules. Recall that A^{op} is the opposite DG ring. The objects of $\mathbf{C}(A^{\text{op}})$ are the right DG A -modules.

Definition 10.3.1. A DG module $P \in \mathbf{C}(A)$ is called *K-flat* if for every acyclic DG module $N \in \mathbf{C}(A^{\text{op}})$, the DG \mathbb{K} -module $N \otimes_A P$ is acyclic.

Proposition 10.3.2. If $P \in \mathbf{C}(A)$ is *K-projective* then it is *K-flat*.

Proof. Let \mathbb{K}^* be an injective cogenerator of $\mathbf{M}(\mathbb{K}) = \text{Mod } \mathbb{K}$. This means that \mathbb{K}^* is an injective \mathbb{K} -module, such that any nonzero \mathbb{K} -module W admits a nonzero homomorphism $W \rightarrow \mathbb{K}^*$. A universal choice is $\mathbb{K}^* = \text{Hom}_{\mathbb{Z}}(\mathbb{K}, \mathbb{Q}/\mathbb{Z})$. It is not hard to see that a DG \mathbb{K} -module W is acyclic if and only if $\text{Hom}_{\mathbb{K}}(W, \mathbb{K}^*)$ is acyclic. (Cf. Exercise 11.5.6 for a stronger assertion.)

Take an acyclic complex $N \in \mathbf{C}(A^{\text{op}})$. Then by Hom-tensor adjunction there is an isomorphism of DG \mathbb{K} -modules

$$\text{Hom}_{\mathbb{K}}(N \otimes_A P, \mathbb{K}^*) \cong \text{Hom}_A(P, \text{Hom}_{\mathbb{K}}(N, \mathbb{K}^*)).$$

The right side is acyclic by our assumptions. Hence so is the left side. It follows that $N \otimes_A P$ is acyclic. \square

The proof above also gives a hint to the next proposition.

Proposition 10.3.3. A DG module $P \in \mathbf{K}(A)$ is *K-flat* iff

$$\text{Hom}_{\mathbf{K}(A)}(P, \text{Hom}_{\mathbb{K}}(N, J)) = 0$$

for every acyclic $N \in \mathbf{C}(A^{\text{op}})$ and every injective $J \in \text{Mod } \mathbb{K}$.

Exercise 10.3.4. Prove Proposition 10.3.3.

The next proposition will be subsumed later, in Section 13, in a theorem about the left derived tensor bifunctor.

Proposition 10.3.5. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A)$, and denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Assume \mathbf{K} has enough K -flat objects. Let B be another central DG \mathbb{K} -ring, let $N \in \mathbf{K}(B \otimes_{\mathbb{K}} A^{\text{op}})$, and define*

$$F : \mathbf{K} \rightarrow \mathbf{D}(B)$$

to be the triangulated functor $F(M) := \mathbf{Q}(N \otimes_A M)$, as in Example 5.4.6 and Theorem 6.4.15. Then F has a left derived functor

$$(\mathbf{L}F, \eta) : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{D}(B).$$

Furthermore, for any object $P \in \mathbf{K}$ which is K -flat, the morphism $\eta_P : \mathbf{L}F(P) \rightarrow F(P)$ in $\mathbf{D}(B)$ is an isomorphism.

Exercise 10.3.6. Prove Proposition 10.3.5. (Hint: look at the proof of Theorem 10.1.25.)

Remark 10.3.7. In view of Proposition 10.3.2, the reader might wonder why we bother with K -flat DG modules. The reason is that on a ringed space (X, \mathcal{A}) there are usually very few projective \mathcal{A} -modules. But, as we shall prove, there are enough K -flat complexes in $\mathbf{C}(\mathcal{A}) = \mathbf{C}(\text{Mod } \mathcal{A})$. This will allow us to have a left derived tensor functor for sheaves.

Exercise 11.1.2. Prove Proposition 11.1.1.

Proposition 11.1.3. *Let \mathbf{C} be a category.*

- (1) *Let $\{M_k\}_{k \in \mathbb{N}}$ be a direct system in \mathbf{C} , and assume the direct limit $M = \lim_{k \rightarrow} M_k$ exists. Then for any object $N \in \mathbf{C}$, the canonical function*

$$\mathrm{Hom}_{\mathbf{C}}(M, N) \rightarrow \lim_{\leftarrow k} \mathrm{Hom}_{\mathbf{C}}(M_k, N)$$

is bijective.

- (2) *Let $\{M_k\}_{k \in \mathbb{N}}$ be an inverse system in \mathbf{C} , and assume the inverse limit $M = \lim_{\leftarrow k} M_k$ exists. Then for any object $N \in \mathbf{C}$, the canonical function*

$$\mathrm{Hom}_{\mathbf{C}}(N, M) \rightarrow \lim_{\leftarrow k} \mathrm{Hom}_{\mathbf{C}}(N, M_k)$$

is bijective.

Exercise 11.1.4. Prove Proposition 11.1.3.

Now we start talking about limits in the abelian category $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$. We have to be careful, because it is often not true that limits exist in abelian categories.

Example 11.1.5. Let \mathbf{M} be the category of finite abelian groups. The inverse system $\{M_k\}_{k \in \mathbb{N}}$, where $M_k := \mathbb{Z}/(2^k)$, and the transition $\mu_k : M_{k+1} \rightarrow M_k$ is the canonical surjection, does not have an inverse limit in \mathbf{M} . We can also make $\{M_k\}_{k \in \mathbb{N}}$ into a direct system, in which the transition $\nu_k : M_k \rightarrow M_{k+1}$ is multiplication by 2. The direct limit does not exist in \mathbf{M} .

Proposition 11.1.6.

- (1) *Let $\{M_k\}_{k \in \mathbb{N}}$ be a direct system in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$. Assume that for every i the direct limit $\lim_{k \rightarrow} M_k^i$ exists in \mathbf{M} . Then the direct limit $M = \lim_{k \rightarrow} M_k$ exists in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$, and in degree i it is $M^i = \lim_{k \rightarrow} M_k^i$.*
- (2) *Let $\{M_k\}_{k \in \mathbb{N}}$ be an inverse system in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$. Assume that for every i the inverse limit $\lim_{\leftarrow k} M_k^i$ exists in \mathbf{M} . Then the inverse limit $M = \lim_{\leftarrow k} M_k$ exists in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$, and in degree i it is $M^i = \lim_{\leftarrow k} M_k^i$.*

Proof. We will only prove item (1); the proof of item (2) is identical. For any integer i define $M^i := \lim_{k \rightarrow} M_k^i \in \mathbf{M}$. By the universal property of the direct limit, the differentials $d : M_k^i \rightarrow M_k^{i+1}$ induce differentials $d : M^i \rightarrow M^{i+1}$, and in this way we obtain a complex $M := \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{C}(\mathbf{M})$. Similarly, any element $a \in A^j$ induces morphisms $a : M^i \rightarrow M^{i+j}$ in \mathbf{M} , and thus M becomes an object of $\mathbf{C}(A, \mathbf{M})$. There are morphisms $M_k \rightarrow M$ in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$, and it is easy to see that these make M into a direct limit of the system $\{M_k\}_{k \in \mathbb{N}}$. \square

Since limits exist in $\mathbf{M} = \mathrm{Mod} \mathbb{K}$, the proposition above says that they exist in $\mathbf{C}(A)$. Similarly they exist in the category $\mathbf{G}(\mathbb{K})$ of graded \mathbb{K} -modules.

We say that a direct system $\{M_k\}_{k \in \mathbb{N}}$ in \mathbf{M} is *eventually stationary* if $\mu_k : M_k \rightarrow M_{k+1}$ are isomorphisms for large k . Similarly we can talk about an eventually stationary inverse system. The limit of an eventually stationary system (direct or inverse) always exists: it is M_k for large enough k .

Proposition 11.1.7.

- (1) *Let $\{M_k\}_{k \in \mathbb{N}}$ be a direct system in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$. Assume that for each i the direct system $\{M_k^i\}_{k \in \mathbb{N}}$ in \mathbf{M} is eventually stationary. Then the direct limit*

$M = \lim_{k \rightarrow} M_k$ exists in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, the direct limit $\lim_{k \rightarrow} \mathbf{H}(M_k)$ exists in $\mathbf{G}^0(\mathbf{M})$, and the canonical morphism

$$\lim_{k \rightarrow} \mathbf{H}(M_k) \rightarrow \mathbf{H}(M)$$

in $\mathbf{G}^0(\mathbf{M})$ is an isomorphism.

- (2) Let $\{M_k\}_{k \in \mathbb{N}}$ be an inverse system in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. Assume that for each i the inverse system $\{M_k^i\}_{k \in \mathbb{N}}$ in \mathbf{M} is eventually stationary. Then the inverse limit $M = \lim_{\leftarrow k} M_k$ exists in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, the inverse limit $\lim_{\leftarrow k} \mathbf{H}(M_k)$ exists in $\mathbf{G}^0(\mathbf{M})$, and the canonical morphism

$$\mathbf{H}(M) \rightarrow \lim_{\leftarrow k} \mathbf{H}(M_k)$$

in $\mathbf{G}^0(\mathbf{M})$ is an isomorphism.

Proof. (1) As mentioned above, for each i the limit $M^i = \lim_{k \rightarrow} M_k^i$ exists in \mathbf{M} . By Proposition 11.1.6 the limit $M = \lim_{k \rightarrow} M_k$ exists in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$.

Regarding the cohomology: fix an integer i . Take k large enough such that $M_k^{i'} \rightarrow M_{k'}^{i'}$ are isomorphisms for all $k \leq k'$ and $i-1 \leq i' \leq i+1$. Then $M_k^{i'} \rightarrow M_{k'}^{i'}$ are isomorphisms in this range, and therefore $\mathbf{H}^i(M_{k'}) \rightarrow \mathbf{H}^i(M)$ are isomorphisms for all $k \leq k'$. We see that the direct system $\{\mathbf{H}^i(M_k)\}_{k \in \mathbb{N}}$ is eventually stationary, and its direct limit is $\mathbf{H}^i(M)$.

- (2) The same. □

When we drop the abstract abelian category \mathbf{M} , i.e. when we work with $\mathbf{M} = \text{Mod } \mathbb{K} = \mathbf{M}(\mathbb{K})$ and $\mathbf{C}_{\text{str}}(A, \mathbf{M}) = \mathbf{C}_{\text{str}}(A)$, there is no problem of existence of limits. The next proposition says that furthermore “direct limits are exact” in $\mathbf{C}_{\text{str}}(A)$.

Proposition 11.1.8. *Let $\{M_k\}_{k \in \mathbb{N}}$ be a direct system in $\mathbf{C}_{\text{str}}(A)$. Then the canonical homomorphism*

$$\lim_{k \rightarrow} \mathbf{H}(M_k) \rightarrow \mathbf{H}(M)$$

in $\mathbf{G}^0(\mathbb{K})$ is bijective.

Exercise 11.1.9. Prove Proposition 11.1.8. (Hint: forget the action of A , and work with complexes of abelian groups.)

Exactness of inverse limits tends to be much more complicated than that of direct limits, even for \mathbb{K} -modules. We always have to make some condition on the inverse system to have exactness in the limit.

Definition 11.1.10. Let $(\{M_k\}_{k \in \mathbb{N}}, \{\mu_k\}_{k \in \mathbb{N}})$ be an inverse system in $\mathbf{M}(\mathbb{K})$. For any $l \geq k$ let $M_{l,k} \subseteq M_k$ be the image of the homomorphism

$$\text{id} \circ \mu_k \circ \cdots \circ \mu_{l-1} : M_l \rightarrow M_k.$$

Note that there are inclusions $M_{l+1,k} \subseteq M_{l,k}$, so for fixed k we have an inverse system $\{M_{l,k}\}_{l \geq k}$.

We say that the inverse system $\{M_k\}_{k \in \mathbb{N}}$ has the *Mittag-Leffler* property if for every index k , the inverse system $\{M_{l,k}\}_{l \geq k}$ is eventually stationary.

Example 11.1.11. If the system

$$(\{M_k\}_{k \in \mathbb{N}}, \{\mu_k\}_{k \in \mathbb{N}})$$

satisfies one of the following conditions, then it has the Mittag-Leffler property:

- (a) The system has surjective transitions.
- (b) The system is eventually stationary.
- (c) For any $k \in \mathbb{N}$ there exists some $l \geq k$ such that $M_{l,k} = 0$. This is called the *trivial Mittag-Leffler property*, and one says that the system is *pro-zero*.

Theorem 11.1.12 (Mittag-Leffler Argument). *Let $\{M_k\}_{k \in \mathbb{N}}$ be an inverse system in $\mathbf{C}_{\text{str}}(A)$, with inverse limit $M = \lim_{\leftarrow k} M_k$. Assume the system satisfies these two conditions:*

- (a) *For every $i \in \mathbb{Z}$ the inverse system $\{M_k^i\}_{k \in \mathbb{N}}$ in $\mathbf{M}(\mathbb{K})$ has the Mittag-Leffler property.*
- (b) *For every $i \in \mathbb{Z}$ the inverse system $\{H^i(M_k)\}_{k \in \mathbb{N}}$ in $\mathbf{M}(\mathbb{K})$ has the Mittag-Leffler property.*

Then the canonical homomorphisms

$$H^i(M) \rightarrow \lim_{\leftarrow k} H^i(M_k)$$

are bijective.

Proof. We can forget all about the graded A -module structure, and just view this as an inverse system in $\mathbf{C}_{\text{str}}(\mathbb{Z})$, i.e. and inverse system of complexes of abelian groups. Now this is a special case of [KaSc1, Proposition 1.12.4] or [EGA III, Ch. 0_{III}, Proposition 13.2.3]. \square

The most useful instance of the ML argument is this:

Corollary 11.1.13. *Let $\{M_k\}_{k \in \mathbb{N}}$ be an inverse system in $\mathbf{C}_{\text{str}}(A)$, with inverse limit $M = \lim_{\leftarrow k} M_k$. Assume the system satisfies these two conditions:*

- (a) *For every $i \in \mathbb{Z}$ the inverse system $\{M_k^i\}_{k \in \mathbb{N}}$ has surjective transitions.*
- (b) *For every k the DG module M_k is acyclic.*

Then M is acyclic.

Proof. Conditions (a) and (b) here imply conditions (a) and (b) of Theorem 11.1.12, respectively. \square

Exercise 11.1.14. Prove Corollary 11.1.13 directly, without resorting to Theorem 11.1.12.

Remark 11.1.15. We will not attempt discussing direct or inverse limits in abstract abelian categories. Such definitions do exist (e.g. for a *Grothendieck abelian category*, cf. [KaSc2, Definition 8.3.24]), but this sort of thing is a source of anxiety (and sometimes of errors).

Before going on, it is good to remember the roles of the objects of cocycles and coboundaries. Let $M \in \mathbf{C}(A, \mathbf{M})$. The object of coboundaries $Z(M) \subseteq M$ is defined by

$$Z^i(M) := \text{Ker}(d : M^i \rightarrow M^{i+1}).$$

The object of cocycles $B(M) \subseteq M$ is defined by

$$B^i(M) := \text{Im}(d : M^{i-1} \rightarrow M^i).$$

Note that $Z(A)$ is a DG ring with trivial differential, and the objects $Z(M)$ and $B(M)$ live in $\mathbf{C}(Z(A), \mathbf{M})$, with trivial differentials too. There are exact sequences

$$(11.1.16) \quad 0 \rightarrow Z(M) \rightarrow M \xrightarrow{d} T(B(M)) \rightarrow 0$$

and

$$(11.1.17) \quad 0 \rightarrow B(M) \rightarrow Z(M) \rightarrow H(M) \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(\mathbf{Z}(A), \mathbf{M})$.

11.2. K-Projective Resolutions in $\mathbf{C}^-(\mathbf{M})$. Recall that \mathbf{M} is some abelian category, and $\mathbf{C}(\mathbf{M})$ is the DG category of complexes in \mathbf{M} . The strict category $\mathbf{C}_{\text{str}}(\mathbf{M})$ is abelian.

A *filtration* on a complex $M \in \mathbf{C}_{\text{str}}(\mathbf{M})$ is a collection $\{F_j(M)\}_{j \geq -1}$ of subobjects of M , such that $F_j(M) \subseteq F_{j+1}(M)$. This is a particular kind of direct system in $\mathbf{C}_{\text{str}}(\mathbf{M})$. We say that $M = \lim_{j \rightarrow} F_j(M)$ if this limit exists in $\mathbf{C}_{\text{str}}(\mathbf{M})$, and the canonical morphism $\lim_{j \rightarrow} F_j(M) \rightarrow M$ is an isomorphism. There are also the subquotients

$$(11.2.1) \quad \text{gr}_j^F(M) := F_j(M)/F_{j-1}(M) \in \mathbf{C}_{\text{str}}(\mathbf{M})$$

for $j \geq 0$. Sometimes we will be interested in filtrations that have finite length, by which we mean a direct system of subobjects $\{F_j(M)\}_{-1 \leq j \leq k}$ for some $k < \infty$. In this case $\text{gr}_j^F(M)$ is defined only for $0 \leq j \leq k$.

The next definition is inspired by the work of Keller [Kel, Section 3.1].

Definition 11.2.2. Let P be an object of $\mathbf{C}(\mathbf{M})$.

- (1) A *semi-projective filtration* on P is a filtration $F = \{F_j(P)\}_{j \geq -1}$ on P as an object of $\mathbf{C}_{\text{str}}(\mathbf{M})$, such that:
 - $F_{-1}(P) = 0$.
 - Each $\text{gr}_j^F(P)$ is a complex of projective objects of \mathbf{M} with zero differential.
 - $P = \lim_{j \rightarrow} F_j(P)$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$.
- (2) The complex P is called a *semi-projective complex* if it admits some semi-projective filtration.

Theorem 11.2.3. *Let \mathbf{M} be an abelian category, and let P be a semi-projective complex in $\mathbf{C}(\mathbf{M})$. Then P is K-projective.*

Proof. Step 1. We start by proving that if $P = T^k(Q)$, the translation of a projective object $Q \in \mathbf{M}$, then P is K-projective. This is easy: given an acyclic complex $N \in \mathbf{C}(\mathbf{M})$, we have

$$\text{Hom}_{\mathbf{M}}(P, N) = \text{Hom}_{\mathbf{M}}(T^k(Q), N) \cong T^{-k}(\text{Hom}_{\mathbf{M}}(Q, N))$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$. But $\text{Hom}_{\mathbf{M}}(Q, -)$ is an exact functor $\mathbf{M} \rightarrow \mathbf{M}(\mathbb{K})$, so $\text{Hom}_{\mathbf{M}}(Q, N)$ is an acyclic complex.

Step 2. Now P is a complex of projective objects of \mathbf{M} with zero differential. This means that

$$P \cong \bigoplus_{k \in \mathbb{Z}} T^k(Q_k)$$

in $\mathbf{C}_{\text{str}}(\mathbf{M})$, where each Q_k is a projective object in \mathbf{M} . But then

$$\text{Hom}_{\mathbf{M}}(P, N) \cong \prod_{k \in \mathbb{Z}} \text{Hom}_{\mathbf{M}}(T^k(Q_k), N).$$

This is an easy case of Proposition 11.1.3. By step 1 and the fact that a product of acyclic complexes in $\mathbf{C}_{\text{str}}(\mathbb{K})$ is acyclic (itself an easy case of the Mittag-Leffler argument), we conclude that $\text{Hom}_{\mathbf{M}}(P, N)$ is acyclic.

Step 3. Fix a semi-projective filtration $F = \{F_j(P)\}_{j \geq -1}$ on P . Here we prove that for every j the complex $F_j(P)$ is \mathbf{K} -projective. This is done by induction on $j \geq -1$. For $j = -1$ it is trivial. For $j \geq 0$ there is an exact sequence of complexes

$$(11.2.4) \quad 0 \rightarrow F_{j-1}(P) \rightarrow F_j(P) \rightarrow \mathrm{gr}_j^F(P) \rightarrow 0$$

in $\mathbf{C}(\mathbf{M})$. In each degree $i \in \mathbb{Z}$ the exact sequence

$$0 \rightarrow F_{j-1}(P)^i \rightarrow F_j(P)^i \rightarrow \mathrm{gr}_j^F(P)^i \rightarrow 0$$

in \mathbf{M} splits, because $\mathrm{gr}_j^F(P)^i$ is a projective object. Thus the exact sequence (11.2.4) is split exact in the abelian category $\mathbf{G}^0(\mathbf{M})$ of graded objects in \mathbf{M} .

Let $N \in \mathbf{C}(\mathbf{M})$ be an acyclic complex. Applying the functor $\mathrm{Hom}_{\mathbf{M}}(-, N)$ to the sequence of complexes (11.2.4) we obtain a sequence

$$(11.2.5) \quad 0 \rightarrow \mathrm{Hom}_{\mathbf{M}}(\mathrm{gr}_j^F(P), N) \rightarrow \mathrm{Hom}_{\mathbf{M}}(F_j(P), N) \rightarrow \mathrm{Hom}_{\mathbf{M}}(F_{j-1}(P), N) \rightarrow 0$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. Because (11.2.4) is split exact in $\mathbf{G}^0(\mathbf{M})$, the sequence (11.2.5) is split exact in $\mathbf{G}^0(\mathbb{K})$. Therefore (11.2.5) is exact in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$.

By the induction hypothesis the complex $\mathrm{Hom}_{\mathbf{M}}(F_{j-1}(P), N)$ is acyclic. By step 1 the complex $\mathrm{Hom}_{\mathbf{M}}(\mathrm{gr}_j^F(P), N)$ is acyclic. The long exact cohomology sequence associated to (11.2.5) shows that the complex $\mathrm{Hom}_{\mathbf{M}}(F_j(P), N)$ is acyclic too.

Step 4. We keep the semi-projective filtration $F = \{F_j(P)\}_{j \geq -1}$ from step 3. Take any acyclic complex $N \in \mathbf{C}(\mathbf{M})$. By Proposition 11.1.3 we know that

$$\mathrm{Hom}_{\mathbf{M}}(P, N) \cong \varprojlim_{\leftarrow j} \mathrm{Hom}_{\mathbf{M}}(F_j(P), N)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. According to step 3 the complexes $\mathrm{Hom}_{\mathbf{M}}(F_j(P), N)$ are all acyclic. The exactness of the sequences (11.2.5) implies that the inverse system

$$\{\mathrm{Hom}_{\mathbf{M}}(F_j(P), N)\}_{j \geq -1}$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$ has surjective transitions. Now the Mittag-Leffler argument (Corollary 11.1.13) says that the inverse limit complex $\mathrm{Hom}_{\mathbf{M}}(P, N)$ is acyclic. \square

Proposition 11.2.6. *Let \mathbf{M} be an abelian category. If $P \in \mathbf{C}(\mathbf{M})$ is a bounded above complex of projectives, then P is a semi-projective complex.*

Proof. Say P is nonzero and $\mathrm{sup}(P) = i_1 \in \mathbb{Z}$. For $j \geq -1$ define

$$F_j(P) := (\cdots \rightarrow 0 \rightarrow P^{i_1-j} \rightarrow \cdots \rightarrow P^{i_1-1} \rightarrow P^{i_1} \rightarrow \cdots) \subseteq P.$$

Then $\{F_j(P)\}_{j \geq -1}$ is a semi-projective filtration on P . \square

The next theorem is dual to [RD, Lemma 4.6(1)], in the sense of changing injectives to projectives. (See Theorem 11.4.7 for the injective case.) We give a much more detailed proof.

Theorem 11.2.7. *Let \mathbf{M} be an abelian category with enough projectives. Any complex $M \in \mathbf{C}^-(\mathbf{M})$ admits a quasi-isomorphism $\rho : P \rightarrow M$ in $\mathbf{C}_{\mathrm{str}}^-(\mathbf{M})$, where P is a bounded above complex of projectives.*

Proof. After translating M , we can assume that $M^i = 0$ for all $i > 0$. The differential of the complex M is $d_M^i : M^i \rightarrow M^{i+1}$.

We start by choosing an epimorphism $\rho^0 : P^0 \rightarrow M^0$ in \mathcal{M} from some projective object P^0 . We get a morphism

$$\delta^0 : M^{-1} \oplus P^0 \rightarrow M^0$$

whose components are d_M^{-1} and ρ^0 . Next we choose an epimorphism

$$\psi^{-1} : P^{-1} \rightarrow \text{Ker}(\delta^0)$$

from some projective object P^{-1} . So there is an exact sequence

$$P^{-1} \xrightarrow{\psi^{-1}} M^{-1} \oplus P^0 \xrightarrow{\delta^0} M^0 \rightarrow 0.$$

The components of ψ^{-1} are denoted by $\rho^{-1} : P^{-1} \rightarrow M^{-1}$ and $d_P^{-1} : P^{-1} \rightarrow P^0$.

Now to the inductive step. Here $i \leq -1$, and we already have objects P^i, \dots, P^0 , and morphisms ρ^i, \dots, ρ^0 and d_P^i, \dots, d_P^0 , that fit into this diagram

$$(11.2.8) \quad \begin{array}{ccccccc} P^i & \xrightarrow{d_P^i} & P^{i+1} & \longrightarrow & \dots & \xrightarrow{d_P^0} & P^0 & \longrightarrow & 0 \\ & & \downarrow \rho^i & & & & \downarrow \rho^0 & & \\ & & M^i & \xrightarrow{d_M^i} & M^{i+1} & \longrightarrow & \dots & \xrightarrow{d_M^0} & M^0 & \longrightarrow & 0 \end{array}$$

in \mathcal{M} . We still did not prove this diagram is commutative.

Define the morphism

$$\delta^i : M^{i-1} \oplus P^i \rightarrow M^i \oplus P^{i+1}$$

to be the one with components $-d_M^{i-1}$, ρ^i and d_P^i . Expressing direct sums of objects as columns, and letting matrices of morphisms act on them from the left, we have this representation of δ^i :

$$(11.2.9) \quad \delta^i = \begin{bmatrix} -d_M^{i-1} & \rho^i \\ 0 & d_P^i \end{bmatrix}.$$

Let us choose an epimorphism

$$\psi^{i-1} : P^{i-1} \rightarrow \text{Ker}(\delta^i)$$

from a projective object P^{i-1} . We get an exact sequence

$$(11.2.10) \quad P^{i-1} \xrightarrow{\psi^{i-1}} M^{i-1} \oplus P^i \xrightarrow{\delta^i} M^i \oplus P^{i+1}.$$

The components of the morphism ψ^{i-1} are denoted by $\rho^{i-1} : P^{i-1} \rightarrow M^{i-1}$ and $d_P^{i-1} : P^{i-1} \rightarrow P^i$. In a matrix representation:

$$\psi^{i-1} = \begin{bmatrix} \rho^{i-1} \\ d_P^{i-1} \end{bmatrix}.$$

In this way we obtain the slightly bigger diagram

$$(11.2.11) \quad \begin{array}{ccccccc} P^{i-1} & \xrightarrow{d_P^{i-1}} & P^i & \xrightarrow{d_P^i} & P^{i+1} & \longrightarrow & \dots & \longrightarrow & P^0 & \longrightarrow & 0 \\ & & \downarrow \rho^{i-1} & & \downarrow \rho^i & & & & \downarrow \rho^0 & & \\ & & M^{i-1} & \xrightarrow{d_M^{i-1}} & M^i & \xrightarrow{d_M^i} & M^{i+1} & \longrightarrow & \dots & \longrightarrow & M^0 & \longrightarrow & 0 \end{array}$$

We carry out this construction inductively for all $i \leq -1$, thus obtaining a diagram like (11.2.11) that goes infinitely to the left.

Because $\delta^i \circ \psi^{i-1} = 0$ in (11.2.10), it follows that $d_P^i \circ d_P^{i-1} = 0$. Letting $P^i := 0$ for positive i , the collection $P := \{P^i\}_{i \in \mathbb{Z}}$ becomes a complex, with differential $d_P := \{d_P^i\}_{i \in \mathbb{Z}}$. The equality $\delta^i \circ \psi^{i-1} = 0$ also implies that

$$(11.2.12) \quad \rho^i \circ d_P^{i-1} = d_M^{i-1} \circ \rho^{i-1},$$

so the collection $\rho := \{\rho^i\}_{i \in \mathbb{Z}}$ is a strict morphism of complexes $\rho : P \rightarrow M$.

Let us examine this commutative diagram:

$$(11.2.13) \quad \begin{array}{ccccc} P^{i-1} & \xrightarrow{\psi^{i-1}} & M^{i-1} \oplus P^i & \xrightarrow{\delta^i} & M^i \oplus P^{i+1} \\ \downarrow (0, \text{id}) & & \downarrow \text{id} & & \downarrow \text{id} \\ M^{i-2} \oplus P^{i-1} & \xrightarrow{\delta^{i-1}} & M^{i-1} \oplus P^i & \xrightarrow{\delta^i} & M^i \oplus P^{i+1} \end{array}$$

The top row is exact, because it is (11.2.10). An easy calculation using (11.2.12) shows that $\delta^i \circ \delta^{i-1} = 0$. These two facts combine prove that the bottom row is also exact.

Let $N = \{N^i\}_{i \in \mathbb{Z}}$ be the complex with components $N^i := M^{i-1} \oplus P^i$ for $i \leq -1$, $N^0 := M^0$ and $N^i := 0$ for $i > 0$. The differential $d_N = \{d_N^i\}_{i \in \mathbb{Z}}$ is

$$d_N^i := \delta^i : N^i \rightarrow N^{i+1}.$$

As we saw in the paragraph above, the complex N is acyclic. On the other hand, by the definition of the morphisms δ^i in (11.2.9), we see that N is just the standard cone on the strict morphism of complexes

$$T^{-1}(\rho) : T^{-1}(P) \rightarrow T^{-1}(M).$$

See Definition 4.2.1. Therefore ρ is a quasi-isomorphism. \square

Corollary 11.2.14. *If \mathbf{M} is an abelian category with enough projectives, then $\mathbf{C}^-(\mathbf{M})$ has enough K -projectives.*

Proof. Combine Theorem 11.2.7, Proposition 11.2.6 and Theorem 11.2.3. \square

For a graded object $N \in \mathbf{G}(\mathbf{M})$ we let

$$(11.2.15) \quad \text{sup}(N) := \sup \{i \mid N^i \neq 0\} \subseteq \mathbb{Z} \cup \{\pm\infty\}.$$

Note that $\text{sup}(N) = -\infty$ if and only if $N = 0$.

Corollary 11.2.16. *Let \mathbf{M} be an abelian category with enough projectives, and let $M \in \mathbf{C}(\mathbf{M})$ be a complex with bounded above cohomology. Then M has a K -projective resolution $P \rightarrow M$ with $\text{sup}(P) = \text{sup}(\mathbf{H}(M))$.*

Proof. We may assume that $\mathbf{H}(M)$ is not zero. Let $i := \text{sup}(\mathbf{H}(M)) \in \mathbb{Z}$, and take $N := \text{smt}^{\leq i}(M)$, the smart truncation from formula (8.3.6). Then $N \rightarrow M$ is a quasi-isomorphism and $\text{sup}(N) = i$. An inspection of the proof of Theorem 11.2.7 shows that the resolution $P \rightarrow N$ can be made with $\text{sup}(P) = i$. The composed quasi-isomorphism $P \rightarrow M$ has the desired properties. \square

Remark 11.2.17. Let \mathbf{M} be an abelian category, and let $\mathbf{N} \subseteq \mathbf{M}$ be a thick abelian subcategory. Assume that \mathbf{N} has enough \mathbf{M} -projectives, namely any object $N \in \mathbf{N}$ admits an epimorphism $P \twoheadrightarrow N$ where $P \in \mathbf{N}$ and it is projective as an object of \mathbf{M} . Suppose $M \in \mathbf{C}(\mathbf{M})$ is a complex satisfying these conditions: $H^i(M) \in \mathbf{N}$ for all i , and $H^i(M) = 0$ for $i \gg 0$. Then there is a quasi-isomorphism $P \rightarrow M$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$, where the P^i are objects of \mathbf{N} that are projective as objects of \mathbf{M} , and $\text{sup}(P) = \text{sup}(H(M))$. See [RD, Lemma I.4.6(3)] for the reverse statement (with injectives). We will prove a slightly less general result for noetherian rings in Example 11.3.33.

11.3. K-Projective Resolutions in $\mathbf{C}(A)$. In this subsection A is a DG ring (without any vanishing assumption).

Recall that the translation $T^{-i}(A)$ is a DG A -module in which the element $t^{-i}(1)$ is in degree i . This element is a cocycle, and when we forget the differentials, the graded module $T^{-i}(A)^\natural$ is free over the graded ring A^\natural , with basis $t^{-i}(1)$. Therefore, for any DG A -module M there is a canonical isomorphism

$$(11.3.1) \quad \text{Hom}_A(T^{-i}(A), M) \cong T^i(M)$$

in $\mathbf{C}(\mathbb{K})$, and canonical isomorphisms

$$(11.3.2) \quad \text{Hom}_{\mathbf{C}_{\text{str}}(A)}(T^{-i}(A), M) \cong Z^0(\text{Hom}_A(T^{-i}(A), M)) \cong Z^i(M)$$

in $\mathbf{M}(\mathbb{K})$. (Actually, (11.3.1) is an isomorphism in $\mathbf{C}_{\text{str}}(A)$, but this uses the DG A -bimodule structure of $T^{-i}(A)$.)

We begin with a definition that is very similar to Definition 11.2.2. Recall the notion of a filtration $F = \{F_j(P)\}_{j \geq -1}$ of a DG module P , and the associated subquotients $\text{gr}_j^F(P)$ from formula (11.2.1).

Definition 11.3.3. Let P be an object of $\mathbf{C}(A)$.

- (1) We say that P is a *free DG A -module* if there is an isomorphism

$$P \cong \bigoplus_{s \in S} T^{-i_s}(A)$$

in $\mathbf{C}_{\text{str}}(A)$, for some indexing set S and some collection of integers $\{i_s\}_{s \in S}$.

- (2) A *semi-free filtration* on P is a filtration $F = \{F_j(P)\}_{j \geq -1}$ of P in $\mathbf{C}_{\text{str}}(A)$, such that:

- $F_{-1}(P) = 0$.
- Each $\text{gr}_j^F(P)$ is a free DG A -module.
- $P = \bigcup_j F_j(P)$.

- (3) The DG module P is called *semi-free* if it admits some semi-free filtration.

Example 11.3.4. If A is a ring, then a free DG A -module P is a complex of free A -modules with zero differential. A semi-free DG A -module P is also a complex of free A -modules, but there is a differential on it, and there is a subtle condition on P imposed by the existence of a semi-free filtration. If the complex P happens to be bounded above, then it is automatically semi-free, with a filtration like the one in the proof of Proposition 11.2.6.

Exercise 11.3.5. Find a ring A , and a complex P of free A -modules, that is not semi-free. (Hint: Take the ring $A = \mathbb{K}[\epsilon]$ of dual numbers. Find a complex of free A -modules P that is acyclic but not null-homotopic. Now use Theorem 11.3.6 and Corollary 10.2.12 to get a contradiction.)

Theorem 11.3.6. *Let P be an object of $\mathbf{C}(A)$. If P is semi-free, then it is K -projective.*

Proof. It is similar to the proof of Theorem 11.2.3.

Step 1. We start by proving that if $P = T^{-i}(A)$, a translation of A , then P is K -projective. This is easy: given an acyclic $N \in \mathbf{C}(A)$, we have

$$\mathrm{Hom}_A(P, N) = \mathrm{Hom}_A(T^{-i}(A), N) \cong T^i(\mathrm{Hom}_A(A, N)) \cong T^i(N)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$, and this is acyclic.

Step 2. Now

$$P \cong \bigoplus_{s \in S} T^{-i_s}(A).$$

Then

$$\mathrm{Hom}_A(P, N) \cong \prod_{s \in S} \mathrm{Hom}_A(T^{-i_s}(A), N).$$

By step 1 and the fact that a product of acyclic complexes in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$ is acyclic, we conclude that $\mathrm{Hom}_M(P, N)$ is acyclic.

Step 3. Fix a semi-free filtration $F = \{F_j(P)\}_{j \geq -1}$ of P . Here we prove that for every $j \geq -1$ the DG module $F_j(P)$ is K -projective. This is done by induction on $j \geq -1$. For $j = -1$ it is trivial. For $j \geq 0$ there is an exact sequence

$$(11.3.7) \quad 0 \rightarrow F_{j-1}(P) \rightarrow F_j(P) \rightarrow \mathrm{gr}_j^F(P) \rightarrow 0$$

in the abelian category $\mathbf{C}_{\mathrm{str}}(A)$. Because $\mathrm{gr}_j^F(P)$ is a free DG module, it is a projective object in the abelian category $\mathbf{G}^0(A^\natural)$ of graded modules over the graded ring A^\natural , gotten by forgetting the differential of A . Therefore the sequence (11.3.7) is split exact in $\mathbf{G}^0(A^\natural)$.

Let $N \in \mathbf{C}(A)$ be an acyclic DG module. Applying the functor $\mathrm{Hom}_A(-, N)$ to the sequence (11.3.7) we obtain a sequence

$$(11.3.8) \quad 0 \rightarrow \mathrm{Hom}_A(\mathrm{gr}_j^F(P), N) \rightarrow \mathrm{Hom}_A(F_j(P), N) \rightarrow \mathrm{Hom}_A(F_{j-1}(P), N) \rightarrow 0$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. If we forget differentials this is a sequence in $\mathbf{G}^0(\mathbb{K})$. Because (11.3.7) is split exact in $\mathbf{G}^0(A^\natural)$, it follows that (11.3.8) is split exact in $\mathbf{G}^0(\mathbb{K})$. Therefore (11.3.8) is exact in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$.

By the induction hypothesis the DG \mathbb{K} -module $\mathrm{Hom}_A(F_{j-1}(P), N)$ is acyclic. By step 2 the DG module $\mathrm{Hom}_A(\mathrm{gr}_j^F(P), N)$ is acyclic. The long exact cohomology sequence associated to (11.3.8) shows that the DG module $\mathrm{Hom}_A(F_j(P), N)$ is acyclic too.

Step 4. We keep the semi-free filtration $F = \{F_j(P)\}_{j \geq -1}$ from step 3. Take any acyclic $N \in \mathbf{C}(M)$. By Proposition 11.1.3 we know that

$$\mathrm{Hom}_A(P, N) \cong \varprojlim_j \mathrm{Hom}_A(F_j(P), N)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. According to step 3 the complexes $\mathrm{Hom}_A(F_j(P), N)$ are all acyclic. The exactness of the sequences (11.3.8) implies that the inverse system

$$\{\mathrm{Hom}_A(F_j(P), N)\}_{j \geq -1}$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$ has surjective transitions. Now the Mittag-Leffler argument (Corollary 11.1.13) says that the inverse limit complex $\mathrm{Hom}_A(P, N)$ is acyclic. \square

Here is a result similar to Theorem 11.2.7.

Theorem 11.3.9. *Let A be a DG ring. Any $M \in \mathbf{C}(A)$ admits a quasi-isomorphism $\rho : P \rightarrow M$ in $\mathbf{C}_{\text{str}}(A)$ from a semi-free DG A -module P .*

Proof. Step 1. In this step we construct a free DG A -module $F_0(P)$ and a homomorphism $F_0(\rho) : F_0(P) \rightarrow M$. For any $i \in \mathbb{Z}$ the cohomology $H^i(M)$ is an $H^0(A)$ -module. Choose a collection of $H^0(A)$ -module generators of $H^i(M)$, indexed by a set S_0^i . There is a canonical surjection $Z^i(M) \rightarrow H^i(M)$, and we lift these generators to a collection $\{m_s\}_{s \in S_0^i}$ of elements of $Z^i(M)$. Define the free DG A -module

$$(11.3.10) \quad Q_0^i := \bigoplus_{s \in S_0^i} T^{-i}(A).$$

The collection $\{m_s\}_{s \in S_0^i}$ induces a homomorphism

$$(11.3.11) \quad \phi_0^i : Q_0^i \rightarrow M$$

in $\mathbf{C}_{\text{str}}(A)$, as in formula (11.3.2). Define the free DG A -module

$$(11.3.12) \quad F_0(P) := \bigoplus_{i \in \mathbb{Z}} Q_0^i,$$

and let

$$(11.3.13) \quad F_0(\rho) : F_0(P) \rightarrow M, \quad F_0(\rho) := \sum_i \phi_0^i$$

be the resulting homomorphism in $\mathbf{C}_{\text{str}}(A)$. By construction we see that

$$(11.3.14) \quad H^i(F_0(\rho)) : H^i(F_0(P)) \rightarrow H^i(M)$$

is surjective for all i .

Step 2. In this step $j \geq 0$, and we are given the following: a DG A -module $F_j(P)$, a homomorphism $F_j(\rho) : F_j(P) \rightarrow M$ in $\mathbf{C}_{\text{str}}(A)$, and a filtration $\{F_{j'}(P)\}_{-1 \leq j' \leq j}$ of $F_j(P)$. These satisfy the following conditions: for all i and all $0 \leq j' \leq j$ the homomorphisms

$$(11.3.15) \quad H^i(F_j(\rho)) : H^i(F_{j'}(P)) \rightarrow H^i(M)$$

are surjective; $F_{-1}(P) = 0$; and the DG A -modules $\text{gr}_{j'}^F(P)$ are free for all $0 \leq j' \leq j$.

For any $i \in \mathbb{Z}$ let K_j^i be the kernel of $H^i(F_j(\rho))$. So there is a short exact sequence

$$(11.3.16) \quad 0 \rightarrow K_j^i \rightarrow H^i(F_j(P)) \xrightarrow{H^i(F_j(\rho))} H^i(M) \rightarrow 0$$

in $\mathbf{M}(H^0(A))$. Choose a collection of $H^0(A)$ -module generators of K_j^i , indexed by a set S_{j+1}^i . Using the canonical surjection $Z^i(F_j(P)) \rightarrow H^i(F_j(P))$, lift these generators to a collection $\{p_s\}_{s \in S_{j+1}^i}$ of elements of the module of cocycles $Z^i(F_j(P))$. Define the free DG A -module

$$(11.3.17) \quad Q_{j+1}^i := \bigoplus_{s \in S_{j+1}^i} T^{-i}(A).$$

The collection of cocycles $\{p_s\}_{s \in S_{j+1}^i}$ induces a homomorphism

$$(11.3.18) \quad \phi_{j+1}^i : Q_{j+1}^i \rightarrow F_j(P)$$

in $\mathbf{C}_{\text{str}}(A)$. Next define the free DG A -module

$$(11.3.19) \quad Q_{j+1} := \bigoplus_{i \in \mathbb{Z}} Q_{j+1}^i$$

and the homomorphism

$$(11.3.20) \quad \phi_{j+1} : Q_{j+1} \rightarrow F_j(P), \quad \phi_{j+1} := \sum_i \phi_{j+1}^i$$

in $\mathbf{C}_{\text{str}}(A)$.

Now let us define the DG A -module $F_{j+1}(P)$ by attaching Q_{j+1} to $F_j(P)$ along ϕ_{j+1} . Namely, as a graded module we let

$$(11.3.21) \quad F_{j+1}(P)^\natural := F_j(P)^\natural \oplus \mathbb{T}(Q_{j+1})^\natural,$$

and the differential is

$$d_{F_{j+1}(P)} := d_{F_j(P)} + d_{\mathbb{T}(Q_{j+1})} + \phi_{j+1} \circ t^{-1}.$$

In other words, $F_{j+1}(P)$ is the standard cone on the strict homomorphism ϕ_{j+1} ; see Definition 4.2.1. We note that the basis of the free DG module Q_{j+1}^i sits inside $F_{j+1}(P)^{i-1}$.

By construction, $F_j(P)$ is a DG submodule of $F_{j+1}(P)$. Let us denote the inclusion by

$$\mu_j : F_j(P) \hookrightarrow F_{j+1}(P).$$

Because the cocycles in $F_j(P)$ representing K_j^i become coboundaries in $F_{j+1}(P)$, it follows that for any i we have

$$(11.3.22) \quad K_j^i \subseteq \text{Ker}(\mathbb{H}^i(\mu_j) : \mathbb{H}^i(F_j(P)) \rightarrow \mathbb{H}^i(F_{j+1}(P))).$$

Step 3. In this step we construct the homomorphism $F_{j+1}(\rho)$, continuing from where we left off in step 2. Consider the element $p_s \in Z^i(F_j(P))$ for some index $s \in S_{j+1}^i$. Because the cohomology class of p_s is in K_j^i , the element $F_j(\rho)(p_s) \in M^i$ is a coboundary. Therefore we can find an element $m_s \in M^{i-1}$ such that $F_j(\rho)(p_s) = d_M(m_s)$. From (11.3.19) we see that the collection of elements $\{m_s\}_{s \in \coprod_i S_{j+1}^i}$ induces a strict homomorphism of DG modules

$$\rho'_{j+1} : \mathbb{T}(Q_{j+1}) \rightarrow M.$$

Define the homomorphism

$$F_{j+1}(\rho) : F_{j+1}(P) \rightarrow M$$

to be

$$F_{j+1}(\rho) := F_j(\rho) + \rho'_{j+1}$$

using the direct sum decomposition (11.3.21). It is easy to check that this is a strict homomorphism of DG modules.

Step 4. After going through steps 2 and 3 inductively, we now have a direct system $\{F_j(P)\}_{j \geq -1}$ in $\mathbf{C}_{\text{str}}(A)$, and a direct system of homomorphisms $F_j(\rho) : F_j(P) \rightarrow M$. Define the DG A -module

$$P := \lim_{j \rightarrow} F_j(P)$$

and the homomorphism

$$\rho := \lim_{j \rightarrow} F_j(\rho) : P \rightarrow M$$

in $\mathbf{C}_{\text{str}}(A)$. The DG module P has on it the filtration $\{F_j(P)\}$, and it is a semi-free filtration. Indeed, there are isomorphisms $\text{gr}_0^F(P) \cong \bigoplus_{i \in \mathbb{Z}} Q_0^i$ and $\text{gr}_{j+1}^F(P) \cong \text{T}(Q_{j+1})$ for $j \geq 0$.

It remains to prove that ρ is a quasi-isomorphism. We know that the homomorphisms $\text{H}^i(F_j(\rho))$ are surjective for all i and all $j \geq 0$. Define

$$L_j^i := \text{Im}(\text{H}^i(\mu_j) : \text{H}^i(F_j(P)) \rightarrow \text{H}^i(F_{j+1}(P))) \subseteq \text{H}^i(F_{j+1}(P)).$$

We get a commutative diagram

$$\begin{array}{ccccccc}
 0 & \longrightarrow & K_j^i & \xrightarrow{\text{inc}} & \text{H}^i(F_j(P)) & \xrightarrow{\text{H}^i(F_j(\rho))} & \text{H}^i(M) \longrightarrow 0 \\
 & & & & \downarrow \alpha_j^i & \nearrow \beta_j^i & \uparrow \\
 & & & & L_j^i & & \\
 & & \text{H}^i(\mu_j) & & \downarrow \text{inc} & & \uparrow \\
 & & & & \text{H}^i(F_{j+1}(P)) & & \text{H}^i(F_{j+1}(\rho))
 \end{array}$$

in $\mathbf{M}(\mathbb{K})$. The top row is an exact sequence (it is (11.3.16)). Because α_j^i is surjective, there is equality

$$\text{Ker}(\beta_j^i) = \alpha_j^i(\text{Ker}(\text{H}^i(F_j(\rho)))) = \alpha_j^i(K_j^i).$$

But by formula (11.3.22) we know that $\alpha_j^i(K_j^i) = 0$. The conclusion is that

$$(11.3.23) \quad \beta_j^i : L_j^i \rightarrow \text{H}^i(M)$$

is an isomorphism. Hence, for every i the direct system $\{L_j^i\}_{j \geq 0}$ has a limit, and the homomorphism

$$(11.3.24) \quad \lim_{j \rightarrow} L_j^i \rightarrow \text{H}^i(M)$$

is bijective. Now the direct systems $\{L_j^i\}_{j \geq 0}$ and $\{\text{H}^i(F_j(P))\}_{j \geq 0}$ are sandwiched; so by Proposition 11.1.1(1) we know that the second direct system also has a limit, and the canonical homomorphism

$$(11.3.25) \quad \lim_{j \rightarrow} \text{H}^i(F_j(P)) \rightarrow \lim_{j \rightarrow} L_j^i$$

is bijective. Finally, according to Proposition 11.1.7 we know that the canonical homomorphism

$$(11.3.26) \quad \lim_{j \rightarrow} \text{H}^i(F_j(P)) \rightarrow \text{H}^i(P)$$

is bijective. The combination of the bijections (11.3.24), (11.3.25) and (11.3.26) implies that

$$\text{H}^i(\rho) : \text{H}^i(P) \rightarrow \text{H}^i(M)$$

is bijective. □

Corollary 11.3.27. *Let A be any DG ring. The category $\mathbf{C}(A)$ has enough K-projectives.*

Proof. Combine Theorems 11.3.6 and 11.3.9. \square

The concept of nonpositive DG ring was introduced in Definition 8.3.11.

Corollary 11.3.28. *Assume A is a nonpositive DG ring. For any $M \in \mathbf{C}(A)$ there is a K -projective resolution $P \rightarrow M$ with $\sup(P) = \sup(\mathbf{H}(M))$.*

Proof. If $\mathbf{H}(M)$ is unbounded above or zero, the assertion is trivial. So we may assume that $i_1 := \sup(\mathbf{H}(M))$ is an integer. In steps 1 and 2 of the proof of Theorem 11.3.9 we choose the indexing sets S_j^i to be empty whenever this is possible. Namely $S_0^i = \emptyset$ when $\mathbf{H}^i(M) = 0$, and $S_{j+1}^i = \emptyset$ when $K_j^i = 0$. We claim that with these choices, the inductive construction will satisfy the following extra condition: the homomorphisms

$$(11.3.29) \quad \mathbf{H}^i(F_j(\rho)) : \mathbf{H}^i(F_j(P)) \rightarrow \mathbf{H}^i(M)$$

are bijective for all $i \geq i_1 + 1 - j$. This in turn implies that $K_j^i = 0$ for all $i \geq i_1 + 1 - j$. We see that $K_j^i = 0$ and $\mathbf{H}^i(M) = 0$ for all $i \geq i_1 + 1$. Since A is nonpositive, this says that $\sup(F_j(P)) \leq i_1$. Therefore in the limit we get $\sup(P) \leq i_1$.

Let us prove the claim, by induction on $j \geq 0$. For $j = 0$ this is trivial, because both modules in (11.3.29) vanish for $i \geq 1$. Now assume that $j \geq 0$ and the claim holds. So $K_j^i = 0$ for all $i \geq i_1 + 1 - j$. Then, by formula (11.3.21), the DG module $F_{j+1}(P)$ coincides with its submodule $F_j(P)$ in degrees $\geq i_1 - j$. This implies that these DG modules have the same cohomologies in degrees $\geq i_1 - j + 1$, and the same cocycles in degree $i_1 - j$. Thus the homomorphisms $\mathbf{H}^i(F_{j+1}(\rho))$ remain bijective for $i \geq i_1 - j + 1$. These homomorphisms are surjective for all i . But in $F_{j+1}(P)$ there are new coboundaries in degree $i_1 - j$, those coming from $Q_{j+1}^{i_1-j-1}$. These cocycles cause the homomorphism $\mathbf{H}^{i_1-j}(F_{j+1}(\rho))$ to be injective. So the inductive step is completed. \square

Definition 11.3.30. Let A be a nonpositive DG ring. A DG A -module P is called *pseudo-finite semi-free* if it admits a semi-free filtration $F = \{F_j(P)\}_{j \geq -1}$ satisfying this extra condition: there are $i_1 \in \mathbb{Z}$ and $r_j \in \mathbb{N}$ such that

$$\mathrm{gr}_j^F(P) \cong \mathrm{T}^{-i_1+j}(A)^{\oplus r_j}$$

in $\mathbf{C}_{\mathrm{str}}(A)$ for all j .

Exercise 11.3.31. Let A be a nonpositive DG ring and let P be a DG A -module. Prove that the following two conditions are equivalent.

- (i) P is pseudo-finite semi-free.
- (ii) There are numbers $i_1 \in \mathbb{Z}$ and $r_j \in \mathbb{N}$, and an isomorphism

$$P^{\natural} \cong \bigoplus_{j \geq 0} \mathrm{T}^{-i_1+j}(A^{\natural})^{\oplus r_j}$$

in $\mathbf{G}^0(A^{\natural})$.

In case A is a ring (i.e. $A^i = 0$ for all $i \neq 0$), prove that these conditions are equivalent to:

- (iii) P is a bounded above complex of finitely generated free A -modules.

Corollary 11.3.32. *Assume that A is a nonpositive DG ring, and the ring $\mathbf{H}^0(A)$ is left noetherian. Let M be a DG A -module satisfying these conditions: each $\mathbf{H}^i(M)$ is a finitely generated $\mathbf{H}^0(A)$ -module, and $\mathbf{H}^i(M) = 0$ for $i \gg 0$. Then there is a*

quasi-isomorphism $P \rightarrow M$ in $\mathbf{C}_{\text{str}}(A)$ from a pseudo-finite semi-free DG A -module P with $\text{sup}(P) = \text{sup}(\mathbf{H}(M))$.

Proof. Like in the proof of Corollary 11.3.28, the key to the proof is to economize. Besides the choice of empty indexing sets S_j^i that we imposed there, here we choose all these sets to be finite. This is possible, since the $\mathbf{H}^0(A)$ -modules $\mathbf{H}^i(M)$, $\mathbf{H}^i(F_j(P))$ and K_j^i will all be finitely generated. \square

Example 11.3.33. A special yet very important case of Corollary 11.3.32 is this: A is a left noetherian ring, and M is a complex of A -modules with bounded above cohomology, such that each $\mathbf{H}^i(M)$ is a finitely generated A -module. Then M has a resolution $P \rightarrow M$, where P is a complex of finitely generated free A -modules, and $\text{sup}(P) = \text{sup}(\mathbf{H}(M))$.

11.4. K-Injective Resolutions in $\mathbf{C}^+(\mathbf{M})$. In this subsection \mathbf{M} is an abelian category, and $\mathbf{C}(\mathbf{M})$ is the category of complexes in \mathbf{M} .

In subsection 1.3 we discussed quotients in categories. A *cofiltration* of a complex $I \in \mathbf{C}(\mathbf{M})$ is an inverse system $G = \{G_q(I)\}_{q \geq -1}$ of quotients of I in $\mathbf{C}_{\text{str}}(\mathbf{M})$. We say that $I = \lim_{\leftarrow q} G_q(I)$ if this inverse limit exists in $\mathbf{C}_{\text{str}}(\mathbf{M})$, and the canonical morphism $I \rightarrow \lim_{\leftarrow q} G_q(I)$ is an isomorphism. The cofiltration G gives rise to the subquotients

$$(11.4.1) \quad \text{gr}_q^G(I) := \text{Ker}(G_q(I) \rightarrow G_{q-1}(I)) \in \mathbf{C}(\mathbf{M}).$$

Definition 11.4.2. Let I be a complex in $\mathbf{C}(\mathbf{M})$.

- (1) A *semi-injective cofiltration* on I is a cofiltration $G = \{G_q(I)\}_{q \geq -1}$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$ such that:
 - $G_{-1}(I) = 0$.
 - Each $\text{gr}_q^G(I)$ is a complex of injective objects of \mathbf{M} with zero differential.
 - $I = \lim_{\leftarrow q} G_q(I)$.
- (2) The complex I is called a *semi-injective complex* if it admits some semi-injective cofiltration.

Theorem 11.4.3. *Let \mathbf{M} be an abelian category, and let I be a semi-injective complex in $\mathbf{C}(\mathbf{M})$. Then I is K-injective.*

Proof. The proof is very similar to that of Theorem 11.2.3.

Step 1. We start by proving that if $I = T^p(J)$, the translation of an injective object $J \in \mathbf{M}$, then I is K-injective. This is easy: given an acyclic complex $N \in \mathbf{C}(\mathbf{M})$, we have

$$\text{Hom}_{\mathbf{M}}(N, I) = \text{Hom}_{\mathbf{M}}(N, T^p(J)) \cong T^p(\text{Hom}_{\mathbf{M}}(N, J))$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$. But $\text{Hom}_{\mathbf{M}}(-, J)$ is an exact functor $\mathbf{M} \rightarrow \mathbf{M}(\mathbb{K})$, so $\text{Hom}_{\mathbf{M}}(N, J)$ is an acyclic complex.

Step 2. Now I is a complex of injective objects of \mathbf{M} with zero differential. This means that

$$I \cong \prod_{p \in \mathbb{Z}} T^p(J_p)$$

in $\mathbf{C}_{\text{str}}(\mathbf{M})$, where each J_p is an injective object in \mathbf{M} . But then

$$\text{Hom}_{\mathbf{M}}(N, I) \cong \prod_{p \in \mathbb{Z}} \text{Hom}_{\mathbf{M}}(N, T^p(J_p)).$$

This is an easy case of Proposition 11.1.3(2). By step 1 and the fact that a product of acyclic complexes in $\mathbf{C}_{\text{str}}(\mathbb{K})$ is acyclic (itself an easy case of the Mittag-Leffler argument), we conclude that $\text{Hom}_{\mathbf{M}}(N, I)$ is acyclic.

Step 3. Fix a semi-injective cofiltration $G = \{G_q(I)\}_{q \geq -1}$ of I . Here we prove that for every q the complex $G_q(I)$ is K-injective. This is done by induction on q . For $q = -1$ it is trivial. For $q \geq 0$ there is an exact sequence of complexes

$$(11.4.4) \quad 0 \rightarrow \text{gr}_q^G(I) \rightarrow G_q(I) \rightarrow G_{q-1}(I) \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(\mathbf{M})$. In each degree $p \in \mathbb{Z}$ the exact sequence

$$0 \rightarrow \text{gr}_q^G(I)^p \rightarrow G_q(I)^p \rightarrow G_{q-1}(I)^p \rightarrow 0$$

in \mathbf{M} splits, because $\text{gr}_q^G(I)^p$ is an injective object. Thus the exact sequence (11.4.4) is split in the category $\mathbf{G}^0(\mathbf{M})$ of graded objects in \mathbf{M} .

Let $N \in \mathbf{C}(\mathbf{M})$ be an acyclic complex. Applying the functor $\text{Hom}_{\mathbf{M}}(N, -)$ to the sequence of complexes (11.4.4) we obtain a sequence

$$(11.4.5) \quad 0 \rightarrow \text{Hom}_{\mathbf{M}}(N, \text{gr}_q^G(I)) \rightarrow \text{Hom}_{\mathbf{M}}(N, G_q(I)) \rightarrow \text{Hom}_{\mathbf{M}}(N, G_{q-1}(I)) \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$. Because (11.4.4) is split exact in $\mathbf{G}^0(\mathbf{M})$, the sequence (11.4.5) is split exact in $\mathbf{G}^0(\mathbb{K})$. Therefore (11.4.5) is exact in $\mathbf{C}_{\text{str}}(\mathbb{K})$.

By the induction hypothesis the complex $\text{Hom}_{\mathbf{M}}(N, G_{q-1}(I))$ is acyclic. By step 2 the complex $\text{Hom}_{\mathbf{M}}(N, \text{gr}_q^G(I))$ is acyclic. The long exact cohomology sequence associated to (11.4.5) shows that the complex $\text{Hom}_{\mathbf{M}}(N, G_q(I))$ is acyclic too.

Step 4. We keep the semi-injective cofiltration $G = \{G_q(I)\}_{q \geq -1}$ from step 3. Take any acyclic complex $N \in \mathbf{C}(\mathbf{M})$. By Proposition 11.1.3 we know that

$$\text{Hom}_{\mathbf{M}}(N, I) \cong \varprojlim_{\leftarrow q} \text{Hom}_{\mathbf{M}}(N, G_q(I))$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$. According to step 3 the complexes $\text{Hom}_{\mathbf{M}}(N, G_q(I))$ are all acyclic. The exactness of the sequences (11.4.5) implies that the inverse system

$$\{\text{Hom}_{\mathbf{M}}(N, G_q(I))\}_{q \geq -1}$$

in $\mathbf{C}_{\text{str}}(\mathbb{K})$ has surjective transitions. Now the Mittag-Leffler argument (Corollary 11.1.13) says that the inverse limit complex $\text{Hom}_{\mathbf{M}}(N, I)$ is acyclic. \square

Proposition 11.4.6. *Let \mathbf{M} be an abelian category. If I is a bounded below complex of injectives, then I is a semi-injective complex.*

Proof. We can assume that $I \neq 0$. Let p_0 be an integer such that $I^p = 0$ for all $p < p_0$. For $q \geq -1$ let $F_q(I)$ be the subcomplex of I defined by $F_q(I)^p := I^p$ if $p \geq p_0 + q + 1$, and $F_q(I)^p := 0$ otherwise. Then let $G_q(I) := I/F_q(I)$. The cofiltration $G = \{G_q(I)\}_{q \geq -1}$ is semi-injective. \square

The next theorem is [RD, Lemma 4.6(1)]. See also [KaSc1, Proposition 1.7.7(i)].

Theorem 11.4.7. *Let \mathbf{M} be an abelian category with enough injectives. Any complex $M \in \mathbf{C}^+(\mathbf{M})$ admits a quasi-isomorphism $\rho : M \rightarrow I$ in $\mathbf{C}_{\text{str}}^+(\mathbf{M})$ into a bounded below complex of injectives I .*

Proof. The proof is the same as that of Theorem 11.2.7, except for a mechanical reversal of arrows. This is because of the symmetry of the axioms of abelian categories, that exchanges projective and injective objects. \square

Exercise 11.4.8. Try to write an explicit proof of Theorem 11.4.7. You will see that this requires a lot of patience. It is a bit like trying to write mirror-flipped text (i.e. text that looks normal when reflected in a mirror).

Remark 11.4.9. One must be careful about using the symmetry of the axioms of abelian categories. It is valid for finitary constructions (as in the proof of Theorem 11.4.7); but it might break down for constructions where limits are involved, such as in the proof of Theorem 11.4.3.

Corollary 11.4.10. *If \mathbf{M} is an abelian category with enough injectives, then $\mathbf{C}^+(\mathbf{M})$ has enough K -injectives.*

Proof. Combine Theorems 11.4.7, Proposition 11.4.6 and Theorem 11.4.3. □

For a graded object $N \in \mathbf{G}(\mathbf{M})$ we let

$$(11.4.11) \quad \inf(N) := \inf \{i \mid N^i \neq 0\} \subseteq \mathbb{Z} \cup \{\pm\infty\}.$$

Note that $\inf(N) = \infty$ if and only if $N = 0$.

Corollary 11.4.12. *Let \mathbf{M} be an abelian category with enough injectives, and let $M \in \mathbf{C}(\mathbf{M})$ be a complex with bounded below cohomology. Then M has a K -injective resolution $M \rightarrow I$ with $\inf(I) = \inf(\mathbf{H}(M))$.*

Proof. We may assume that $\mathbf{H}(M)$ is nonzero. Let $p := \inf(\mathbf{H}(M)) \in \mathbb{Z}$, and let $N := \text{smt}^{\geq p}(M)$, the smart truncation from formula 8.3.7. So $M \rightarrow N$ is a quasi-isomorphism. By proof of Theorem 11.2.7 (with sides flipped) we see that there is a K -injective resolution $N \rightarrow I$ with $\inf(I) = \inf(\mathbf{H}(M))$. The composed quasi-isomorphism $M \rightarrow I$ is what we are looking for. □

Remark 11.4.13. Let \mathbf{M} be an abelian category, and let $\mathbf{N} \subseteq \mathbf{M}$ be a thick abelian subcategory. Assume that \mathbf{N} has enough \mathbf{M} -injectives, namely any object $N \in \mathbf{N}$ admits a monomorphism $N \hookrightarrow I$ where $I \in \mathbf{N}$ and it is injective as an object of \mathbf{M} . Suppose $M \in \mathbf{C}(\mathbf{M})$ is a complex satisfying these conditions: $\mathbf{H}^i(M) \in \mathbf{N}$ for all i , and $\mathbf{H}^i(M) = 0$ for $i \ll 0$. Then there is a quasi-isomorphism $M \rightarrow I$ in $\mathbf{C}_{\text{str}}(\mathbf{M})$, where the I^p are objects of \mathbf{N} that are injective as objects of \mathbf{M} , and $\inf(I) = \inf(\mathbf{H}(M))$. See [RD, Lemma I.4.6(3)] for a very sketchy proof.

An important example is this: (X, \mathcal{O}_X) is a noetherian scheme, $\mathbf{M} = \text{Mod } \mathcal{O}_X$ and $\mathbf{N} = \text{QCoh } \mathcal{O}_X$. According to [RD, Proposition II.7.6] the category \mathbf{N} has enough \mathbf{M} -injectives.

11.5. K -Injective Resolutions in $\mathbf{C}(A)$. Recall that we are working over a nonzero commutative base ring \mathbb{K} , and A is a central DG \mathbb{K} -ring.

An *injective cogenerator* of the abelian category $\mathbf{M}(\mathbb{K}) = \text{Mod } \mathbb{K}$ is an injective \mathbb{K} -module \mathbb{K}^* with this property: if M is a nonzero \mathbb{K} -module, then $\text{Hom}_{\mathbb{K}}(M, \mathbb{K}^*)$ is nonzero. These always exist. Here are a few examples.

Example 11.5.1. For any nonzero ring \mathbb{K} there is a canonical choice for an injective cogenerator:

$$\mathbb{K}^* := \text{Hom}_{\mathbb{Z}}(\mathbb{K}, \mathbb{Q}/\mathbb{Z}).$$

See proof of Theorem 2.6.13. Usually this a very big module!

Example 11.5.2. Assume \mathbb{K} is a complete noetherian local ring, with maximal ideal \mathfrak{m} and residue field $\mathbb{k} = \mathbb{K}/\mathfrak{m}$. In this case we would prefer to take the smallest possible injective cogenerator \mathbb{K}^* , and this is the injective hull of \mathbb{k} as a \mathbb{K} -module.

Here are some special cases. If \mathbb{K} is a field, then $\mathbb{K}^* = \mathbb{K} = \mathbb{k}$. If $\mathbb{K} = \widehat{\mathbb{Z}}_p$, the ring of p -adic integers, then $\mathbb{k} = \mathbb{F}_p$, and $\mathbb{K}^* \cong \widehat{\mathbb{Q}}_p/\widehat{\mathbb{Z}}_p$, which is the p -primary part of \mathbb{Q}/\mathbb{Z} . If \mathbb{K} contains some field, then there exists a ring homomorphism $\mathbb{k} \rightarrow \mathbb{K}$ that lifts the canonical surjection $\mathbb{K} \rightarrow \mathbb{k}$. After choosing such a lifting, there is an isomorphism of \mathbb{K} -modules

$$\mathbb{K}^* \cong \mathrm{Hom}_{\mathbb{k}}^{\mathrm{cont}}(\mathbb{K}, \mathbb{k}),$$

where continuity is for the \mathfrak{m} -adic topology on \mathbb{K} and the discrete topology on \mathbb{k} .

In this subsection we fix an injective cogenerator \mathbb{K}^* of $\mathbf{M}(\mathbb{K})$. For any $p \in \mathbb{Z}$ there is the DG \mathbb{K} -module $T^{-p}(\mathbb{K}^*)$, which is concentrated in degree p , and has the trivial differential.

Definition 11.5.3. A DG \mathbb{K} -module W is called *cofree* if

$$W \cong \prod_{s \in S} T^{-p_s}(\mathbb{K}^*)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$, for some indexing set S and some collection of integers $\{p_s\}_{s \in S}$.

The differential of a cofree DG \mathbb{K} -module W is trivial. It is not hard to see that W is a \mathbb{K} -injective DG \mathbb{K} -module. When we view W as a graded \mathbb{K} -module, i.e. as an object of the abelian category $\mathbf{G}^0(\mathbb{K})$, it is injective.

A few more words on the structure of cofree DG \mathbb{K} -modules. Let's partition the set S as follows: $S = \coprod_{p \in \mathbb{Z}} S^p$, where $S^p := \{s \in S \mid p_s = p\}$. Then $W^p = \prod_{s \in S^p} \mathbb{K}^*$ as \mathbb{K} -modules.

Remark 11.5.4. It will be convenient to blur the distinction between DG modules with zero differentials and graded modules. Specifically, let N be a DG module such that $d_N = 0$. We are going to identify N with the graded modules N^{\natural} and $H(N)$. Typical examples are these: a cofree DG \mathbb{K} -module W , and the DG modules $Z(M)$ and $B(M)$ arising from any DG module M .

Lemma 11.5.5. *Let M be a DG \mathbb{K} -module, let W be a cofree DG \mathbb{K} -module, and let $\xi : M \rightarrow W$ be a homomorphism in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. If $H(\xi) : H(M) \rightarrow W$ is the zero homomorphism, then ξ is a coboundary in the DG module $\mathrm{Hom}_{\mathbb{K}}(M, W)$.*

Proof. Because W has zero differential, the homomorphism $H(\xi)$ is zero iff $\xi|_{Z(M)} : Z(M) \rightarrow W$ is zero. Consider the exact sequence

$$0 \rightarrow Z(M) \rightarrow M^{\natural} \xrightarrow{t \circ d_M} T(B(M)) \rightarrow 0$$

in $\mathbf{G}^0(\mathbb{K})$. Applying $\mathrm{Hom}_{\mathbb{K}}(-, W)$, and taking only the degree 0 part, we obtain the exact sequence

$$0 \rightarrow \mathrm{Hom}_{\mathbb{K}}(B(M), W)^{-1} \xrightarrow{\mathrm{Hom}(d, \mathrm{id})} \mathrm{Hom}_{\mathbb{K}}(M, W)^0 \rightarrow \mathrm{Hom}_{\mathbb{K}}(Z(M), W)^0 \rightarrow 0.$$

We are using the fact that W is injective in $\mathbf{G}^0(\mathbb{K})$. The homomorphism ξ lives in the middle term, and it goes to zero in the right term; hence it comes from some ζ in the left term. Thus $\xi = \zeta \circ d$ for a degree -1 homomorphism $\zeta : B(M) \rightarrow W$. Again using the fact that W is injective in $\mathbf{G}^0(\mathbb{K})$, and considering the embedding $B(M) \hookrightarrow M^{\natural}$, we see that ζ extends to a degree -1 homomorphism $\zeta : M^{\natural} \rightarrow W$. \square

Exercise 11.5.6. In the situation of Lemma 11.5.5, prove that there is a canonical isomorphism

$$\mathrm{Hom}_{\mathbb{K}}(\mathrm{H}(M), W) \cong \mathrm{H}(\mathrm{Hom}_{\mathbb{K}}(M, W))$$

in $\mathbf{G}^0(\mathbb{K})$. (Hint: look at the proof of [PSY, Corollary 2.12].)

Lemma 11.5.7. *Let M be a DG \mathbb{K} -module with zero differential. There is an injective homomorphism $\chi : M \rightarrow W$ into some cofree DG \mathbb{K} -module W .*

Proof. It is enough to prove that for any nonzero element $m \in M^p$ there is a homomorphism $\chi_m : M^p \rightarrow \mathbb{K}^*$ such that $\chi_m(m) \neq 0$. This is a direct consequence of the fact that \mathbb{K}^* is an injective cogenerator; see the proof of Theorem 2.6.13 for details. \square

Definition 11.5.8. Let W be a cofree DG \mathbb{K} -module. The *cofree DG A -module coinduced from W* is the DG A -module

$$I_W := \mathrm{Hom}_{\mathbb{K}}(A, W).$$

There is a homomorphism

$$\theta_W : I_W \rightarrow W, \quad \theta(\chi) := \chi(1)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. It is called the *trace*.

Definition 11.5.9. A DG A -module I is called *cofree* if there is an isomorphism $I \cong I_W$ in $\mathbf{C}_{\mathrm{str}}(A)$ for some cofree DG \mathbb{K} -module W .

A special cofree DG A -module is $A^* := \mathrm{Hom}_{\mathbb{K}}(A, \mathbb{K}^*)$. Any other cofree DG module I is built from A^* , in the sense that there is an isomorphism

$$I \cong \prod_{s \in S} T^{-p_s}(A^*)$$

in $\mathbf{C}_{\mathrm{str}}(A)$, using the notation of Definition 11.5.3.

Lemma 11.5.10 (Adjunction). *Let W be a cofree DG \mathbb{K} -module, and let M be a DG A -module. The homomorphism*

$$\mathrm{Hom}(\mathrm{id}_M, \theta_W) : \mathrm{Hom}_A(M, I_W) \rightarrow \mathrm{Hom}_{\mathbb{K}}(M, W)$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$ is an isomorphism.

Proof. Given $\chi \in \mathrm{Hom}_{\mathbb{K}}(M, W)^p$, let $\phi : M \rightarrow I_W$ be the function

$$\phi(m)(a) := (-1)^{ql} \cdot \chi(a \cdot m) \in W$$

for $m \in M^q$ and $a \in A^l$. Then $\phi \in \mathrm{Hom}_A(M, I_W)^p$, and

$$\mathrm{Hom}(\mathrm{id}_M, \theta)(\phi) = \theta \circ \phi = \chi.$$

We see that $\chi \mapsto \phi$ is an inverse of $\mathrm{Hom}(\mathrm{id}_M, \theta)$. \square

Recall that $\mathbf{G}^0(A^{\natural})$ is the abelian category whose objects are the graded A^{\natural} -modules, and the morphisms are the A -linear homomorphisms of degree 0. The forgetful functor

$$\mathbf{C}_{\mathrm{str}}(A) \rightarrow \mathbf{G}^0(A^{\natural}), \quad M \mapsto M^{\natural},$$

is faithful.

Lemma 11.5.11. *Let I be a cofree DG A -module. Then I^{\natural} is an injective object of $\mathbf{G}^0(A^{\natural})$.*

Proof. We can assume that $I = I_W$ for some cofree DG \mathbb{K} -module W . For any $M \in \mathbf{G}^0(A^\natural)$ there are isomorphisms

$$\begin{aligned} \mathrm{Hom}_{\mathbf{G}^0(A^\natural)}(M, I_W^\natural) &= \mathrm{Hom}_A(M, I_W)^0 \\ &\cong^{\heartsuit} \mathrm{Hom}_{\mathbb{K}}(M, W)^0 = \prod_{p \in \mathbb{Z}} \mathrm{Hom}_{\mathbb{K}}(M^p, W^p). \end{aligned}$$

The isomorphism \cong^{\heartsuit} is by Lemma 11.5.10. For every p the functor $\mathbf{G}^0(A^\natural) \rightarrow \mathbf{M}(\mathbb{K})$, $M \mapsto M^p$, is exact. Because each W^p is an injective object of $\mathbf{M}(\mathbb{K})$, the functor $\mathrm{Hom}_{\mathbb{K}}(-, W^p)$ is exact. And the product of exact functors into $\mathbf{M}(\mathbb{K})$ is exact. We conclude that the functor $\mathrm{Hom}_{\mathbf{G}^0(A^\natural)}(-, I_W^\natural)$ is exact. \square

The next definition is dual to Definition 11.3.3.

Definition 11.5.12. Let I be an object of $\mathbf{C}(A)$.

- (1) A *semi-cofree cofiltration* on I is a cofiltration $G = \{G_q(I)\}_{q \geq -1}$ of I in $\mathbf{C}_{\mathrm{str}}(A)$ such that:
 - $G_{-1}(I) = 0$.
 - Each $\mathrm{gr}_q^G(I)$ is a cofree DG A -module.
 - $I = \lim_{\leftarrow q} G_q(I)$.
- (2) The DG A -module I is called a *semi-cofree* if it admits a semi-cofree cofiltration.

Theorem 11.5.13. *Let I be an object of $\mathbf{C}(A)$. If I is semi-cofree, then it is K -injective.*

Proof. The proof is very similar to those of Theorems 11.2.3 and 11.3.6. But because the arguments involve limits, we shall give the full proof.

Step 1. Suppose I is cofree; say $I \cong \prod_{s \in S} T^{-p_s}(A^*)$. The adjunction formula (Lemma 11.5.10) implies that for any DG A -module N there is an isomorphism

$$\mathrm{Hom}_A(N, I) \cong \prod_{s \in S} \mathrm{Hom}_{\mathbb{K}}(T^{p_s}(N), \mathbb{K}^*)$$

of graded \mathbb{K} -modules. It follows that if N is acyclic, then so is $\mathrm{Hom}_A(N, I)$.

Step 2. Fix a semi-cofree cofiltration $G = \{G_q(I)\}_{q \geq -1}$ of I . Here we prove that for every $q \geq -1$ the DG module $G_q(I)$ is K -injective. This is done by induction on $q \geq -1$. For $q = -1$ it is trivial. For $q \geq 0$ there is an exact sequence

$$(11.5.14) \quad 0 \rightarrow \mathrm{gr}_q^F(I) \rightarrow G_q(I) \rightarrow G_{q-1}(I) \rightarrow 0$$

in the category $\mathbf{C}_{\mathrm{str}}(A)$. Because $\mathrm{gr}_q^G(I)$ is a cofree DG A -module, it is an injective object in the abelian category $\mathbf{G}^0(A^\natural)$; see Lemma 11.5.11. Therefore the sequence (11.5.14) is split exact in $\mathbf{G}^0(A^\natural)$.

Let $N \in \mathbf{C}(A)$ be an acyclic DG module. Applying the functor $\mathrm{Hom}_A(N, -)$ to the sequence (11.5.14) we obtain a sequence

$$(11.5.15) \quad 0 \rightarrow \mathrm{Hom}_A(N, \mathrm{gr}_q^G(I)) \rightarrow \mathrm{Hom}_A(N, G_q(I)) \rightarrow \mathrm{Hom}_A(N, G_{q-1}(I)) \rightarrow 0$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. If we forget differentials this is a sequence in $\mathbf{G}^0(\mathbb{K})$. Because (11.5.14) is split exact in $\mathbf{G}^0(A^\natural)$, it follows that (11.5.15) is split exact in $\mathbf{G}^0(\mathbb{K})$. Therefore (11.5.15) is exact in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$.

By the induction hypothesis the DG \mathbb{K} -module $\mathrm{Hom}_A(N, G_{q-1}(I))$ is acyclic. By step 1 the DG \mathbb{K} -module $\mathrm{Hom}_A(N, \mathrm{gr}_q^G(I))$ is acyclic. The long exact cohomology sequence associated to (11.5.15) shows that the DG \mathbb{K} -module $\mathrm{Hom}_A(N, G_q(I))$ is acyclic too.

Step 3. We keep the semi-cofree cofiltration $G = \{G_q(I)\}_{q \geq -1}$ from step 2. Take any acyclic $N \in \mathbf{C}(A)$. By Proposition 11.1.3 we know that

$$\mathrm{Hom}_A(N, I) \cong \lim_{\leftarrow j} \mathrm{Hom}_A(N, G_q(I))$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$. According to step 2 the complexes $\mathrm{Hom}_A(N, G_q(I))$ are all acyclic. The exactness of the sequences (11.5.15) implies that the inverse system

$$\{\mathrm{Hom}_A(N, G_q(I))\}_{q \geq -1}$$

in $\mathbf{C}_{\mathrm{str}}(\mathbb{K})$ has surjective transitions. Now the Mittag-Leffler argument (Corollary 11.1.13) says that the inverse limit complex $\mathrm{Hom}_A(N, I)$ is acyclic. \square

Theorem 11.5.16. *Let A be a DG ring. Any DG A -module M admits a quasi-isomorphism $\rho : M \rightarrow I$ in $\mathbf{C}_{\mathrm{str}}(A)$ to a semi-cofree DG A -module I .*

We shall need three lemmas before the proof of the theorem.

Lemma 11.5.17. *Let W be a cofree DG \mathbb{K} -module, let M be a DG A -module, and let $\chi : \mathrm{H}(M) \rightarrow \mathrm{H}(W)$ be a homomorphism in $\mathbf{G}^0(\mathbb{K})$. Then there is a homomorphism $\phi : M \rightarrow I_W$ in $\mathbf{C}_{\mathrm{str}}(A)$, such that the diagram*

$$\begin{array}{ccccc} \mathrm{H}(M) & \xrightarrow{\mathrm{H}(\phi)} & \mathrm{H}(I_W) & \xrightarrow{\mathrm{H}(\theta_W)} & \mathrm{H}(W) \\ & \searrow & \xrightarrow{\chi} & \nearrow & \\ & & & & \end{array}$$

in $\mathbf{G}^0(\mathbb{K})$ is commutative.

Proof. We can assume that

$$W = \prod_{p \in \mathbb{Z}} \prod_{s \in S^p} \mathrm{T}^{-p}(\mathbb{K}^*)$$

for some graded set $S = \coprod_{p \in \mathbb{Z}} S^p$. Then

$$I_W = \prod_{p \in \mathbb{Z}} \prod_{s \in S^p} \mathrm{T}^{-p}(A^*),$$

where $A^* = \mathrm{Hom}_{\mathbb{K}}(A, \mathbb{K}^*)$ as before. The trace θ_W is a product of translations of the trace $\theta : A^* \rightarrow \mathbb{K}^*$. The homomorphism $\chi : \mathrm{H}(M) \rightarrow \mathrm{H}(W)$ is a product of \mathbb{K} -linear homomorphisms $\chi_s : \mathrm{H}^p(M) \rightarrow \mathbb{K}^*$. We see that it suffices to find, for each p and each $s \in S^p$, a homomorphism $\phi_s : M \rightarrow \mathrm{T}^{-p}(A^*)$ in $\mathbf{C}_{\mathrm{str}}(A)$, such that $\theta \circ \mathrm{H}^p(\phi_s) = \chi_s$.

Now we consider the simplified situation: $\chi : \mathrm{H}^p(M) \rightarrow \mathbb{K}^*$ is a \mathbb{K} -linear homomorphism, and we are looking for a homomorphism $\phi : M \rightarrow \mathrm{T}^{-p}(A^*)$ in $\mathbf{C}_{\mathrm{str}}(A)$ such that $\theta \circ \mathrm{H}^p(\phi) = \chi$.

For any integer p let

$$Y^p(M) := \mathrm{Coker}(d_M^{p-1} : M^{p-1} \rightarrow M^p).$$

See Remark 8.3.10. In each degree p there are canonical exact sequences of \mathbb{K} -modules

$$(11.5.18) \quad 0 \rightarrow B^p(M) \rightarrow M^p \rightarrow Y^p(M) \rightarrow 0$$

and

$$(11.5.19) \quad 0 \rightarrow H^p(M) \rightarrow Y^p(M) \xrightarrow{d} B^{p+1}(M) \rightarrow 0.$$

Because \mathbb{K}^* is injective in $\mathbf{M}(\mathbb{K})$, we can extend $\chi : H^p(M) \rightarrow \mathbb{K}^*$ to a homomorphism $\chi : Y^p(M) \rightarrow \mathbb{K}^*$ in $\mathbf{M}(\mathbb{K})$, relative to the embedding $H^p(M) \hookrightarrow Y^p(M)$ in (11.5.19). Next we compose with the surjection $M^p \rightarrow Y^p(M)$ in (11.5.18) to obtain a \mathbb{K} -linear homomorphism $\chi : M^p \rightarrow \mathbb{K}^*$. Note that $\chi \circ d_M^{p-1} = 0$ by the exact sequence (11.5.18).

We now view χ as a degree $-p$ homomorphism $\chi : M \rightarrow \mathbb{K}^*$ in $\mathbf{G}(\mathbb{K})$ that sends all other components of M to zero. As an element of the DG \mathbb{K} -module $\text{Hom}_{\mathbb{K}}(M, \mathbb{K}^*)$, χ is a degree $-p$ cocycle. By adjunction (Lemma 11.5.10) we get an element $\psi \in \text{Hom}_A(M, A^*)$, and it is a cocycle of degree $-p$. Then

$$\phi := \mathfrak{t}^{-p} \circ \psi : M \rightarrow T^{-p}(A^*)$$

is a homomorphism in $\mathbf{C}_{\text{str}}(A)$ with the desired property. \square

Lemma 11.5.20. *In the situation of Lemma 11.5.17, let $N := \text{Cone}(T^{-1}(\phi))$, the standard cone on the homomorphism*

$$T^{-1}(\phi) : T^{-1}(M) \rightarrow T^{-1}(I_W)$$

in $\mathbf{C}_{\text{str}}(A)$. Consider the canonical exact sequence

$$(11.5.21) \quad 0 \rightarrow T^{-1}(I_W) \rightarrow N \xrightarrow{\pi} M \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(A)$, shown in formula (4.2.4). Then the composed homomorphism

$$\chi \circ H(\pi) : H(N) \rightarrow H(W)$$

in $\mathbf{G}^0(\mathbb{K})$ is zero.

Proof. Passing to the long exact sequence in cohomology of (11.5.21), and then applying $\text{Hom}_{\mathbb{K}}(-, W^p)$, we obtain this long exact sequence:

$$\cdots \rightarrow \text{Hom}_{\mathbb{K}}(H^p(I_W), W^p) \rightarrow \text{Hom}_{\mathbb{K}}(H^p(M), W^p) \rightarrow \text{Hom}_{\mathbb{K}}(H^p(N), W^p) \rightarrow \cdots$$

in $\mathbf{M}(\mathbb{K})$. The homomorphism $\chi^p : H^p(M) \rightarrow W^p$ in the middle term comes from $H^p(\theta_W) : H^p(I_W) \rightarrow W^p$ in the left term. Therefore its image $\chi^p \circ H^p(\pi) : H^p(N) \rightarrow W^p$ in the right term is zero. \square

Lemma 11.5.22. *In the situation of Lemma 11.5.20, suppose $\rho : L \rightarrow M$ is a homomorphism in $\mathbf{C}_{\text{str}}(A)$ such that $H(\theta_W) \circ H(\phi) \circ H(\rho) = 0$. Then there exists a homomorphism $\sigma : L \rightarrow N$ in $\mathbf{C}_{\text{str}}(A)$ such that $\pi \circ \sigma = \rho$.*

See the next commutative diagrams, in $\mathbf{C}_{\text{str}}(A)$ and $\mathbf{G}^0(\mathbb{K})$ respectively.

$$\begin{array}{ccccccc}
 & & & N & & & \\
 & & \nearrow & \downarrow \pi & & & \\
 & \sigma & & & & & \\
 L & \xrightarrow{\rho} & M & \xrightarrow{\phi} & I_W & \xrightarrow{\theta_W} & W \\
 & \searrow & & & & \searrow & \\
 & & & & & & \\
 & & \xrightarrow{\xi} & & & &
 \end{array}$$

$$\begin{array}{ccccccc}
 & & & \mathbf{H}(N) & & & \\
 & & & \downarrow \mathbf{H}(\pi) & & & \\
 & \nearrow \mathbf{H}(\sigma) & & & & & \\
 \mathbf{H}(L) & \xrightarrow{\mathbf{H}(\rho)} & \mathbf{H}(M) & \xrightarrow{\mathbf{H}(\phi)} & \mathbf{H}(I_W) & \xrightarrow{\mathbf{H}(\theta_W)} & W \\
 & \searrow & & & & \searrow & \\
 & & & & & & \\
 & & & \mathbf{H}(\xi)=0 & & &
 \end{array}$$

Proof. It will be convenient to express $N = \text{Cone}(\mathbf{T}^{-1}(\phi))$ in terms of matrices. We will use the equality $\mathbf{T}(\mathbf{T}^{-1}(M)) = M$ to write the graded A^\natural -module N^\natural as a column:

$$(11.5.23) \quad N^\natural = \begin{bmatrix} \mathbf{T}^{-1}(I_W)^\natural \\ \mathbf{T}(\mathbf{T}^{-1}(M))^\natural \end{bmatrix} = \begin{bmatrix} \mathbf{T}^{-1}(I_W)^\natural \\ M^\natural \end{bmatrix}.$$

A small calculation, using Definition 4.1.5 and Proposition 4.1.10(1), shows that

$$\mathbf{T}^{-1}(\phi) = \mathbf{t}_{\mathbf{T}^{-1}(I_W)}^{-1} \circ \phi \circ \mathbf{t}_{\mathbf{T}^{-1}(M)}.$$

Note that

$$\mathbf{t}_{\mathbf{T}^{-1}(I_W)} : \mathbf{T}^{-1}(I_W) \rightarrow \mathbf{T}(\mathbf{T}^{-1}(I_W)) = I_W$$

is an invertible degree -1 homomorphism, and its inverse

$$\mathbf{t}_{\mathbf{T}^{-1}(I_W)}^{-1} : I_W \rightarrow \mathbf{T}^{-1}(I_W)$$

has degree 1. So the differential of N is

$$(11.5.24) \quad d_N = \begin{bmatrix} d_{\mathbf{T}^{-1}(I_W)} & \mathbf{T}^{-1}(\phi) \circ \mathbf{t}_{\mathbf{T}^{-1}(M)}^{-1} \\ 0 & d_M \end{bmatrix} = \begin{bmatrix} d_{\mathbf{T}^{-1}(I_W)} & \mathbf{t}_{\mathbf{T}^{-1}(I_W)}^{-1} \circ \phi \\ 0 & d_M \end{bmatrix}.$$

Define $\xi := \theta_W \circ \phi \circ \rho$. This is a homomorphism $\xi : L \rightarrow W$ in $\mathbf{C}_{\text{str}}(\mathbb{K})$, and by assumption $\mathbf{H}(\xi) = 0$. According to Lemma 11.5.5, ξ is a coboundary in the DG module $\text{Hom}_{\mathbb{K}}(L, W)$. So there is some $\omega \in \text{Hom}_{\mathbb{K}}(L, W)^{-1}$ such that $\xi = d(\omega) = \omega \circ d_L$. Let $\alpha : L \rightarrow I_W$ be the unique A -linear homomorphism of degree -1 such that $\theta_W \circ \alpha = \omega$; see Lemma 11.5.10. Define the homomorphism $\sigma : L^\natural \rightarrow N^\natural$ in $\mathbf{G}^0(A^\natural)$ to be the column

$$\sigma := \begin{bmatrix} \mathbf{t}^{-1} \circ \alpha \\ \rho \end{bmatrix},$$

where from here to the end of the proof we write $\mathbf{t} := \mathbf{t}_{\mathbf{T}^{-1}(I_W)}$. It is clear that $\pi \circ \sigma = \rho$.

It remains to prove that σ is strict, namely that $\sigma \circ d_L = d_N \circ \sigma$. Let us write out these homomorphisms as matrices. We have

$$\sigma \circ d_L = \begin{bmatrix} \mathbf{t}^{-1} \circ \alpha \circ d_L \\ \rho \circ d_L \end{bmatrix}$$

and

$$d_N \circ \sigma = \begin{bmatrix} d_{\mathbf{T}^{-1}(I_W)} & \mathbf{t}^{-1} \circ \phi \\ 0 & d_M \end{bmatrix} \circ \begin{bmatrix} \mathbf{t}^{-1} \circ \alpha \\ \rho \end{bmatrix} = \begin{bmatrix} d_{\mathbf{T}^{-1}(I_W)} \circ \mathbf{t}^{-1} \circ \alpha + \mathbf{t}^{-1} \circ \phi \circ \rho \\ d_M \circ \rho \end{bmatrix}.$$

Since ρ is strict, there is equality $\rho \circ d_L = d_M \circ \rho$. We need to verify that

$$t^{-1} \circ \alpha \circ d_L = d_{T^{-1}(I_W)} \circ t^{-1} \circ \alpha + t^{-1} \circ \phi \circ \rho$$

as A -linear homomorphisms $L \rightarrow T^{-1}(I_W)$. We are allowed to postcompose with t ; so now we have to verify that

$$\alpha \circ d_L = t \circ d_{T^{-1}(I_W)} \circ t^{-1} \circ \alpha + \phi \circ \rho$$

as A -linear homomorphisms $L \rightarrow I_W$. By adjunction (Lemma 11.5.10) it suffices to verify that they are equal as \mathbb{K} -linear homomorphisms after postcomposing with θ_W . But

$$\theta_W \circ t \circ d_{T^{-1}(I_W)} \circ t^{-1} \circ \alpha = -\theta_W \circ d_{I_W} \circ \alpha = -d_W \circ \theta_W \circ \alpha = 0;$$

and

$$\theta_W \circ \phi \circ \rho = \xi = \theta_W \circ \alpha \circ d_L.$$

□

Proof of Theorem 11.5.16. The proof is morally dual to that of Theorem 11.3.9, but the details are much more complicated. This is the strategy: we will construct an inverse system $\{G_q(I)\}_{q \geq -1}$ in $\mathbf{C}_{\text{str}}(A)$, and an inverse system of homomorphisms $G_q(\rho) : M \rightarrow G_q(I)$ in $\mathbf{C}_{\text{str}}(A)$. Then we will prove that the DG module $I := \lim_{\leftarrow q} G_q(I)$ is semi-cofree, and the homomorphism $\lim_{\leftarrow q} G_q(\rho) : M \rightarrow I$ is a quasi-isomorphism.

Step 1. In this step we handle $q = 0$. By Lemma 11.5.7 there is an injective homomorphism $\chi : H(M) \rightarrow W$ in $\mathbf{G}^0(\mathbb{K})$ for some cofree DG \mathbb{K} -module W . Next, by Lemma 11.5.17, there is a homomorphism $\phi : M \rightarrow I_W$ in $\mathbf{C}_{\text{str}}(A)$, such that $\chi = H(\theta_W) \circ H(\phi)$.

Define the cofree DG A -module $G_0(I) := I_W$ and the homomorphism

$$G_0(\rho) := \phi : M \rightarrow G_0(I).$$

Then the homomorphism

$$H(G_0(\rho)) : H(M) \rightarrow H(G_0(I))$$

is injective.

Step 2. In this step $q \geq 0$, and we are given the following: a DG A -module $G_q(I)$, a cofiltration $\{G_{q'}(I)\}_{-1 \leq q' \leq q}$ of $G_q(I)$, and an inverse system of homomorphisms $G_{q'}(\rho) : M \rightarrow G_{q'}(I)$ in $\mathbf{C}_{\text{str}}(A)$. These satisfy the following conditions: the homomorphisms

$$H(G_{q'}(\rho)) : H(M) \rightarrow H(G_{q'}(I))$$

in $\mathbf{G}^0(\mathbb{K})$ are injective for all $0 \leq q' \leq q$; $G_{-1}(I) = 0$; and the DG A -modules

$$\text{Ker}(G_{q'}(I) \rightarrow G_{q'-1}(I))$$

are cofree for all $0 \leq q' \leq q$.

Let N be the cokernel of $H(G_q(\rho))$. So there is a short exact sequence

$$(11.5.25) \quad 0 \rightarrow H(M) \xrightarrow{H(G_q(\rho))} H(G_q(I)) \xrightarrow{\alpha} N \rightarrow 0$$

in $\mathbf{G}^0(\mathbb{K})$. By Lemma 11.5.7 there is an injective homomorphism $\chi : N \rightarrow W$ in $\mathbf{G}^0(\mathbb{K})$ for some cofree DG \mathbb{K} -module W . Next, by Lemma 11.5.17, there is a homomorphism $\phi : G_q(I) \rightarrow I_W$ in $\mathbf{C}_{\text{str}}(A)$, such that

$$\chi \circ \alpha = H(\theta_W) \circ H(\phi)$$

as homomorphisms $H(G_q(I)) \rightarrow W$. Define the DG A -module

$$G_{q+1}(I) := \text{Cone}(\mathbb{T}^{-1}(\phi)),$$

the standard cone on the strict homomorphism $\mathbb{T}^{-1}(\phi)$. There is a canonical exact sequence

$$(11.5.26) \quad 0 \rightarrow \mathbb{T}^{-1}(I_W) \rightarrow G_{q+1}(I) \xrightarrow{\mu_q} G_q(I) \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(A)$. According to Lemma 11.5.20, the homomorphism

$$\chi \circ \alpha \circ H(\mu_q) : H(G_{q+1}(I)) \rightarrow W$$

in $\mathbf{G}^0(\mathbb{K})$ is zero. Since χ is an injective homomorphism, we conclude that the homomorphism $\alpha \circ H(\mu_q)$ in the commutative diagram below is zero.

$$(11.5.27) \quad \begin{array}{ccccc} H(G_{q+1}(I)) & & & & \\ \downarrow H(\mu_q) & \searrow 0 & & \searrow 0 & \\ H(G_q(I)) & \xrightarrow{\alpha} & N & \xrightarrow{\chi} & W \\ & \searrow H(\phi) & & \nearrow H(\theta_W) & \\ & & H(I_W) & & \end{array}$$

Step 3. We continue from step 2. We know from formula (11.5.25) and diagram (11.5.27) that

$$H(\theta_W) \circ H(\phi) \circ H(G_q(\rho)) = 0.$$

According to Lemma 11.5.22 there is a homomorphism

$$G_{q+1}(\rho) : M \rightarrow G_{q+1}(I)$$

in $\mathbf{C}_{\text{str}}(A)$ such that the diagram

$$(11.5.28) \quad \begin{array}{ccc} & G_{q+1}(I) & \\ G_{q+1}(\rho) \nearrow & & \downarrow \mu_q \\ M & \xrightarrow{G_q(\rho)} & G_q(I) \end{array}$$

in $\mathbf{C}_{\text{str}}(A)$ is commutative.

The next diagram, in $\mathbf{G}^0(\mathbb{K})$, is also commutative, and the bottom row is exact:

$$(11.5.29) \quad \begin{array}{ccccccc} & & & H(G_{q+1}(I)) & & & \\ & & & \downarrow H(\mu_q) & & & \\ 0 & \longrightarrow & H(M) & \xrightarrow{H(G_q(\rho))} & H(G_q(I)) & \xrightarrow{\alpha} & N \longrightarrow 0 \\ & & \nearrow H(G_{q+1}(\rho)) & & \searrow 0 & & \end{array}$$

Let us define

$$L_q := \text{Im}(H(\mu_q)) \subseteq H(G_q(I)).$$

From diagram (11.5.29) we see that the homomorphism

$$(11.5.30) \quad H(G_q(\rho)) : H(M) \rightarrow L_q$$

in $\mathbf{G}^0(\mathbb{K})$ is bijective. This implies that

$$\mathrm{H}(G_{q+1}(\rho)) : \mathrm{H}(M) \rightarrow \mathrm{H}(G_{q+1}(I))$$

in an injective homomorphism, a fact that is needed to keep the induction going.

Step 4. Proceeding with steps 2 and 3 inductively, we obtain an inverse system $\{G_q(I)\}_{q \geq -1}$ of objects in $\mathbf{C}_{\mathrm{str}}(A)$, and an inverse system $G_q(\rho) : M \rightarrow G_q(I)$ of homomorphisms in $\mathbf{C}_{\mathrm{str}}(A)$. The DG module $I := \lim_{\leftarrow q} G_q(I)$ comes equipped with the semi-cofree cofiltration $\{G_q(I)\}_{q \geq -1}$, and thus it is semi-cofree.

It remains to prove that the homomorphism

$$\rho := \lim_{\leftarrow q} G_q(\rho) : M \rightarrow I$$

is a quasi-isomorphism. From formula (11.5.30) we know that $\mathrm{H}(M) \rightarrow \lim_{\leftarrow q} L_q$ is bijective. The inverse systems $\{L_q\}_{q \geq 0}$ and $\{\mathrm{H}(G_q(I))\}_{q \geq 0}$ are sandwiched, so by Proposition 11.1.1(2) the limit of the second inverse system exists, and the canonical homomorphism

$$\lim_{\leftarrow q} L_q \rightarrow \lim_{\leftarrow q} \mathrm{H}(G_q(I))$$

is bijective.

Finally, the inverse systems $\{G_q(I)\}_{q \geq 0}$ and $\{\mathrm{H}(G_q(I))\}_{q \geq 0}$ satisfy the ML condition: the first has surjective transitions, and the images of the transitions $\mathrm{H}(G_{q'}(I)) \rightarrow \mathrm{H}(G_q(I))$ are stationary for $q' \geq q + 1$. Therefore the homomorphism

$$\mathrm{H}(I) \rightarrow \lim_{\leftarrow q} \mathrm{H}(G_q(I))$$

is bijective. Putting these facts together, we deduce that ρ is a quasi-isomorphism. \square

Corollary 11.5.31. *Let A be any DG ring. The category $\mathbf{C}(A)$ has enough K -injectives.*

Proof. Combine Theorems 11.5.13 and 11.5.16. \square

Corollary 11.5.32. *Assume A is a nonpositive DG ring (Definition 8.3.11). For any $M \in \mathbf{C}(A)$ there is a K -injective resolution $M \rightarrow I$ with $\mathrm{inf}(I) = \mathrm{inf}(\mathrm{H}(M))$.*

Proof. For any cofree DG \mathbb{K} -module W , the cofree DG A -module I_W has $\mathrm{inf}(I_W) = \mathrm{inf}(W)$. (Assuming that A is nonzero.) Looking at steps 1 and 2 of the proof of Theorem 11.5.16, we see that the DG modules $G_q(I)$ can be chosen such that $\mathrm{inf}(G_q(I)) = \mathrm{inf}(\mathrm{H}(M))$. \square

Remark 11.5.33. The proof of Theorem 11.5.16 is quite long and complicated. It would be nice to have a quicker proof.

In Keller's paper [Kel, Section 3.2] there is a slick proof of an even stronger result than Theorem 11.5.16 – but we were unable to understand the details!

cmnt: End of first part (in book)

Second Part

cmnt: Start of course III.

12. RECALLING MATERIAL FROM LAST YEAR [TEMPORARY]

12.1. Generalities. We fix a nonzero commutative base ring \mathbb{K} (e.g. a field or \mathbb{Z}). All linear operations are by default \mathbb{K} -linear. Thus a ring A is assumed to be \mathbb{K} -central; an additive category \mathbf{M} is assumed to be \mathbb{K} -linear; etc.

The concepts of classical homological algebra: abelian category, additive functor, injective and projective objects, and so on, are all assumed to be familiar.

12.2. DG Algebra. Let me quickly go over the important ideas of DG algebra, because they are not so well-known. This is a review of Section 3.

A DG ring is a graded ring $A = \bigoplus_{i \in \mathbb{Z}} A^i$, with a differential d of degree 1, satisfying the graded Leibniz rule

$$d(a_1 \cdot a_2) = d(a_1) \cdot a_2 + (-1)^{i_1} \cdot a_1 \cdot d(a_2)$$

for elements $a_j \in A^{i_j}$.

Over a DG ring A there are left DG modules, right DG modules and DG bimodules. The default is always left modules.

Given DG A -modules M, N , we can form the DG \mathbb{K} -module

$$(12.2.1) \quad \text{Hom}_A(M, N) = \bigoplus_{i \in \mathbb{Z}} \text{Hom}_A(M, N)^i.$$

The i -th summand consists of degree i homomorphisms that commute, in the graded sense, with the action of A (this is a bit subtle).

If L is a right DG A -module, then

$$L \otimes_A M = \bigoplus_{i \in \mathbb{Z}} (L \otimes_A M)^i$$

is also a DG \mathbb{K} -module.

A strict homomorphism of DG A -modules is a homomorphism $\phi : M \rightarrow N$ that commutes with the grading, the action of A , and the differentials. Equivalently, ϕ is a 0-cocycle in the DG module $\text{Hom}_A(M, N)$.

Generalizing the notion of DG ring, we get DG categories. A DG category \mathbf{C} is a \mathbb{K} -linear category, whose Hom modules have a DG structure. I.e. for any pair of objects $M, N \in \mathbf{C}$, the set $\text{Hom}_{\mathbf{C}}(M, N)$ is a DG \mathbb{K} -module. The identity automorphism $\text{id}_M = 1_M$ is a degree 0 cocycle. For three objects, the composition is a strict homomorphism of DG \mathbb{K} -modules:

$$- \circ - : \text{Hom}_{\mathbf{C}}(M_1, M_2) \otimes_{\mathbb{K}} \text{Hom}_{\mathbf{C}}(M_0, M_1) \rightarrow \text{Hom}_{\mathbf{C}}(M_0, M_2).$$

Generalizing the notion of homomorphism of DG rings, we obtain the notion of DG functor

$$F : \mathbf{C} \rightarrow \mathbf{D}$$

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between a pair of DG categories. If $G : \mathbf{C} \rightarrow \mathbf{D}$ is another DG functor, we can talk about a degree i morphism $\eta : F \rightarrow G$ of DG functors, and its differential $d(\eta) : F \rightarrow G$, that's a degree $i + 1$ morphism.

To a DG category \mathbf{C} we attach two other categories, with the same sets of objects as \mathbf{C} . There is the strict category \mathbf{C}_{str} , whose morphisms are the strict morphisms:

$$\text{Hom}_{\mathbf{C}_{\text{str}}}(M, N) := Z^0(\text{Hom}_{\mathbf{C}}(M, N)).$$

And there is the homotopy category $\text{Ho}(\mathbf{C})$, whose morphisms are the homotopy classes of strict morphisms:

$$\text{Hom}_{\text{Ho}(\mathbf{C})}(M, N) := H^0(\text{Hom}_{\mathbf{C}}(M, N)).$$

One basic example of a DG category is $\mathbf{C}(A)$, the category of DG A -modules. By definition we take

$$\text{Hom}_{\mathbf{C}(A)}(M, N) := \text{Hom}_A(M, N),$$

the DG module from formula (12.2.1). We have special notation in this context:

$$\mathbf{C}(A)_{\text{str}} := \mathbf{C}_{\text{str}}(A)$$

and

$$\text{Ho}(\mathbf{C}(A)) := \mathbf{K}(A).$$

Another basic example of a DG category is the category $\mathbf{C}(\mathbf{M})$ of complexes over an abelian category \mathbf{M} . Its strict category is $\mathbf{C}_{\text{str}}(\mathbf{M})$, and the morphisms here are what is classically called homomorphisms of complexes. The homotopy category is, as usual, denoted by $\mathbf{K}(\mathbf{M})$.

A useful innovation in this course is the merging of these last two types of DG categories into a single entity. Suppose A is a DG ring, and \mathbf{M} is an abelian category. For a complex $M = \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{C}(\mathbf{M})$, its set of endomorphisms

$$\text{End}_{\mathbf{C}}(M) := \text{Hom}_{\mathbf{C}}(M, M)$$

is a DG ring (central over \mathbb{K}). By definition, a DG A -module in \mathbf{M} is a complex $M \in \mathbf{C}(\mathbf{M})$, together with a DG ring homomorphism $A \rightarrow \text{End}_{\mathbf{C}}(M)$. There is an obvious (once contemplating this long enough...) notion of degree i A -linear morphism between two such DG modules. In this way we obtain the DG category $\mathbf{C}(A, \mathbf{M})$. Its strict and homotopy categories are $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ and $\mathbf{K}(A, \mathbf{M})$ respectively. Note that $\mathbf{C}_{\text{str}}(A, \mathbf{M})$ is (secretly) an abelian category.

Just to state the relationship: when $A = \mathbb{K}$ we get

$$\mathbf{C}(A, \mathbf{M}) = \mathbf{C}(\mathbf{M}),$$

and when $\mathbf{M} = \mathbf{M}(\mathbb{K}) = \text{Mod } \mathbb{K}$, we get

$$\mathbf{C}(A, \mathbf{M}) = \mathbf{C}(A).$$

12.3. Translations. The category $\mathbf{G}(\mathbf{M})$ of graded objects of \mathbf{M} has an automorphism called the translation. Given a graded object $M = \{M^i\}_{i \in \mathbb{Z}}$, its translation $T(M)$ is the graded object whose degree i component is $T(M)^i := M^{i+1}$. There is a canonical degree -1 morphism

$$t_M : M \rightarrow T(M)$$

in $\mathbf{G}(\mathbf{M})$, which is the identity after forgetting the grading. This is called the little t operator. Observe that t_M is an isomorphism in $\mathbf{G}(\mathbf{M})$; its inverse t_M^{-1} is of degree $+1$.

If $\phi : M \rightarrow N$ is a degree i morphism in $\mathbf{G}(\mathbf{M})$, we let

$$\mathbf{T}(\phi) : \mathbf{T}(M) \rightarrow \mathbf{T}(M)$$

be

$$\mathbf{T}(\phi) := t_N \circ \phi \circ t_M^{-1}.$$

In this way \mathbf{T} is indeed an automorphism of the category $\mathbf{G}(\mathbf{M})$.

Now consider a complex $M \in \mathbf{C}(\mathbf{M})$. Its differential d_M is a degree 1 morphism in $\mathbf{G}(\mathbf{M})$, so we can define

$$d_{\mathbf{T}(M)} := \mathbf{T}(d_M),$$

and this is a differential on $\mathbf{T}(M)$.

All this works just as well for DG A -modules in \mathbf{M} . We get a DG functor

$$\mathbf{T} : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(A, \mathbf{M}),$$

and it is an automorphism of this DG category. The little t operator is a degree -1 morphism of DG functors

$$t : \text{Id} \rightarrow \mathbf{T},$$

and it is a cocycle.

12.4. Cones. In the DG category $\mathbf{C}(A, \mathbf{M})$ there is an intrinsic notion of standard cone. Suppose $\phi : M \rightarrow N$ is a strict morphism in $\mathbf{C}(A, \mathbf{M})$. The standard cone of ϕ is the DG module

$$(12.4.1) \quad \text{Cone}(\phi) := N \oplus \mathbf{T}(M) = \begin{bmatrix} N \\ \mathbf{T}(M) \end{bmatrix},$$

in column notation. The differential d_{cone} is the following matrix of degree 1 operators, acting on the column from the left:

$$d_{\text{cone}} : \begin{bmatrix} d_N & \phi \circ t_M^{-1} \\ 0 & d_{\mathbf{T}(M)} \end{bmatrix}.$$

The standard cone sits inside the standard triangle. This is the diagram

$$(12.4.2) \quad M \xrightarrow{\phi} N \xrightarrow{e_\phi} \text{Cone}(\phi) \xrightarrow{p_\phi} \mathbf{T}(M)$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$, where e_ϕ and p_ϕ are the obvious morphisms.

The standard cone, and also the standard triangle, are functorial in the strict morphism ϕ .

12.5. DG Functors and Triangles. We now review Section 5.

DG functors respect all the structure mentioned above. Let me explain. Suppose

$$F : \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(B, \mathbf{N})$$

is a DG functor. Let us denote by $\mathbf{T}_{A, \mathbf{M}}$ and $\mathbf{T}_{B, \mathbf{N}}$ the two translation functors. There is a strict isomorphism of DG functors

$$(12.5.1) \quad \tau_F : F \circ \mathbf{T}_{A, \mathbf{M}} \xrightarrow{\cong} \mathbf{T}_{B, \mathbf{N}} \circ F$$

called the translation isomorphism. This is the formula, for any DG module $M \in \mathbf{C}(A, \mathbf{M})$:

$$\tau_{F, M} := t_{F(M)} \circ F(t_M)^{-1} : F(\mathbf{T}_{A, \mathbf{M}}(M)) \xrightarrow{\cong} \mathbf{T}_{B, \mathbf{N}}(F(M)).$$

Next, suppose we are given a strict morphism $\phi : M_0 \rightarrow M_1$ in $\mathbf{C}(A, \mathbf{M})$. Then $F(\phi)$ is also a strict morphism. We can form the standard cones $\text{Cone}_{A, \mathbf{M}}(\phi)$ and $\text{Cone}_{B, \mathbf{N}}(F(\phi))$.

It turns out that there is a strict isomorphism

$$(12.5.2) \quad \text{cone}(F, \phi) : F(\text{Cone}_{A, \mathbf{M}}(\phi)) \xrightarrow{\cong} \text{Cone}_{B, \mathbf{N}}(F(\phi))$$

in $\mathbf{C}(B, \mathbf{N})$, whose formula is

$$\text{cone}(F, \phi) := \begin{bmatrix} \text{id}_{F(M_1)} & 0 \\ 0 & \tau_{F, M_0} \end{bmatrix}.$$

The following diagram in $\mathbf{C}_{\text{str}}(B, \mathbf{N})$ is commutative:

$$(12.5.3) \quad \begin{array}{ccccccc} F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{F(e_\phi)} & F(\text{Cone}_{A, \mathbf{M}}(\phi)) & \xrightarrow{F(p_\phi)} & F(\mathbf{T}_{A, \mathbf{M}}(M_0)) \\ \downarrow = & & \downarrow = & & \downarrow \text{cone}(F, \phi) & & \downarrow \tau_{F, M_0} \\ F(M_0) & \xrightarrow{F(\phi)} & F(M_1) & \xrightarrow{e_{F(\phi)}} & \text{Cone}_{B, \mathbf{N}}(F(\phi)) & \xrightarrow{p_{F(\phi)}} & \mathbf{T}_{B, \mathbf{N}}(F(M_0)) \end{array}$$

cmnt: to here on 2 Nov 2016

12.6. Pretriangulated Categories and Triangulated Functors. This is a review of Section 6.

The translation isomorphism introduced above has an abstract version. This is the notion of a \mathbf{T} -additive category, which consists of an additive category \mathbf{K} , together with an additive automorphism \mathbf{T} . Suppose (\mathbf{K}, \mathbf{T}) and $(\mathbf{K}', \mathbf{T}')$ are \mathbf{T} -additive categories. A \mathbf{T} -additive functor

$$(F, \tau) : (\mathbf{K}, \mathbf{T}) \rightarrow (\mathbf{K}', \mathbf{T}')$$

consists of an additive functor F with an isomorphism of functors

$$\tau : F \circ \mathbf{T} \xrightarrow{\cong} \mathbf{T}' \circ F.$$

There is a rather obvious notion of composition of \mathbf{T} -additive functors. See Definition 6.1.4.

Intrinsic to a \mathbf{T} -additive category is the notion of triangle; it is a diagram like this:

$$(12.6.1) \quad L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} \mathbf{T}(L).$$

A pretriangulated category is a \mathbf{T} -additive category (\mathbf{K}, \mathbf{T}) , equipped with a set of triangles, called the distinguished triangles. The set of distinguished triangles must satisfy the following three axioms:

- (TR1) It is closed under isomorphisms; every morphism α sits inside a distinguished triangle like (12.6.1); and every object L sits inside a distinguished triangle with $\alpha = \text{id}_L$ and $N = 0$.
- (TR2) Closure under turning.
- (TR3) Closure under extension (weak functoriality of the cone).

We are deliberately ignoring the octahedral axiom (TR4). This is because it is hard to understand, hard to prove, and unnecessary for our purposes. The “price” for ignoring it is that we only talk about pretriangulated categories – i.e. the prefix “pre” is added everywhere.

Suppose now (\mathbf{K}, \mathbf{T}) and $(\mathbf{K}', \mathbf{T}')$ are pretriangulated categories. A triangulated functor

$$(F, \tau) : (\mathbf{K}, \mathbf{T}) \rightarrow (\mathbf{K}', \mathbf{T}')$$

is a \mathbf{T} -additive functor that respects distinguished triangles, in the following sense: for any distinguished triangle (12.6.1) in \mathbf{K} , the triangle

$$F(L) \xrightarrow{F(\alpha)} F(M) \xrightarrow{F(\beta)} F(N) \xrightarrow{\tau_L \circ F(\gamma)} \mathbf{T}'(F(L))$$

in \mathbf{K}' is distinguished. The composition of triangulated functors is their composition as \mathbf{T} -additive functors.

There is a vast source of pretriangulated categories and triangulated functors. For any pair (A, M) the homotopy category $\mathbf{K} := \mathbf{K}(A, M)$ inherits the translation functor \mathbf{T} from the DG category $\mathbf{C}(A, M)$, under the canonical full functor

$$P : \mathbf{C}(A, M) \rightarrow \mathbf{K}(A, M).$$

By definition, the distinguished triangles in $\mathbf{K}(A, M)$ are those that are isomorphic to the images, under the functor P , of standard triangles. A calculation (Theorem 6.4.4) shows that they satisfy the axioms of pretriangulated category.

We proved (Theorem 6.4.15) that for any DG functor

$$F : \mathbf{C}(A, M) \rightarrow \mathbf{C}(B, N),$$

the induced \mathbf{T} -additive functor

$$(F, \tau_F) : \mathbf{K}(A, M) \rightarrow \mathbf{K}(B, N)$$

is triangulated.

Another source of triangulated functors is by composing other triangulated functors. This will turn out to be of tremendous importance. A mere shadow of this feature is the Grothendieck spectral sequence associated to a composition of functors.

12.7. Localization of Categories.

Here we review Section 7. Suppose \mathbf{K} is a category, and \mathbf{S} is a multiplicatively closed set of morphism in it (just like in a ring). There is always the formal localization of \mathbf{K} with respect to \mathbf{S} – this is a category $\mathbf{K}_{\mathbf{S}}$, with a functor

$$Q : \mathbf{K} \rightarrow \mathbf{K}_{\mathbf{S}},$$

that is the identity on objects, it sends any morphism $s \in \mathbf{S}$ to an isomorphism, and it is initial among all such pairs $(\mathbf{K}_{\mathbf{S}}, Q)$.

The localization is manageable if it has a calculus of fractions, a.k.a. Ore localization. The set \mathbf{S} is called a right denominator set if it satisfies the right Ore condition (R1) and the right cancellation condition (R2). We proved in full detail that \mathbf{S} is a right denominator set iff $(\mathbf{K}_{\mathbf{S}}, Q)$ is a right Ore localization. The same is true on the left side.

12.8. The Derived Category. Now we recall Section 8. We know that the homotopy category $\mathbf{K}(A, \mathbf{M})$ is a pretriangulated category. A morphism $\psi : M \rightarrow N$ in $\mathbf{K}(A, \mathbf{M})$ is called a quasi-isomorphism if all the cohomologies

$$H^i(\psi) : H^i(M) \rightarrow H^i(N)$$

are isomorphisms (in the category \mathbf{M}). The set of quasi-isomorphisms is denoted by $\mathbf{S}(A, \mathbf{M})$.

We proved that $\mathbf{S}(A, \mathbf{M})$ is both a left and right denominator set. The derived category is the localization

$$\mathbf{D}(A, \mathbf{M}) := \mathbf{K}(A, \mathbf{M})_{\mathbf{S}(A, \mathbf{M})}.$$

It is a pretriangulated category, and the localization functor

$$Q : \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{D}(A, \mathbf{M})$$

is triangulated.

For a boundedness condition \star , that could be $+$, $-$ or b , we denote by $\mathbf{K}^\star(A, \mathbf{M})$ the full subcategory of $\mathbf{K}(A, \mathbf{M})$ on the DG modules with this condition. The localization of $\mathbf{K}^\star(A, \mathbf{M})$ w.r.t. its quasi-isomorphisms is $\mathbf{D}^\star(A, \mathbf{M})$. If the relevant truncation functor exists (this is always so for $\mathbf{K}(\mathbf{M})$), then the functor $\mathbf{K}^\star(A, \mathbf{M}) \rightarrow \mathbf{K}(A, \mathbf{M})$ is fully faithful.

As before, in the special cases we write $\mathbf{D}(A) := \mathbf{D}(A, \text{Mod } \mathbb{K})$ and $\mathbf{D}(\mathbf{M}) := \mathbf{D}(\mathbb{K}, \mathbf{M})$. In this latter case the canonical functor $\mathbf{M} \rightarrow \mathbf{D}(\mathbf{M})$, that sends an object M to the complex M concentrated in degree 0, is fully faithful.

12.9. Derived Functors. This is a summary of Section 9. Since we want to treat $\mathbf{K}^\star(A, \mathbf{M})$ for various boundedness conditions \star , we now revert to the more general setting of a pretriangulated category \mathbf{K} with a denominator set \mathbf{S} of cohomological origin (like the quasi-isomorphisms in $\mathbf{K}(A, \mathbf{M})$).

Setup 12.9.1. The following are given:

- Pretriangulated categories \mathbf{K} and \mathbf{E} .
- A triangulated functor $F : \mathbf{K} \rightarrow \mathbf{E}$.
- A denominator set of cohomological origin $\mathbf{S} \subseteq \mathbf{K}$. The morphisms in it will be called quasi-isomorphisms.

Definition 12.9.2. A right derived functor of F is a pair $(\mathbf{R}F, \eta)$, where

$$\mathbf{R}F : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}$$

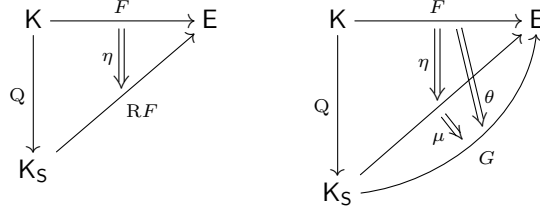
is a triangulated functor, and

$$\eta : F \Rightarrow \mathbf{R}F \circ Q$$

is a morphism of triangulated functors $\mathbf{K} \rightarrow \mathbf{E}$. The pair $(\mathbf{R}F, \eta)$ must have this universal property:

- (\diamond) Given any pair (G, θ) , consisting of a triangulated functor $G : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}$ and a morphism of triangulated functors $\theta : F \Rightarrow G \circ Q$, there is a unique morphism of triangulated functors $\mu : \mathbf{R}F \Rightarrow G$ such that $\theta = (\mu \circ \text{id}_Q) * \eta$.

Above we used a bit of 2-categorical notation. It is pictured in the following 2-diagrams:



It is quite easy to prove that a right derived functor is unique (up to a unique isomorphism).

Existence rests on the availability of suitable resolutions. Here is the theorem.

Theorem 12.9.3. *Assume there is a full pretriangulated subcategory $J \subseteq K$ with these two properties:*

- (a) *If $\phi : I \rightarrow I'$ is a quasi-isomorphism in J , then $F(\phi) : F(I) \rightarrow F(I')$ is an isomorphism in E .*
- (b) *Every object $M \in K$ admits a quasi-isomorphism $\rho : M \rightarrow I$ to some object $I \in J$.*

Then the right derived functor

$$(R.F, \eta) : K_S \rightarrow E$$

exists. Moreover, for any object $I \in J$ the morphism

$$\eta_I : F(I) \rightarrow (R.F \circ Q)(I)$$

in E is an isomorphism.

We refer to J as a category of right F -acyclic objects.

Analogously we can talk about left derived functors.

Definition 12.9.4. A *left derived functor* of F is a pair $(L.F, \eta)$, where

$$L.F : K_S \rightarrow E$$

is a triangulated functor, and

$$\eta : L.F \circ Q \Rightarrow F$$

is a morphism of triangulated functors $K \rightarrow E$. The pair $(L.F, \eta)$ must have a universal property opposite to the one in Definition 12.9.2.

As for the right derived functor, there is a uniqueness here. And existence relies on the availability of resolutions.

Theorem 12.9.5. *Assume there is a full pretriangulated subcategory $P \subseteq K$ with these two properties:*

- (a) *If $\phi : P \rightarrow P'$ is a quasi-isomorphism in P , then $F(\phi) : F(P) \rightarrow F(P')$ is an isomorphism in E .*
- (b) *Every object $M \in K$ admits a quasi-isomorphism $\rho : P \rightarrow M$ from some object $P \in P$.*

Then the right derived functor

$$(L.F, \eta) : K_S \rightarrow E$$

exists. Moreover, for any object $P \in P$ the morphism

$$\eta_P : (L.F \circ Q)(P) \rightarrow F(P)$$

in \mathbf{E} is an isomorphism.

We refer to \mathbf{P} as a category of left F -acyclic objects.

12.10. Resolutions of DG Modules. This is a review of Section 10. As we just saw, a sufficient condition for existence of derived functors (left or right) of F is the existence of enough acyclic objects.

In the original book [RD], existence of resolutions was proved for bounded (above or below) complexes, or when the additive functor F was finite dimensional (it was called “way-out” there).

At around 1990 several mathematicians discovered, independently, the secret to unbounded acyclic resolutions. It involves filtrations, and it goes by several names. We prefer the name “K-something resolution”, following Spaltenstein.

As before, A is a DG ring and \mathbf{M} is an abelian category. A DG module N is called acyclic if $H^i(N) = 0$ for all i .

Definition 12.10.1. A DG module $I \in \mathbf{C}(A, \mathbf{M})$ is called *K-injective* if for every acyclic DG module $N \in \mathbf{C}(A, \mathbf{M})$, the DG \mathbb{K} -module $\mathrm{Hom}_{A, \mathbf{M}}(N, I)$ is acyclic.

It turns out that K-injectives are right F -acyclic for any triangulated functor F .

By K-injective resolution of a DG module M we mean a quasi-isomorphism $M \rightarrow I$ into a K-injective DG module I .

For a full pretriangulated subcategory $\mathbf{K} \subseteq \mathbf{K}(A, \mathbf{M})$, we denote by $\mathbf{K}_{\mathrm{inj}}$ the full subcategory of \mathbf{K} on the K-injectives in it. It too is pretriangulated.

Theorem 12.10.2. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Assume \mathbf{K} has enough K-injectives. Let \mathbf{E} be any pretriangulated category, and let*

$$F : \mathbf{K} \rightarrow \mathbf{E}$$

be any triangulated functor. Then F has a right derived functor

$$(RF, \eta) : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}.$$

Furthermore, for any $I \in \mathbf{K}_{\mathrm{inj}}$ the morphism $\eta_I : F(I) \rightarrow RF(I)$ in \mathbf{E} is an isomorphism.

There is a bonus, already proved in [RD] for $\mathbf{K}^+(\mathbf{M})$:

Theorem 12.10.3. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. Denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Then the localization functor*

$$Q : \mathbf{K}_{\mathrm{inj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is fully faithful.

Thus, if \mathbf{K} has enough K-injectives, the functor Q above is an equivalence of pretriangulated categories.

There is a dual notion, generalizing projective resolutions.

Definition 12.10.4. A DG module $P \in \mathbf{C}(A, \mathbf{M})$ is called *K-projective* if for every acyclic DG module $N \in \mathbf{C}(A, \mathbf{M})$, the DG \mathbb{K} -module $\mathrm{Hom}_{A, \mathbf{M}}(P, N)$ is acyclic.

For a full pretriangulated subcategory $\mathbf{K} \subseteq \mathbf{K}(A, \mathbf{M})$, we denote by $\mathbf{K}_{\mathrm{prj}}$ the full subcategory of \mathbf{K} on the K-projectives in it. It too is pretriangulated.

Theorem 12.10.5. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$, and denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Assume \mathbf{K} has enough K -projectives. Let \mathbf{E} be any pretriangulated category, and let*

$$F : \mathbf{K} \rightarrow \mathbf{E}$$

be any triangulated functor. Then F has a left derived functor

$$(\mathbf{L}F, \eta) : \mathbf{K}_{\mathbf{S}} \rightarrow \mathbf{E}.$$

Furthermore, for any $P \in \mathbf{K}_{\text{prj}}$ the morphism $\eta_P : \mathbf{L}F(P) \rightarrow F(P)$ in \mathbf{E} is an isomorphism.

Once more, for K -projectives there is no need to invert quasi-isomorphisms. This was known in [RD] for $\mathbf{K}^-(\mathbf{M})$:

Theorem 12.10.6. *Let \mathbf{K} be a full pretriangulated subcategory of $\mathbf{K}(A, \mathbf{M})$. Denote by \mathbf{S} the set of quasi-isomorphisms in \mathbf{K} . Then the localization functor*

$$Q : \mathbf{K}_{\text{prj}} \rightarrow \mathbf{K}_{\mathbf{S}}$$

is fully faithful.

Thus, if \mathbf{K} has enough K -projectives, the functor Q above is an equivalence of pretriangulated categories.

12.11. Existence of Resolutions. This is a review of Section 11. We consider four situations where we can prove existence of resolutions. Further situations will be considered later, in geometry.

First, a rephrasing of a semi-classical result from [RD].

Theorem 12.11.1. *If \mathbf{M} is an abelian category with enough injectives, and if M is a complex in $\mathbf{C}(\mathbf{M})$ with bounded below cohomology, then M has a K -injective resolution $M \rightarrow I$ with $\inf(I) = \inf(\mathbf{H}(M))$.*

This implies:

Corollary 12.11.2. *If \mathbf{M} is an abelian category with enough injectives, then $\mathbf{C}^+(\mathbf{M})$ has enough K -injectives.*

Next a more recent result (from around 1990).

Theorem 12.11.3. *Let A be any DG ring. The category $\mathbf{C}(A)$ has enough K -injectives.*

Here are two existence results for K -projective resolutions. First, a rephrasing of a semi-classical result from [RD].

Theorem 12.11.4. *If \mathbf{M} is an abelian category with enough projectives, and if M is a complex in $\mathbf{C}(\mathbf{M})$ with bounded above cohomology, then M has a K -projective resolution $P \rightarrow M$ with $\sup(P) = \sup(\mathbf{H}(M))$.*

This implies:

Corollary 12.11.5. *If \mathbf{M} is an abelian category with enough injectives, then $\mathbf{C}^-(\mathbf{M})$ has enough K -projectives.*

Finally a more recent result (from around 1990).

Theorem 12.11.6. *Let A be any DG ring. The category $\mathbf{C}(A)$ has enough K -projectives.*

There are notions of K -flat and K -flasque DG modules. We will talk about them in details when we study derived categories in geometry.

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13. DERIVED BIFUNCTORS

In this section we extend the theory of derived functors to the setting of bifunctors, and study the important special cases of the Hom and tensor bifunctors.

13.1. DG Bifunctors. We had already talked about bifunctors in Subsection 1.6. That was for categories without further structure. Here we will consider \mathbb{K} -linear DG categories, and matters become more complicated.

Definition 13.1.1. Let \mathcal{C}_1 , \mathcal{C}_2 and \mathcal{D} be \mathbb{K} -linear categories. A \mathbb{K} -linear bifunctor

$$F : \mathcal{C}_1 \times \mathcal{C}_2 \rightarrow \mathcal{D}$$

is a bifunctor such that for any objects $M_i, N_i \in \mathcal{C}_i$ the function

$$F : \text{Hom}_{\mathcal{C}_1}(M_1, N_1) \times \text{Hom}_{\mathcal{C}_2}(M_2, N_2) \rightarrow \text{Hom}_{\mathcal{D}}(F(M_1, M_2), F(N_1, N_2))$$

is \mathbb{K} -bilinear.

Thus, a linear functor F induces, for every quadruple of objects, a \mathbb{K} -linear homomorphism

(13.1.2)

$$F : \text{Hom}_{\mathcal{C}_1}(M_1, N_1) \otimes_{\mathbb{K}} \text{Hom}_{\mathcal{C}_2}(M_2, N_2) \rightarrow \text{Hom}_{\mathcal{D}}(F(M_1, M_2), F(N_1, N_2)).$$

We now upgrade this operation to the DG level. In order to treat sign issues properly we make the next definition.

Definition 13.1.3. Let \mathcal{C}_1 and \mathcal{C}_2 be \mathbb{K} -linear DG categories. We define the DG category $\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2$ as follows: the set of objects is

$$\text{Ob}(\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2) := \text{Ob}(\mathcal{C}_1) \times \text{Ob}(\mathcal{C}_2).$$

For any pair of objects

$$(M_1, M_2), (N_1, N_2) \in \text{Ob}(\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2),$$

i.e. $M_i, N_i \in \text{Ob}(\mathcal{C}_i)$, we let

$$\text{Hom}_{\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2}((M_1, M_2), (N_1, N_2)) := \text{Hom}_{\mathcal{C}_1}(M_1, N_1) \otimes_{\mathbb{K}} \text{Hom}_{\mathcal{C}_2}(M_2, N_2).$$

The formula for the composition is this: given morphisms

$$\phi_i \in \text{Hom}_{\mathcal{C}_i}(L_i, M_i)^{d_i}$$

and

$$\psi_i \in \text{Hom}_{\mathcal{C}_i}(M_i, N_i)^{e_i}$$

for $i = 1, 2$, their tensors are morphisms

$$\phi_1 \otimes \phi_2 \in \text{Hom}_{\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2}((L_1, L_2), (M_1, M_2))$$

and

$$\psi_1 \otimes \psi_2 \in \text{Hom}_{\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2}((M_1, M_2), (N_1, N_2)).$$

Any morphism in $\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2$ is a sum of such tensors. We define the composition to be

$$\begin{aligned} (\psi_1 \otimes \psi_2) \circ (\phi_1 \otimes \phi_2) &:= (-1)^{d_1 \cdot e_2} \cdot (\psi_1 \circ \phi_1) \otimes (\psi_2 \circ \phi_2) \\ &\in \text{Hom}_{\mathcal{C}_1 \otimes_{\mathbb{K}} \mathcal{C}_2}((L_1, L_2), (N_1, N_2))^{d_1 + d_2 + e_1 + e_2}. \end{aligned}$$

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Example 13.1.4. Suppose C_1 and C_2 are single-object \mathbb{K} -linear DG categories. Then $C_1 \otimes_{\mathbb{K}} C_2$ is also a single-object \mathbb{K} -linear DG category. Denoting this single object by $*$, as the topologists like to do, the endomorphism DG rings satisfy

$$(C_1 \otimes_{\mathbb{K}} C_2)(*) = C_1(*) \otimes_{\mathbb{K}} C_2(*)$$

See Examples 3.1.7 and 3.3.9.

DG functors between DG categories were introduced in Definition 3.5.1.

Definition 13.1.5. Let C_1, C_2 and D be \mathbb{K} -linear DG categories. A \mathbb{K} -linear DG bifunctor

$$F : C_1 \times C_2 \rightarrow D$$

is, by definition, a \mathbb{K} -linear DG functor

$$F : C_1 \otimes_{\mathbb{K}} C_2 \rightarrow D,$$

where $C_1 \otimes_{\mathbb{K}} C_2$ is the DG category from Definition 13.1.3.

Warning: due to the signs that odd morphisms acquire, a DG bifunctor F is not a \mathbb{K} -linear bifunctor in the sense of Definition 13.1.1. Still, the induced functors on the strict subcategories

$$\text{Str}(F) : \text{Str}(C_1) \times \text{Str}(C_2) \rightarrow \text{Str}(D)$$

and on the homotopy categories

$$\text{Ho}(F) : \text{Ho}(C_1) \times \text{Ho}(C_2) \rightarrow \text{Ho}(D)$$

are genuine \mathbb{K} -linear bifunctors.

cmnt: Definition 13.1.6 and ?? belong in Section 3

We need to talk about contravariant DG functors.

Definition 13.1.6. Let C and D be DG categories. A *contravariant \mathbb{K} -linear DG functor*

$$F : C \rightarrow D$$

is, by definition, a \mathbb{K} -linear DG functor

$$F : C^{\text{op}} \rightarrow D.$$

Here C^{op} is the DG category from Definition 3.8.2.

To make things explicit, a contravariant DG functor F amounts to a function

$$F : \text{Ob}(C) \rightarrow \text{Ob}(D),$$

together with a strict homomorphism of DG \mathbb{K} -modules

$$F : \text{Hom}_C(M, N) \rightarrow \text{Hom}_D(F(N), F(M))$$

for and pair of objects M, N , such that for any morphisms $\phi \in \text{Hom}_C(L, M)^d$ and $\psi \in \text{Hom}_C(M, N)^e$ there is equality

$$F(\psi \circ \phi) = (-1)^{d \cdot e} \cdot F(\phi) \circ F(\psi) \in \text{Hom}_D(F(N), F(L))^{d+e}.$$

And of course $F(\text{id}_M) = \text{id}_{F(M)}$. Once more, such F is not a genuine contravariant functor (because of the signs), but it induces genuine contravariant functors between the strict categories and between the homotopy categories.

Example 13.1.7. Let \mathbf{C} be a DG category. The canonical operation $\text{op} : \mathbf{C}^{\text{op}} \rightarrow \mathbf{C}$ is a contravariant DG functor.

The definitions above tell us what is a DG bifunctor that is contravariant in the first or the second argument. They also tell us how to treat compositions of contravariant DG functors or bifunctors. And they tell us what are morphisms between contravariant DG functors and between DG bifunctors. The rule is always to write the opposite category in the first argument whenever there is a contravariance, and that puts us in the covariant situation.

Here are the two main examples of DG bifunctors. We give each of them in the commutative version and the noncommutative version (which is very confusing!).

Example 13.1.8. Consider a commutative ring A . The category of complexes of A -modules is the DG category $\mathbf{C}(A)$, and we take $\mathbf{C}_1 = \mathbf{C}_2 = \mathbf{D} := \mathbf{C}(A)$. For any pair of objects $M_1, M_2 \in \mathbf{C}(A)$ there is an object

$$F(M_1, M_2) := M_1 \otimes_A M_2 \in \mathbf{C}(A).$$

This is the usual tensor product of complexes. We define the action of F on morphisms as follows: given

$$\phi_i \in \text{Hom}_{\mathbf{C}(A)}(M_i, N_i)^{k_i} = \text{Hom}_A(M_i, N_i)^{k_i},$$

we let

$$\begin{aligned} F(\phi_1, \phi_2) &:= \phi_1 \otimes \phi_2 \in \text{Hom}_A(M_1 \otimes_A M_2, N_1 \otimes_A N_2)^{k_1+k_2} \\ &= \text{Hom}_{\mathbf{C}(A)}(F(M_1, M_2), F(N_1, N_2))^{k_1+k_2}. \end{aligned}$$

The result is a DG bifunctor

$$F : \mathbf{C}(A) \times \mathbf{C}(A) \rightarrow \mathbf{C}(A).$$

Example 13.1.9. Consider DG rings A_0, A_1, A_2 (possibly noncommutative, but \mathbb{K} -central). Let us define the new DG rings $B_i := A_{i-1} \otimes_{\mathbb{K}} A_i^{\text{op}}$ for $i = 1, 2$. There are corresponding DG categories $\mathbf{C}_i := \mathbf{C}(B_i)$. An object of \mathbf{C}_i is just a DG A_{i-1} - A_i -bimodule. Let us also define the DG ring $C := A_0 \otimes_{\mathbb{K}} A_2^{\text{op}}$ and the DG category $\mathbf{D} := \mathbf{C}(C)$. For any pair of objects $M_1 \in \mathbf{C}_1$ and $M_2 \in \mathbf{C}_2$ there is a DG \mathbb{K} -module

$$F(M_1, M_2) := M_1 \otimes_{A_1} M_2;$$

see Definition 3.3.21. This has a canonical DG C -module structure:

$$(a_0 \otimes a_2) \cdot (m_1 \otimes m_2) := (-1)^{j_2 \cdot (k_1+k_2)} \cdot (a_0 \cdot m_1) \otimes (m_2 \cdot a_2)$$

for elements $a_i \in A_i^{j_i}$ and $m_i \in M_i^{k_i}$. In this way $F(M_1, M_2)$ becomes an object of \mathbf{D} . We define the action of F on morphisms as follows: given

$$\phi_i \in \text{Hom}_{\mathbf{C}_i}(M_i, N_i)^{k_i} = \text{Hom}_{B_i}(M_i, N_i)^{k_i},$$

we let

$$F(\phi_1, \phi_2) := \phi_1 \otimes \phi_2 \in \text{Hom}_{\mathbf{D}}(F(M_1, M_2), F(N_1, N_2))^{k_1+k_2}.$$

The result is a DG bifunctor

$$F : \mathbf{C}_1 \times \mathbf{C}_2 \rightarrow \mathbf{D}.$$

Compare this example to the one-sided construction in Example 5.4.2.

Example 13.1.10. Again we take a commutative ring A , but now our bifunctor F arises from Hom , and so there is contravariance in the first argument. In order to rectify this we work with the opposite category in the first argument. (A certain amount of confusion is unavoidable here!) So we define the DG categories $\mathbf{C}_1 := \mathbf{C}(A)^{\text{op}}$ and $\mathbf{C}_2 = \mathbf{D} := \mathbf{C}(A)$. For any pair of objects $M_1, M_2 \in \mathbf{C}(A)$ there is an object

$$F(M_1, M_2) := \text{Hom}_A(M_1, M_2) \in \mathbf{C}(A).$$

This is the usual Hom complex. We define the action of F on morphisms as follows: given

$$\phi_1 \in \text{Hom}_{\mathbf{C}_1}(M_1, N_1)^{k_1} = \text{Hom}_{\mathbf{C}(A)^{\text{op}}}(M_1, N_1)^{k_1} = \text{Hom}_A(N_1, M_1)^{k_1}$$

and

$$\phi_2 \in \text{Hom}_{\mathbf{C}_2}(M_2, N_2)^{k_2} = \text{Hom}_{\mathbf{C}(A)}(M_2, N_2)^{k_2} = \text{Hom}_A(M_2, N_2)^{k_2}$$

we let

$$\begin{aligned} F(\phi_1, \phi_2) &:= \text{Hom}(\phi_1, \phi_2) \in \text{Hom}_A(\text{Hom}_A(M_1, M_2), \text{Hom}_A(N_1, N_2))^{k_1+k_2} \\ &= \text{Hom}_{\mathbf{D}}(F(M_1, M_2), F(N_1, N_2))^{k_1+k_2}. \end{aligned}$$

The result is a DG bifunctor

$$F : \mathbf{C}_1 \times \mathbf{C}_2 \rightarrow \mathbf{D}.$$

Example 13.1.11. Consider DG rings A, A_1, A_2 (possibly noncommutative, but \mathbb{K} -central). There is DG bifunctor

$$F := \text{Hom}_A(-, -) : \mathbf{C}(A \otimes_{\mathbb{K}} A_1^{\text{op}})^{\text{op}} \times \mathbf{C}(A \otimes_{\mathbb{K}} A_2^{\text{op}}) \rightarrow \mathbf{C}(A_1 \otimes_{\mathbb{K}} A_2^{\text{op}}).$$

The details here are so confusing that we just leave them out. (We will come back to this in Section 19, when discussing noncommutative dualizing complexes).

13.2. Triangulated Bifunctors. Recall the notions of T-additive category and pretriangulated category, from Section 6.

Suppose Let $(\mathbf{K}_1, \mathbf{T}_1)$ and $(\mathbf{K}_2, \mathbf{T}_2)$ are T-additive categories (linear over \mathbb{K}). There are two induced translation automorphism of the category $\mathbf{K}_1 \times \mathbf{K}_2$:

$$\mathbf{T}_1(M_1, M_2) := (\mathbf{T}_1(M_1), M_2)$$

and

$$\mathbf{T}_2(M_1, M_2) := (M_1, \mathbf{T}_2(M_2))$$

These two functors commute: $\mathbf{T}_2 \circ \mathbf{T}_1 = \mathbf{T}_1 \circ \mathbf{T}_2$.

Definition 13.2.1. Let $(\mathbf{K}_1, \mathbf{T}_1)$, $(\mathbf{K}_2, \mathbf{T}_2)$ and (\mathbf{L}, \mathbf{T}) be T-additive categories. A *T-additive bifunctor*

$$(F, \tau_1, \tau_2) : (\mathbf{K}_1, \mathbf{T}_1) \times (\mathbf{K}_2, \mathbf{T}_2) \rightarrow (\mathbf{L}, \mathbf{T})$$

is made up of an additive bifunctor

$$F : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{L},$$

as in Definition 13.1.1, together with isomorphisms

$$\tau_i : F \circ \mathbf{T}_i \xrightarrow{\cong} \mathbf{T} \circ F$$

of bifunctors $\mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{L}$. The condition is that

$$\tau_1 \circ \tau_2 = -\tau_2 \circ \tau_1,$$

as isomorphism

$$F \circ T_2 \circ T_1 = F \circ T_1 \circ T_2 \xrightarrow{\cong} T \circ T \circ F.$$

In the next exercises we let the reader establish several operations on T -additive bifunctors.

Exercise 13.2.2. In the situation of Definition 13.2.1, suppose

$$(G, \tau) : (\mathbf{L}, T) \rightarrow (\mathbf{L}', T')$$

is a T -additive functor into a fourth T -additive category (\mathbf{L}', T') . Write the explicit formula for the T -additive bifunctor

$$(G, \tau) \circ (F, \tau_1, \tau_2) : (\mathbf{K}_1, T_1) \times (\mathbf{K}_2, T_2) \rightarrow (\mathbf{L}', T').$$

This should be compared to Definition 6.1.4.

Exercise 13.2.3. In the situation of Definition 13.2.1, suppose

$$(F', \tau'_1, \tau'_2) : (\mathbf{K}_1, T_1) \times (\mathbf{K}_2, T_2) \rightarrow (\mathbf{L}, T)$$

is another T -additive bifunctor. Write the definition of a morphism of T -additive bifunctors

$$\eta : (F, \tau_1, \tau_2) \rightarrow (F', \tau'_1, \tau'_2).$$

Use Definition 6.1.4 as a template.

Exercise 13.2.4. Give a definition of a T -additive trifunctor. Show that if F and G are T -additive bifunctors, then $G(-, F(-, -))$ and $G(F(-, -), -)$ are T -additive trifunctors (whenever these compositions makes sense).

We now move to pretriangulated categories.

Definition 13.2.5. Let (\mathbf{K}_1, T_1) , (\mathbf{K}_2, T_2) and (\mathbf{L}, T) be pretriangulated categories. A *triangulated bifunctor*

$$(F, \tau_1, \tau_2) : (\mathbf{K}_1, T_1) \times (\mathbf{K}_2, T_2) \rightarrow (\mathbf{L}, T)$$

is a T -additive bifunctor that respects the pretriangulated structure in each argument. Namely, for any distinguished triangle

$$L_1 \xrightarrow{\alpha_1} M_1 \xrightarrow{\beta_1} N_1 \xrightarrow{\gamma_1} T_1(L_1)$$

in \mathbf{K}_1 , and any object $L_2 \in \mathbf{K}_2$, the triangle

$$F(L_1, L_2) \xrightarrow{F(\alpha_1, \text{id})} F(M_1, L_2) \xrightarrow{F(\beta_1, \text{id})} F(N_1, L_2) \xrightarrow{\tau_1 \circ F(\gamma_1, \text{id})} T(F(L_1, L_2))$$

in \mathbf{L} is distinguished; and the same for distinguished triangles in the second argument.

The operations on triangulated bifunctors are the same as those on T -additive bifunctors (see exercises above).

We now connect DG bifunctors and triangulated bifunctors in our favorite setup: DG modules in abelian categories.

Setup 13.2.6. We are given central DG \mathbb{K} -rings A_1, A_2, B , \mathbb{K} -linear abelian categories $\mathbf{M}_1, \mathbf{M}_2, \mathbf{N}$, and a \mathbb{K} -linear DG bifunctor

$$F : \mathbf{C}(A_1, \mathbf{M}_1) \times \mathbf{C}(A_2, \mathbf{M}_2) \rightarrow \mathbf{C}(B, \mathbf{N})$$

(Definition 13.1.5).

For any pair of objects (M_1, M_2) , with $M_i \in \mathbf{C}(A_i, M_i)$, there are isomorphisms

$$(13.2.7) \quad \tau_{i, M_1, M_2} : F(\mathbf{T}_i(M_1, M_2)) \xrightarrow{\cong} \mathbf{T}(F(M_1, M_2))$$

in $\mathbf{C}(B, \mathbf{N})$, arising from Definition 5.2.1. Let us make it explicit (only for $i = 2$, since the case $i = 1$ is so similar). Fixing the object M_1 we obtain a DG functor

$$G : \mathbf{C}(A_2, M_2) \rightarrow \mathbf{C}(B, \mathbf{N}), \quad G(M_2) := F(M_1, M_2).$$

The isomorphism

$$\tau_{2, M_1, M_2} : G(\mathbf{T}_2(M_2)) \xrightarrow{\cong} \mathbf{T}(G(M_2))$$

is then

$$\tau_{2, M_1, M_2} = \mathfrak{t}_{G(M_2)} \circ G(\mathfrak{t}_{M_2})^{-1}.$$

Lemma 13.2.8. *Fix $i \in \{1, 2\}$. Letting the pairs of objects vary, we get an isomorphism*

$$\tau_i : F \circ \mathbf{T}_i \xrightarrow{\cong} \mathbf{T} \circ F$$

of additive bifunctors

$$\mathbf{C}_{\text{str}}(A_1, M_1) \times \mathbf{C}_{\text{str}}(A_2, M_2) \rightarrow \mathbf{C}_{\text{str}}(B, \mathbf{N}).$$

Proof. This is an almost immediate consequence of the fact that the little \mathfrak{t} operators are morphisms of functors (see Theorem 4.1.7(2)), \square

These pass to the homotopy categories.

Theorem 13.2.9. *Under Setup 13.2.6, the data*

$$(F, \tau_1, \tau_2) : \mathbf{K}(A_1, M_1) \times \mathbf{K}(A_2, M_2) \rightarrow \mathbf{K}(B, \mathbf{N})$$

is a triangulated bifunctor.

Proof. The only challenge is to prove that (F, τ_1, τ_2) is a \mathbf{T} -additive bifunctor; and in that, all we have to prove is that

$$(13.2.10) \quad \tau_1 \circ \tau_2 = -\tau_2 \circ \tau_1.$$

The rest hinges on single-argument considerations, that are handled in Theorems 5.2.3 and 6.4.15.

So let us prove (13.2.10). Choose a pair of objects (M_1, M_2) . We have the diagram

(13.2.11)

$$\begin{array}{ccccc}
 & & F(\mathbf{T}_1(M_1), \mathbf{T}_2(M_2)) & & \\
 & \swarrow^{F(\text{id}, \mathfrak{t}_{M_2}^{-1})} & & \searrow^{F(\mathfrak{t}_{M_1}^{-1}, \text{id})} & \\
 & F(\mathbf{T}_1(M_1), M_2) & & F(M_1, \mathbf{T}_2(M_2)) & \\
 \mathfrak{t}_{F(\mathbf{T}_1(M_1), M_2)} \downarrow & \swarrow^{F(\mathfrak{t}_{M_1}^{-1}, \text{id})} & & \swarrow^{F(\text{id}, \mathfrak{t}_{M_2}^{-1})} & \downarrow \mathfrak{t}_{F(M_1, \mathbf{T}_2(M_2))} \\
 \mathbf{T}(F(\mathbf{T}_1(M_1), M_2)) & & F(M_1, M_2) & & \mathbf{T}(F(M_1, \mathbf{T}_2(M_2))) \\
 \mathbf{T}(F(\mathfrak{t}_{M_1}^{-1}, \text{id})) \downarrow & \swarrow^{\mathfrak{t}_{F(M_1, M_2)}} & & \swarrow^{\mathfrak{t}_{F(M_1, M_2)}} & \downarrow \mathbf{T}(F(\text{id}, \mathfrak{t}_{M_2}^{-1})) \\
 \mathbf{T}(F(M_1, M_2)) & & & & \mathbf{T}(F(M_1, M_2)) \\
 & \swarrow^{\mathbf{T}(\mathfrak{t}_{F(M_1, M_2)})} & & \swarrow^{\mathbf{T}(\mathfrak{t}_{F(M_1, M_2)})} & \\
 & & \mathbf{T}(\mathbf{T}(F(M_1, M_2))) & &
 \end{array}$$

in $\mathbf{C}(B, \mathbf{N})$. Going from top to bottom on the left edge is the morphism $\tau_1 \circ \tau_2$, and going on the right edge is the morphism $\tau_2 \circ \tau_1$. The bottom diamond is trivially commutative. The two triangles, with common vertex at $F(M_1, M_2)$, are (-1) -commutative, because $t : \text{Id} \rightarrow \mathbf{T}$ is a degree -1 morphism of DG functors. Since they occur on both sides, these signs cancel each other. Finally, the top diamond is (-1) -commutative, because

$$(t_{M_1}^{-1}, \text{id}) \circ (\text{id}, t_{M_2}^{-1}) = (t_{M_1}^{-1}, t_{M_2}^{-1}) = -(\text{id}, t_{M_2}^{-1}) \circ (t_{M_1}^{-1}, \text{id}).$$

□

cmnt: The material below should be moved to Section 6

We now address the contravariant case. Let \mathbf{K} be a pretriangulated category. In Proposition 6.2.8 we explained how to make the opposite category \mathbf{K}^{op} pretriangulated. This is used in the next two definitions.

Definition 13.2.12. Suppose \mathbf{K} and \mathbf{L} are pretriangulated categories. A *contravariant triangulated functor* $F : \mathbf{K} \rightarrow \mathbf{L}$ is, by definition, a triangulated functor $F : \mathbf{K}^{\text{op}} \rightarrow \mathbf{L}$.

Let us provide an explicit formula. For this we need to bring in the translation functors $T_{\mathbf{K}}$ and $T_{\mathbf{L}}$, and the translation isomorphism τ . Using Proposition 6.2.8 we see that the triangulated property of F is this: for any distinguished triangle

$$L \xrightarrow{\alpha} M \xrightarrow{\beta} N \xrightarrow{\gamma} T_{\mathbf{K}}(L)$$

in \mathbf{K} , the triangle

$$F(N) \xrightarrow{F(\beta)} F(M) \xrightarrow{F(\alpha)} F(L) \xrightarrow{\tau_N \circ F(-T_{\mathbf{K}}^{-1}(\gamma))} T_{\mathbf{L}}(F(N))$$

is a distinguished triangle in \mathbf{L} .

For bifunctors there are several options for contravariance.

Definition 13.2.13. Let \mathbf{K}_1 , \mathbf{K}_2 and \mathbf{L} be pretriangulated categories. A *triangulated bifunctor that is contravariant in the first or the second argument* is, by definition, a triangulated bifunctor

$$F : \mathbf{K}_1^{\diamond_1} \times \mathbf{K}_2^{\diamond_2} \rightarrow \mathbf{L}$$

as in Definition 13.2.5, where the symbols \diamond_1 and \diamond_2 are either empty or op , as the case may be.

This is nice and clean at first, until we try to employ Theorem 13.2.9 – because we still don’t know anything useful about the pretriangulated category $\mathbf{C}(A, \mathbf{M})^{\text{op}}$. This is our next task.

cmnt: following stuff should be moved to an earlier section

Lemma 13.2.14. *Let A be a DG ring and \mathbf{M} an abelian category. There is a canonical isomorphism of DG categories*

$$G : \mathbf{C}(A, \mathbf{M})^{\text{op}} \xrightarrow{\cong} \mathbf{C}(A^{\text{op}}, \mathbf{M}^{\text{op}}).$$

Proof. In [KaSc1, Remark 1.8.11] there is an explicit formula for an isomorphism of categories $G : \mathbf{C}(\mathbf{M})^{\text{op}} \xrightarrow{\cong} \mathbf{C}(\mathbf{M}^{\text{op}})$. It goes like this. For a complex $M = \{M^i\}_{i \in \mathbb{Z}} \in \mathbf{C}(\mathbf{M})$ they define the complex

$$G(M) = \{G(M)^i\}_{i \in \mathbb{Z}} \in \mathbf{C}(\mathbf{M}^{\text{op}})$$

to have components $G(M)^i := \text{op}(M^{-i})$. The differential $d_{G(M)} = \{d_{G(M)}^i\}$ is as follows. The morphism

$$d_{G(M)}^i : G(M)^i \rightarrow G(M)^{i+1}$$

is

$$(-1)^{-i-1} \cdot \text{op}(d_M^{-i-1}) : \text{op}(M^{-i}) \rightarrow \text{op}(M^{-i-1}).$$

It was not mentioned in [KaSc1], but G is in fact an isomorphism of DG categories (i.e. a DG functor that is an isomorphism).

cmnt: this needs to be verified !

For any object $M \in \mathbf{C}(\mathbf{M})$, its endomorphism DG ring in $\mathbf{C}(\mathbf{M})^{\text{op}} \cong \mathbf{C}(\mathbf{M}^{\text{op}})$ is the opposite of its endomorphism DG ring in $\mathbf{C}(\mathbf{M})$. Hence there is a DG ring homomorphism from A^{op} to it. This makes $G(M)$ into a DG A^{op} -module in \mathbf{M}^{op} . Lastly we need to check that this A^{op} -module structure is functorial – But that is straightforward. □

cmnt: to here lecture 16 Nov 2016

Remark 13.2.15. Unlike what one might be tempted to think, the lemma above does not say that $\mathbf{C}(A)^{\text{op}}$, the opposite DG category of the category of DG A -modules $\mathbf{C}(A)$, is equivalent to the category $\mathbf{C}(A^{\text{op}})$ of right DG A -modules. What it does say is that

$$\mathbf{C}(A)^{\text{op}} = \mathbf{C}(A, \text{Mod } \mathbb{K})^{\text{op}} \cong \mathbf{C}(A^{\text{op}}, (\text{Mod } \mathbb{K})^{\text{op}}).$$

On the other hand,

$$\mathbf{C}(A^{\text{op}}) = \mathbf{C}(A^{\text{op}}, \text{Mod } \mathbb{K}).$$

But there is never (except for the trivial ring \mathbb{K}) an equivalence between $(\text{Mod } \mathbb{K})^{\text{op}}$ and $\text{Mod } \mathbb{K}$.

Since the homotopy category of $\mathbf{C}(A, \mathbf{M})^{\text{op}}$ is $\mathbf{K}(A, \mathbf{M})^{\text{op}}$, the lemma above gives rise to an isomorphism of additive categories

$$(13.2.16) \quad \bar{G} : \mathbf{K}(A, \mathbf{M})^{\text{op}} \rightarrow \mathbf{K}(A^{\text{op}}, \mathbf{M}^{\text{op}}).$$

Now $\mathbf{K}(A, \mathbf{M})^{\text{op}}$ is a pretriangulated category, by virtue of being the opposite of the pretriangulated category $\mathbf{K}(A, \mathbf{M})$. And $\mathbf{K}(A^{\text{op}}, \mathbf{M}^{\text{op}})$ is a pretriangulated category on its own.

Lemma 13.2.17. *There is an isomorphism of additive functors*

$$\tau : \bar{G} \circ \mathbf{T}_{\mathbf{K}(A, \mathbf{M})^{\text{op}}} \xrightarrow{\cong} \mathbf{T}_{\mathbf{K}(A^{\text{op}}, \mathbf{M}^{\text{op}})} \circ \bar{G}$$

such that

$$(\bar{G}, \tau) : \mathbf{K}(A, \mathbf{M})^{\text{op}} \rightarrow \mathbf{K}(A^{\text{op}}, \mathbf{M}^{\text{op}}).$$

is a triangulated functor.

Proof.

cmnt: I hope it is true. Needs a proof!

□

Corollary 13.2.18. *Let*

$$F : \mathbf{C}(A_1, M_1)^{\diamond_1} \times \mathbf{C}(A_2, M_2)^{\diamond_2} \rightarrow \mathbf{C}(B, N)$$

be a DG bifunctor, where symbols \diamond_1 and \diamond_2 are either empty or op . Then the induced bifunctor on the homotopy categories

$$F : \mathbf{K}(A_1, M_1)^{\diamond_1} \times \mathbf{K}(A_2, M_2)^{\diamond_2} \rightarrow \mathbf{K}(B, N)$$

is a triangulated bifunctor

Proof. Using Lemma 13.2.14 we can get rid of the symbols \diamond_i . Then we apply Theorem 13.2.9 to get a triangulated bifunctor, including the data of translation isomorphisms τ_1 and τ_2 . Finally we use Lemma 13.2.17 to re-insert the symbols \diamond_i . □

13.3. Right Derived Bifunctors. We now tackle localized categories. Here, for the sake of simplicity, we shall mostly ignore the translation functors (enough was said about them in the previous subsection).

Setup 13.3.1. The following are given:

- (1) Pretriangulated categories $\mathbf{K}_1, \mathbf{K}_2$ and \mathbf{E} .
- (2) A triangulated bifunctor $F : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{E}$.
- (3) Denominator sets of cohomological origin $S_1 \subseteq \mathbf{K}_1$ and $S_2 \subseteq \mathbf{K}_2$.

cmnt: merge setup with next def?

The morphisms in S_i , for $i = 1, 2$, are referred to as quasi-isomorphisms. The localized category $\mathbf{D}_i := (\mathbf{K}_i)_{S_i}$ is pretriangulated, and the localization functor $Q_i : \mathbf{K}_i \rightarrow \mathbf{D}_i$ is triangulated. On the product categories we get a functor

$$Q_1 \times Q_2 : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{D}_1 \times \mathbf{D}_2.$$

In the next definition we use the 2-categorical notation from Subsection 9.1.

Definition 13.3.2. Under Setup 13.3.1, a *right derived bifunctor* of F is a pair $(\mathbf{R}F, \eta)$, where

$$\mathbf{R}F : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{E}$$

is a triangulated bifunctor, and

$$\eta : F \Rightarrow \mathbf{R}F \circ (Q_1 \times Q_2)$$

is a morphism of triangulated bifunctors, such that the following universal property holds:

- (R) Given any pair (G, θ) , consisting of a triangulated bifunctor

$$G : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{E}$$

and a morphism of triangulated bifunctors $\theta : F \Rightarrow G \circ (Q_1 \times Q_2)$, there is a unique morphism of triangulated functors $\mu : \mathbf{R}F \Rightarrow G$ such that $\theta = (\mu \circ \text{id}_{Q_1 \times Q_2}) * \eta$.

Here is a diagram showing property (R):

(13.3.3)

$$\begin{array}{ccc}
 K_1 \times K_2 & \xrightarrow{F} & E \\
 \downarrow Q_1 \times Q_2 & \searrow RF & \downarrow \eta \\
 D_1 \times D_2 & \xrightarrow{G} & E
 \end{array}$$

The diagram shows a commutative square with an additional arrow. The top-left node is $K_1 \times K_2$, the top-right node is E , the bottom-left node is $D_1 \times D_2$, and the bottom-right node is E . A horizontal arrow F points from $K_1 \times K_2$ to E . A vertical arrow $Q_1 \times Q_2$ points from $K_1 \times K_2$ down to $D_1 \times D_2$. A diagonal arrow RF points from $K_1 \times K_2$ down and right to E . A diagonal arrow G points from $D_1 \times D_2$ up and right to E . A vertical arrow η points from F down to RF . A diagonal arrow μ points from RF down and right to G . A diagonal arrow θ points from F down and right to G .

Proposition 13.3.4. *If a right derived bifunctor exists, then it is unique up to a unique isomorphism.*

Proof. This is just like the proof of Proposition 9.3.2. We leave the small changes up to the reader. \square

Existence in general is like Theorem 9.3.3, but more complicated.

Definition 13.3.5. Let K be a pretriangulated category, let $S \subseteq K$ be a denominator set of cohomological origin, and let $J \subseteq K$ be a full pretriangulated subcategory. We refer to the morphisms in S as quasi-isomorphisms.

- (1) Let $M \in K$. A *right J-resolution* of M is a quasi-isomorphism $\rho : M \rightarrow I$ to an object $I \in J$.
- (2) We say that K *has enough right J-resolutions* if every object $M \in K$ admits a right J-resolution.

cmnt: this def should be moved to Sec 8

Theorem 13.3.6. *Under Setup 13.3.1,*

cmnt: change wording - no setup?

assume there are full pretriangulated subcategories $J_1 \subseteq K_1$ and $J_2 \subseteq K_2$ with these two properties:

- (a) *Acyclicity: if $\phi_1 : I_1 \rightarrow J_1$ is a quasi-isomorphism in J_1 and $\phi_2 : I_2 \rightarrow J_2$ is a quasi-isomorphism in J_2 , then*

$$F(\phi_1, \phi_2) : F(I_1, I_2) \rightarrow F(J_1, J_2)$$

is an isomorphism in E .

- (b) *Abundance: K_1 has enough right J_1 -resolutions, and K_2 has enough right J_2 -resolutions.*

Then the right derived bifunctor

$$(RF, \eta) : D_1 \times D_2 \rightarrow E$$

exists. Moreover, for any objects $I_1 \in J_1$ and $I_2 \in J_2$ the morphism

$$\eta_{I_1, I_2} : F(I_1, I_2) \rightarrow RF(I_1, I_2)$$

in E is an isomorphism.

In applications we will see that either $J_1 = K_1$ or $J_2 = K_2$; namely we will only need to resolve in the second or in the first argument, respectively.

The proof of the theorem requires some more work on 2-categorical material. We will therefore interrupt our discussion, and return to the proof of Theorem 13.3.6 in Subsection 13.5.

13.4. Abstract Derived Functors.

cmnt: this subsec should be moved to Sec 6, just after Subsec 6.2 ?

cmnt: This subsection, and possibly also subsection 9.1, should be moved to Section 6, just after Subsec 6.2.

Here we deal with right and left derived functors in an abstract setup (as opposed to the triangulated setup).

We first introduce *functor categories*; these will extend our understanding of 2-categorical ideas. All set theoretical issues (sizes of sets) are neglected; the justification is in Subsection 1.1.

Definition 13.4.1. Given categories C and D , let $\text{Fun}(C, D)$ be the category whose objects are the functors $F : C \rightarrow D$, and the morphisms are the morphisms of functors $\eta : F \rightarrow F'$, i.e. the natural transformations.

Remark 13.4.2. In the full-fledged 2-category framework, there is the 2-category **Cat**. Its objects are the categories. The 1-morphisms are the functors, and the 2-morphisms are the morphisms between functors. Thus using the categories $\text{Fun}(C, D)$ we can talk about part of the structure of **Cat**, without having to worry about the whole 2-category story.

Suppose $G : C' \rightarrow C$ and $H : D \rightarrow D'$ are functors. There is an induced functor

$$(13.4.3) \quad F(G, H) : \text{Fun}(C, D) \rightarrow \text{Fun}(C', D')$$

defined by $F(G, H)(F) := H \circ F \circ G$.

Proposition 13.4.4. *If G and H are equivalences, then the functor $F(G, H)$ in (13.4.3) is an equivalence.*

Exercise 13.4.5. Prove Proposition 13.4.4.

Recall that for a category C and a multiplicatively closed set of morphisms $S \subseteq C$ we denote by C_S the localization. It comes with the localization functor $Q : C \rightarrow C_S$. See Definition 7.1.2.

For a category E let $E^\times \subseteq E$ be the category of isomorphisms; it has all the objects, but its morphisms are just the isomorphisms in E .

Definition 13.4.6. Given categories C and E , a multiplicatively closed set of morphisms $S \subseteq C$, and a functor $F : C \rightarrow E$, we say that F is *localizable to S* if $F(S) \subseteq E^\times$. We denote by $\text{Fun}_S(C, E)$ the full subcategory of $\text{Fun}(C, E)$ on the localizable functors.

Here is a useful formulation of the universal property of localization. Recall that a functor is an isomorphism of categories iff it is an equivalence that is bijective on sets of objects.

Proposition 13.4.7. *Let \mathcal{C} and \mathcal{E} be categories, and let $\mathcal{S} \subseteq \mathcal{C}$ be a multiplicatively closed set of morphisms. Then the functor*

$$F(Q, \text{Id}_{\mathcal{E}}) : \text{Fun}(\mathcal{C}_{\mathcal{S}}, \mathcal{E}) \rightarrow \text{Funs}_{\mathcal{S}}(\mathcal{C}, \mathcal{E})$$

is an isomorphism of categories.

Exercise 13.4.8. Prove Proposition 13.4.7.

By definition a bifunctor $F : \mathcal{C} \times \mathcal{D} \rightarrow \mathcal{E}$ is a functor from the product category $\mathcal{C} \times \mathcal{D}$. See Subsection 1.6. It will be useful to retain both meanings; so we shall write

$$(13.4.9) \quad \text{BiFun}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) := \text{Fun}(\mathcal{C} \times \mathcal{D}, \mathcal{E}),$$

where in the first expression we recall that $\mathcal{C} \times \mathcal{D}$ is a product.

The next proposition describes bifunctors in a non-symmetric fashion.

Proposition 13.4.10. *Let \mathcal{C} , \mathcal{D} and \mathcal{E} be categories. There is an isomorphism of categories*

$$\Xi : \text{Fun}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) \rightarrow \text{Fun}(\mathcal{C}, \text{Fun}(\mathcal{D}, \mathcal{E}))$$

with the following formula: for a functor $F : \mathcal{C} \times \mathcal{D} \rightarrow \mathcal{E}$, the functor

$$\Xi(F) : \mathcal{C} \rightarrow \text{Fun}(\mathcal{D}, \mathcal{E})$$

is $\Xi(F)(C) := F(C, -)$.

Exercise 13.4.11. Prove Proposition 13.4.10.

Proposition 13.4.12. *Let \mathcal{C} and \mathcal{D} be categories, and let $\mathcal{S} \subseteq \mathcal{C}$ and $\mathcal{T} \subseteq \mathcal{D}$ be multiplicatively closed sets of morphisms. Then the canonical functor*

$$\Theta : (\mathcal{C} \times \mathcal{D})_{\mathcal{S} \times \mathcal{T}} \rightarrow \mathcal{C}_{\mathcal{S}} \times \mathcal{D}_{\mathcal{T}}$$

is an isomorphism of categories.

Proof. The functor Θ is the identity on objects. Thus Θ is an equivalence iff it is an isomorphism. We will produce a functor

$$G : \mathcal{C}_{\mathcal{S}} \times \mathcal{D}_{\mathcal{T}} \rightarrow (\mathcal{C} \times \mathcal{D})_{\mathcal{S} \times \mathcal{T}}$$

that is inverse to Θ .

Consider another category \mathcal{E} . Invoking Propositions 13.4.10 and 13.4.7 we get a sequence of isomorphisms of categories

$$\text{Fun}(\mathcal{C}_{\mathcal{S}} \times \mathcal{D}_{\mathcal{T}}, \mathcal{E}) \rightarrow \text{Fun}(\mathcal{C}_{\mathcal{S}}, \text{Fun}(\mathcal{D}_{\mathcal{T}}, \mathcal{E})) \rightarrow \text{Funs}_{\mathcal{S}}(\mathcal{C}, \text{Fun}_{\mathcal{T}}(\mathcal{D}, \mathcal{E})).$$

A short examination shows that the isomorphism Ξ restricts to an isomorphism on the full subcategories

$$\Xi : \text{Funs}_{\mathcal{S} \times \mathcal{T}}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) \rightarrow \text{Funs}_{\mathcal{S}}(\mathcal{C}, \text{Fun}_{\mathcal{T}}(\mathcal{D}, \mathcal{E})).$$

Thus we get a commutative diagram of categories

$$(13.4.13) \quad \begin{array}{ccccc} \text{Fun}(\mathcal{C}_{\mathcal{S}} \times \mathcal{D}_{\mathcal{T}}, \mathcal{E}) & \longrightarrow & \text{Funs}_{\mathcal{S} \times \mathcal{T}}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) & \longleftarrow & \text{Fun}((\mathcal{C} \times \mathcal{D})_{\mathcal{S} \times \mathcal{T}}, \mathcal{E}) \\ & \searrow & \downarrow & \swarrow & \\ & & \text{Fun}(\mathcal{C} \times \mathcal{D}, \mathcal{E}) & & \end{array}$$

in which the horizontal arrows are isomorphisms of categories.

Now we take $E := (C \times D)_{S \times T}$, and look at the identity functor Id_E as an object in the rightmost category in diagram (13.4.13). There is a unique object G in the leftmost category. It is the inverse of Θ we are looking for. \square

Denominator sets were introduced in Definition 7.2.14.

Proposition 13.4.14. *In the situation of Proposition 13.4.12, the following conditions are equivalent:*

- (i) *The multiplicatively closed sets $S \subseteq C$ and $T \subseteq D$ are left (resp. right) denominator sets.*
- (i) *The multiplicatively closed set $S \times T \subseteq C \times D$ is a left (resp. right) denominator set.*

Exercise 13.4.15. Prove Proposition 13.4.14.

Exercise 13.4.16. Assume the categories C , D and E are \mathbb{K} -linear. Let's denote by $\text{AdFun}(C, D)$ the category of \mathbb{K} -linear functors $F : C \rightarrow D$, and by $\text{AdBiFun}(C \times D, E)$ the category of \mathbb{K} -linear bifunctors $F : C \times D \rightarrow E$. Give linear versions of Propositions 13.4.4, 13.4.7, 13.4.10 and 13.4.12.

cmnt: to here lecture 23 Nov 2016

cmnt: There is a mistake in the proof of Thm 8.3.3. The problem: Lemma 8.3.13. Use Thm 13.4.20 instead.

Definition 13.4.17. Consider a category K and a multiplicatively closed set of morphisms $S \subseteq K$, with localization functor $Q : K \rightarrow K_S$. Let $F : K \rightarrow E$ be a functor. A *right derived functor* of F with respect to S is a pair (RF, η) , where

$$RF : K_S \rightarrow E$$

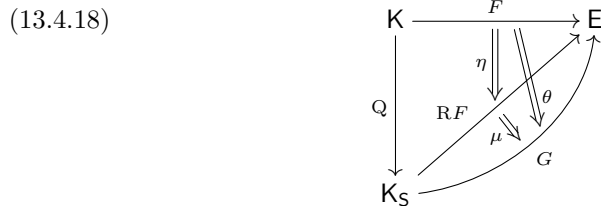
is a functor, and

$$\eta : F \Rightarrow RF \circ Q$$

is a morphism of functors, such that the following universal property holds:

- (R) Given any pair (G, θ) , consisting of a functor $G : K_S \rightarrow E$ and a morphism of functors $\theta : F \Rightarrow G \circ Q$, there is a unique morphism of functors $\mu : RF \Rightarrow G$ such that $\theta = (\mu \circ \text{id}_Q) * \eta$.

Here is a 2-diagram showing property (R):



Proposition 13.4.19. *If a right derived functor (RF, η) exists, then it is unique, up to a unique isomorphism. Namely, if (G, θ) is another right derived functor of F , then there is a unique isomorphism of functors $\mu : RF \xrightarrow{\cong} G$ such that $\theta = (\mu \circ \text{id}_Q) * \eta$.*

Proof. Despite the apparent complication of the situation, the usual argument for uniqueness of universals (here it is a universal 1-morphism) applies. It shows that the morphism μ from condition (R) is an isomorphism. \square

Here is a rather general existence result.

Theorem 13.4.20. *In the situation of Definition 13.4.17, assume there is a full subcategory $J \subseteq K$ such the following three conditions hold:*

- (a) *The multiplicatively closed set S is a left denominator set in K .*
- (b) *For every object $M \in K$ there is a morphism $\rho : M \rightarrow I$ in S , with target $I \in J$.*
- (c) *If ψ is a morphism in $S \cap J$, then $F(\psi)$ is an isomorphism in E .*

Then the right derived functor

$$(RF, \eta) : K_S \rightarrow E$$

exists. Moreover, for any object $I \in J$ the morphism

$$\eta_I : F(I) \rightarrow RF(I)$$

in E is an isomorphism.

This same result is [KaSc2, Proposition 7.3.2]. However their notation is different: what we call “left denominator set”, they call “right multiplicative system”.

We need a definition and a few lemmas before giving the proof of the theorem.

Definition 13.4.21. In the situation of Theorem 13.4.20, by a *system of right J -resolutions* we mean a pair (I, ρ) , where $I : \text{Ob}(K) \rightarrow \text{Ob}(J)$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(K)}$ is a collection of morphisms $\rho_M : M \rightarrow I(M)$ in S . Moreover, if $M \in \text{Ob}(J)$, then $I(M) = M$ and $\rho_M = \text{id}_M$.

Property (b) of Theorem 13.4.20 guarantees that a system of right J -resolutions (I, ρ) exists.

Let us introduce some new notation that will make the proofs more readable:

$$(13.4.22) \quad K' := J, \quad S' := J \cap S, \quad D := K_S \quad \text{and} \quad D' := K'_S.$$

The inclusion functor is $U : K' \rightarrow K$, and its localization is $V : D' \rightarrow D$. These sit in a commutative diagram

$$(13.4.23) \quad \begin{array}{ccc} K' & \xrightarrow{U} & K \\ Q' \downarrow & & \downarrow Q \\ D' & \xrightarrow{V} & D \end{array}$$

Lemma 13.4.24. *The multiplicatively closed set S' is a left denominator set in K' .*

Proof. We need to verify conditions (LD1) and (LD2) in Definition 7.2.14.

(LD1): Given morphisms $a' : L' \rightarrow N'$ in K' and $s' : L' \rightarrow M'$ in S' , we must find morphisms $b' : M' \rightarrow K'$ in K' and $t' : N' \rightarrow K'$ in S' , such that $t' \circ a' = b' \circ s'$. Because $S \subseteq K$ satisfies this condition, we can find morphisms $b : M' \rightarrow K$ in K and $t : N' \rightarrow K$ in S such that $t \circ a' = b \circ s'$. There is a morphism $\rho : K \rightarrow K'$ in S with target $K' \in K'$. Then the morphisms $t' := \rho \circ t$ and $b' := \rho \circ b$ satisfy $t' \circ a' = b' \circ s'$, and $t' \in S'$.

(LD2): Given morphisms $a', b' : M' \rightarrow N'$ in \mathcal{K}' and $s' : L' \rightarrow M'$ in \mathcal{S}' , that satisfy $a' \circ s' = b' \circ s'$, we must find a morphism $t' : N' \rightarrow K'$ in \mathcal{S}' such that $t' \circ a' = t' \circ b'$. Because $\mathcal{S} \subseteq \mathcal{K}$ satisfies this condition, we can find a morphism $t : N' \rightarrow K$ in \mathcal{S} such that $t \circ a' = t \circ b'$. There is a morphism $\rho : K \rightarrow K'$ in \mathcal{S} with target $K' \in \mathcal{K}'$. Then the morphism $t' := \rho \circ t$ has the required property. \square

Lemma 13.4.25. *The the functor $V : \mathcal{D}' \rightarrow \mathcal{D}$ is an equivalence.*

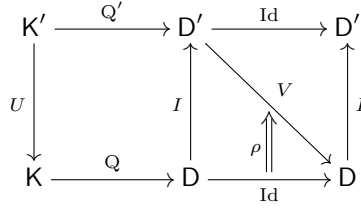
Proof. This is the same as the proof of Proposition 8.2.5 with condition (r).

cmnt: In Proposition 8.2.5 the labels (r) and (l) have to be flipped. (l) should go with “left denominator”... After the flipping, above has to be “with condition (l)”.

\square

Lemma 13.4.26. *Suppose a system of right \mathcal{K}' -resolutions (I, ρ) has been chosen. Then the function $I : \text{Ob}(\mathcal{K}) \rightarrow \text{Ob}(\mathcal{K}')$ extends uniquely to a functor $I : \mathcal{D} \rightarrow \mathcal{D}'$, such that $I \circ V = \text{Id}_{\mathcal{D}'}$, and $\rho : \text{Id}_{\mathcal{D}} \Rightarrow V \circ I$ is an isomorphism of functors. Therefore the functor I is a a quasi-inverse of V .*

The relevant 2-diagram is this:



Recall that in a 2-diagram, an empty polygon means it is commutative, namely it can be filled with $\xrightarrow{\text{id}}$.

Proof. Consider a morphism $\psi : M \rightarrow N$ in \mathcal{D} . Since $V : \mathcal{D}' \rightarrow \mathcal{D}$ is an equivalence, and since $V(I(M)) = I(M)$ and $V(I(N)) = I(N)$, there is a unique morphism

$$I(\psi) : I(M) \rightarrow I(N)$$

in \mathcal{D}' satisfying

$$(13.4.27) \quad V(I(\psi)) := Q(\rho_N) \circ \psi \circ Q(\rho_M)^{-1}.$$

in \mathcal{D} .

Let us check that $I : \mathcal{D} \rightarrow \mathcal{D}'$ is really a functor. Suppose $\phi : L \rightarrow M$ and $\psi : M \rightarrow N$ are morphisms in \mathcal{D} . Then

$$\begin{aligned} V(I(\psi) \circ I(\phi)) &= V(I(\psi)) \circ V(I(\phi)) \\ &= (Q(\rho_N) \circ \psi \circ Q(\rho_M)^{-1}) \circ (Q(\rho_M) \circ \phi \circ Q(\rho_L)^{-1}) \\ &= Q(\rho_N) \circ (\psi \circ \phi) \circ Q(\rho_L)^{-1} \\ &= V(I(\psi \circ \phi)). \end{aligned}$$

It follows that $I(\psi) \circ I(\phi) = I(\psi \circ \phi)$.

Because $\rho_{M'} : M' \rightarrow I(M')$ is the identity for any object $M' \in \mathcal{K}'$, we see that there is equality $I \circ V = \text{Id}_{\mathcal{D}'}$. By the defining formula (13.4.27) of $I(\psi)$ we have a

commutative diagram

$$\begin{array}{ccc}
 V(I(M)) & \xrightarrow{V(I(\psi))} & V(I(M)) \\
 \uparrow Q(\rho_M) & & \uparrow Q(\rho_N) \\
 M & \xrightarrow{\psi} & N
 \end{array}$$

in \mathcal{D} . Hence $\rho : \text{Id}_{\mathcal{D}} \Rightarrow V \circ I$ is an isomorphism of functors. □

Proof of Theorem 13.4.20. Diagram (13.4.23) induces a commutative diagram of categories:

$$(13.4.28) \quad \begin{array}{ccc}
 \text{Fun}(K', E) & \xleftarrow{F(U, \text{Id})} & \text{Fun}(K, E) \\
 \uparrow \text{f.f. inc} & & \uparrow \text{f.f. inc} \\
 \text{Fun}_{\mathcal{S}'}(K', E) & \xleftarrow[\text{equiv}]{F(U, \text{Id})} & \text{Fun}_{\mathcal{S}}(K, E) \\
 \uparrow \text{isom} & & \uparrow \text{isom} \\
 \text{Fun}(D', E) & \xleftarrow[\text{equiv}]{F(V, \text{Id})} & \text{Fun}(D, E)
 \end{array}$$

The vertical arrows marked “f.f. incl” are fully faithful inclusions by definition. According to Proposition 13.4.7 the vertical arrows marked “isom” are isomorphisms of categories. And by Lemma 13.4.25 the arrow $F(V, \text{Id})$ is an equivalence. As a consequence, the arrow $F(U, \text{Id})$ is also an equivalence.

Step 1. We are given a functor F that is an object of the category in the upper right corner of diagram (13.4.28). Let $F' := F \circ U$; it lives in the the upper left corner of the diagram. But condition (c) says that F' actually belongs to the middle left term in diagram (13.4.28). Because the arrow $F(Q', \text{Id})$ is an isomorphism, there is a unique functor $\text{R}F'$ that is an object of the category in the bottom left of diagram (13.4.28). It satisfies $\text{R}F' \circ Q' = F'$. See next commutative diagram.

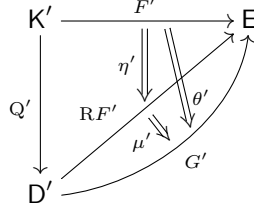
$$(13.4.29) \quad \begin{array}{ccc}
 K' & \xrightarrow{F'} & E \\
 \downarrow Q' & \nearrow \text{R}F' & \\
 D' & &
 \end{array}$$

Let $\eta' := \text{id}_{F'}$. We claim that the pair $(\text{R}F', \eta')$ is a right derived functor of F' . Indeed, suppose we are given a pair (G', θ') , where G' is a functor in the bottom left corner of diagram (13.4.28), and $\theta' : F' \Rightarrow G' \circ Q'$ is a morphism in the top corner of that diagram. See the 2-diagram (13.4.31). Because the function

$$(13.4.30) \quad \text{Hom}_{\text{Fun}(D', E)}(\text{R}F', G') \rightarrow \text{Hom}_{\text{Fun}(K', E)}(F', G' \circ Q')$$

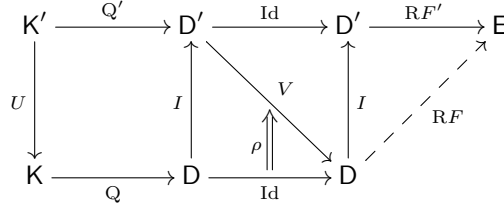
is bijective – this is the left edge of diagram (13.4.28) – there is a unique morphism $\mu' : \text{R}F' \Rightarrow G'$ that goes to θ' under (13.4.30).

(13.4.31)



Step 2. Now we choose a system of right K' -resolutions (I, ρ) , in the sense of Definition 13.4.21. By Lemma 13.4.26 we get an equivalence of categories $I : D \rightarrow D'$, that is a quasi-inverse to V , and an isomorphism of functors $\rho : \text{Id}_D \xrightarrow{\cong} V \circ I$. See the following 2-diagram (the solid arrows).

(13.4.32)



Define the functor

$$(13.4.33) \quad R F := R F' \circ I : D \rightarrow E.$$

It is the dashed arrow in diagram (13.4.32). So the functor $R F$ lives in the bottom right corner of (13.4.28), and $R F' = R F \circ V$.

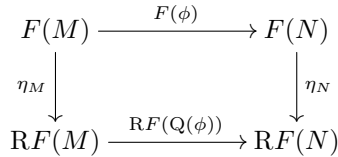
Step 3. We will now produce a morphism of functors $\eta : F \Rightarrow R F \circ Q$. This morphism should live in the category upper right corner of diagram (13.4.28).

Take an object $M \in K$. There is a morphism $\rho_M : M \rightarrow I(M)$ in S , and the target $I(M)$ is an object of K' . Define the morphism

$$(13.4.34) \quad \eta_M := F(\rho_M) : F(M) \rightarrow F(I(M)) = R F(M)$$

in E . We must prove that the collection of morphisms $\eta = \{\eta_M\}_{M \in K}$ is a morphism of functors (i.e. a natural transformation). Suppose $\phi : M \rightarrow N$ is a morphism in K . We have to show that the diagram

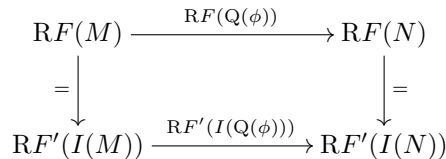
(13.4.35)



in E is commutative.

Now by definition of $R F$ there is a commutative diagram

(13.4.36)



in \mathbf{E} . Lemma 13.4.24 tells us that the morphism $I(Q(\phi))$ in \mathbf{D}' can be written as a left fraction

$$I(Q(\phi)) = Q'(\psi_1)^{-1} \circ Q'(\psi_0)$$

of morphisms $\psi_0 \in \mathbf{K}'$ and $\psi_1 \in \mathbf{S}'$. We get a diagram

$$(13.4.37) \quad \begin{array}{ccc} M & \xrightarrow{\phi} & N \\ \rho_M \downarrow & & \downarrow \rho_N \\ I(M) & \xrightarrow{I(Q(\phi))} & I(N) \\ \psi_0 \searrow & & \swarrow \psi_1 \\ & J & \end{array}$$

where the solid arrows are in the category \mathbf{K} , the dashed arrow is in \mathbf{D}' , and the object J belongs to \mathbf{K}' . This diagram might fail to be commutative; but after applying Q to it, it becomes a commutative diagram in \mathbf{D} . By condition (LO4) of the left Ore localization $Q : \mathbf{K} \rightarrow \mathbf{D}$, there is a morphism $\psi : J \rightarrow L$ in \mathbf{S} such that

$$\psi \circ \psi_0 \circ \rho_M = \psi \circ \psi_1 \circ \rho_N \circ \phi$$

in \mathbf{K} . There is the morphism $\rho_L : L \rightarrow I(L)$ in \mathbf{S} , whose target $I(L)$ belongs to \mathbf{K}' . Thus, after replacing the object J with $I(L)$, the morphism ψ_0 by $\rho_L \circ \psi \circ \psi_0$, and the morphism ψ_1 by $\rho_L \circ \psi \circ \psi_1$, and noting that the latter is a morphism in \mathbf{S}' , we can now assume that the solid diagram (13.4.37) in \mathbf{K} is commutative.

Applying the functor F to the solid commutative diagram (13.4.37) we obtain the solid commutative diagram

$$(13.4.38) \quad \begin{array}{ccc} F(M) & \xrightarrow{F(\phi)} & F(N) \\ F(\rho_M) \downarrow & & \downarrow F(\rho_N) \\ F'(I(M)) & \xrightarrow{RF'(I(Q(\phi)))} & F'(I(N)) \\ F'(\psi_0) \searrow & & \swarrow F'(\psi_1) \\ & F'(J) & \end{array}$$

in \mathbf{E} . But the morphism $F'(\psi_1)$ is an isomorphism in \mathbf{E} ; and

$$RF'(I(Q(\phi))) = F'(\psi_1)^{-1} \circ F'(\psi_0)$$

in \mathbf{E} . It follows that the top square in (13.4.38) is commutative. Therefore, making use of the commutative diagram (13.4.36), we conclude that diagram (13.4.35) is commutative. So the proof that η is a natural transformation is done.

Step 4. It remains to prove that the pair (RF, η) is a right derived functor of F . Suppose (G, θ) is a pair, where G is a functor in the category in bottom right corner of diagram (13.4.28), and $\theta : F \Rightarrow G \circ Q$ is a morphism in the top right corner of the diagram. We are looking for a morphism $\mu : RF \Rightarrow G$ in the bottom right category in diagram (13.4.28) for which $\theta = (\mu \circ \text{id}_Q) * \eta$. Let $G' := G \circ V$, and let $\theta' : F' \Rightarrow G' \circ Q'$ be the morphism in the top left corner of (13.4.28) corresponding

to θ . Because of the equivalence $F(V, \text{Id})$, finding such μ is the same as finding a morphism $\mu' : RF' \Rightarrow G'$ in the bottom left category in diagram (13.4.28), satisfying (13.4.39)

$$\theta' = (\mu' \circ \text{id}_{Q'}) * \eta'.$$

Finally, by step 1 the pair (RF', η') is a right derived functor of F' . This says that there is a unique morphism μ' satisfying (13.4.39). \square

Now to left derived functors.

Definition 13.4.40. Consider a category K and a multiplicatively closed set of morphisms $S \subseteq K$, with localization functor $Q : K \rightarrow K_S$. Let $F : K \rightarrow E$ be a functor. A *left derived functor* of F with respect to S is a pair (LF, η) , where

$$LF : K_S \rightarrow E$$

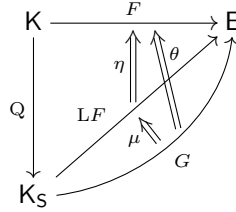
is a functor, and

$$\eta : LF \circ Q \Rightarrow F$$

is a morphism of functors, such that the following universal property holds:

- (L) Given any pair (G, θ) , consisting of a functor $G : K_S \rightarrow E$ and a morphism of functors $\theta : G \circ Q \Rightarrow F$, there is a unique morphism of functors $\mu : G \Rightarrow LF$ such that $\theta = \eta * (\mu \circ \text{id}_Q)$.

Here it is in a 2-diagram:



Proposition 13.4.41. *If a left derived functor (LF, η) exists, then it is unique, up to a unique isomorphism. Namely, if (G, θ) is another right derived functor of F , then there is a unique isomorphism of functors $\mu : G \xrightarrow{\cong} LF$ such that $\theta = \eta * (\mu \circ \text{id}_Q)$.*

The proof is the same as that of Proposition 13.4.19, only some arrows have to be reversed.

Theorem 13.4.42. *In the situation of Definition 13.4.40, assume there is a full subcategory $P \subseteq K$ such the following three conditions hold:*

- (a) *The multiplicatively closed set S is a right denominator set in K .*
- (b) *For every object $M \in K$ there is a morphism $\rho : P \rightarrow M$ in S , with source $P \in P$.*
- (c) *If ψ is a morphism in $P \cap S$, then $F(\psi)$ is an isomorphism in E .*

Then the left derived functor

$$(LF, \eta) : K_S \rightarrow E$$

exists. Moreover, for any object $P \in P$ the morphism

$$\eta_P : LF(P) \rightarrow F(P)$$

in E is an isomorphism.

The proof is the same as that of Theorem 13.4.20, only some arrows have to be reversed.

For reference we give the next definition.

Definition 13.4.43. In the situation of Theorem 13.4.42, by a *system of left P-resolutions* we mean a pair (P, ρ) , where $P : \text{Ob}(\mathbb{K}) \rightarrow \text{Ob}(\mathbb{P})$ is a function, and $\rho = \{\rho_M\}_{M \in \text{Ob}(\mathbb{K})}$ is a collection of morphisms $\rho_M : P(M) \rightarrow M$ in \mathbb{S} . Moreover, if $M \in \text{Ob}(\mathbb{P})$, then $P(M) = M$ and $\rho_M = \text{id}_M$.

Property (b) of Theorem 13.4.42 guarantees that a system of left P-resolutions (P, ρ) exists.

13.5. Right Derived Bifunctors (continued).

cmnt: reorganize. no splitting of this material

After the interlude on general categories of functors, we return to the triangulated setting.

cmnt: proof of Thm 9.3.3 has to be fixed!!

cmnt: the lemmas below should be imported to Subsec 9.3 for proving Thm 9.3.3

Definition 13.5.1. Let $\mathbb{K}_1, \mathbb{K}_2$ and \mathbb{E} be \mathbb{K} -linear pretriangulated categories. We denote by $\text{TrBiFun}(\mathbb{K}_1 \times \mathbb{K}_2, \mathbb{E})$ the category of \mathbb{K} -linear triangulated bifunctors $F : \mathbb{K}_1 \times \mathbb{K}_2 \rightarrow \mathbb{E}$.

Implicit in the definition above is that each object of $\text{TrBiFun}(\mathbb{K}_1 \times \mathbb{K}_2, \mathbb{E})$ is a triple (F, τ_1, τ_2) . The morphisms in this category are compatible with the translation isomorphism. See Definitions 6.3.1, 6.1.3 and 6.1.5. The category TrBiFun is \mathbb{K} -linear.

Suppose $U_i : \mathbb{K}'_i \rightarrow \mathbb{K}_i$ are triangulated functors between pretriangulated categories. We get an induced additive functor

$$(13.5.2) \quad F(U_1 \times U_1, \text{Id}) : \text{TrBiFun}(\mathbb{K}_1 \times \mathbb{K}_2, \mathbb{E}) \rightarrow \text{TrBiFun}(\mathbb{K}'_1 \times \mathbb{K}'_2, \mathbb{E})$$

with the same formula as in (13.4.3).

Lemma 13.5.3. *If the functors U_1 and U_2 are equivalences, then the functor $F(U_1 \times U_1, \text{Id})$ in (13.5.2) is an equivalence.*

Proof. This is basically the same as the proof of Proposition 13.4.4 (that itself was an exercise...). The delicate change is that here we have to consider the translation isomorphisms τ_1 and τ_2 . But these are controlled by the equivalence

$$F(U_1 \times U_1, \text{Id}_{\mathbb{E}}) : \text{AdBiFun}(\mathbb{K}_1 \times \mathbb{K}_2, \mathbb{E}) \rightarrow \text{AdBiFun}(\mathbb{K}'_1 \times \mathbb{K}'_2, \mathbb{E}).$$

□

Let $S_i \subseteq \mathbb{K}_i$ be denominator sets of cohomological origin. These are left (and right) denominator sets. We know that the localizations $\mathbb{D}_i := (\mathbb{K}_i)_{S_i}$ are pretriangulated categories, and the localization functors $Q_i : \mathbb{K}_i \rightarrow \mathbb{D}_i$ are triangulated. See Theorem 7.4.3.

As in Definition 13.4.6 we denote by

$$\mathrm{TrBiFun}_{S_1 \times S_2}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E}) \subseteq \mathrm{TrBiFun}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E})$$

the full subcategory on the triangulated bifunctors F such that $F(S_1 \times S_2) \subseteq \mathbf{E}^\times$.

Lemma 13.5.4. *In the situation above the functor*

$$F(Q_1 \times Q_2, \mathrm{Id}_{\mathbf{E}}) : \mathrm{TrBiFun}(D_1 \times D_2, \mathbf{E}) \rightarrow \mathrm{TrBiFun}_{S_1 \times S_2}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E})$$

is an isomorphism of categories.

Proof. This is basically that same as the proof of Proposition 13.4.7, combined with the isomorphism of pretriangulated categories

$$Q : (\mathbf{K}_1 \times \mathbf{K}_2)_{S_1 \times S_2} \rightarrow D_1 \times D_2$$

from Proposition 13.4.12. The fine point is that the translation isomorphisms τ_i are controlled by this isomorphism of categories:

$$F(Q_1 \times Q_2, \mathrm{Id}_{\mathbf{E}}) : \mathrm{AdBiFun}(D_1 \times D_2, \mathbf{E}) \rightarrow \mathrm{AdBiFun}_{S_1 \times S_2}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E}).$$

□

We can now give:

Proof of Theorem 13.3.6. It will be convenient to change notation. For $p = 1, 2$ let's define $\mathbf{K}'_p := \mathbf{J}_p$, $S'_p := \mathbf{K}'_p \cap S_p$ and $D'_p := (\mathbf{K}'_p)_{S'_p}$. The localization functors are $Q'_p : \mathbf{K}'_p \rightarrow D'_p$. The inclusions are $U_p : \mathbf{K}'_p \rightarrow \mathbf{K}_p$, and their localizations are the functors $V_p : D'_p \rightarrow D_p$. By Lemma 13.4.25 the functors V_p are equivalences.

The situation is depicted in these diagrams. We have this commutative diagram of products of triangulated functors between products of pretriangulated categories:

$$(13.5.5) \quad \begin{array}{ccc} \mathbf{K}'_1 \times \mathbf{K}'_2 & \xrightarrow{U_1 \times U_2} & \mathbf{K}_1 \times \mathbf{K}_2 \\ Q'_1 \times Q'_2 \downarrow & & \downarrow Q_1 \times Q_2 \\ D'_1 \times D'_2 & \xrightarrow{V_1 \times V_2} & D_1 \times D_2 \end{array}$$

The arrow $V_1 \times V_2$ is an equivalence. Diagram (13.5.5) induces a commutative diagram of linear categories:

$$(13.5.6) \quad \begin{array}{ccc} \mathrm{TrBiFun}(\mathbf{K}'_1 \times \mathbf{K}'_2, \mathbf{E}) & \xleftarrow{F(U_1 \times U_2, \mathrm{Id})} & \mathrm{TrBiFun}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E}) \\ \uparrow \text{f.f. inc} & & \uparrow \text{f.f. inc} \\ \mathrm{TrBiFun}_{S'_1 \times S'_2}(\mathbf{K}'_1 \times \mathbf{K}'_2, \mathbf{E}) & \xleftarrow[\text{equiv}]{F(U_1 \times U_2, \mathrm{Id})} & \mathrm{TrBiFun}_{S_1 \times S_2}(\mathbf{K}_1 \times \mathbf{K}_2, \mathbf{E}) \\ \uparrow F(Q'_1 \times Q'_2, \mathrm{Id}) \text{ isom} & & \uparrow \text{isom } F(Q_1 \times Q_2, \mathrm{Id}) \\ \mathrm{TrBiFun}(D'_1 \times D'_2, \mathbf{E}) & \xleftarrow[\text{equiv}]{F(V_1 \times V_2, \mathrm{Id})} & \mathrm{TrBiFun}(D_1 \times D_2, \mathbf{E}) \end{array}$$

According to Lemmas 13.5.3 and 13.5.4, the arrows in the diagram above that are marked “isom” or “equiv” are isomorphisms or equivalences, respectively. By definition the arrows marked “f.f. inc” are fully faithful inclusions.

We know that $S_i \subseteq K_i$ are left denominator sets. Therefore (see Proposition 13.4.14)

$$S_1 \times S_2 \subseteq K_1 \times K_2$$

is a left denominator set. Condition (a) of Theorem 13.3.6 says that F sends morphisms in $S'_1 \times S'_2$ to isomorphisms in \mathbf{E} . Condition (b) there says that there are enough right $K'_1 \times K'_2$ -resolutions in $K_1 \times K_2$.

Thus we are in a position to use the abstract Theorem 13.4.20. It says that there is an abstract right derived functor

$$(RF, \eta) : D_1 \times D_2 \rightarrow \mathbf{E}.$$

However, going over the proof of Theorem 13.4.20, we see that all constructions there can be made within the triangulated setting, namely in diagram (13.5.6) instead of in diagram (13.4.28). Therefore RF is an object of the category in the bottom right corner of (13.5.6), and the morphism $\eta : F \Rightarrow RF \circ Q$ is in the category in the top right corner of (13.5.6).

cmnt: there might be a general yoga to deduce the above...

□

13.6. The Bifunctor \mathbf{RHom} . Consider a DG ring A and an abelian category \mathbf{M} . Like in Example 13.1.10 we get a DG bifunctor

$$F := \mathrm{Hom}_{A, \mathbf{M}}(-, -) : \mathbf{C}(A, \mathbf{M})^{\mathrm{op}} \times \mathbf{C}(A, \mathbf{M}) \rightarrow \mathbf{C}(\mathbb{K}).$$

Passing to homotopy categories, and postcomposing with $Q : \mathbf{K}(\mathbb{K}) \rightarrow \mathbf{D}(\mathbb{K})$, we obtain a triangulated bifunctor

$$F = \mathrm{Hom}_{A, \mathbf{M}}(-, -) : \mathbf{K}(A, \mathbf{M})^{\mathrm{op}} \times \mathbf{K}(A, \mathbf{M}) \rightarrow \mathbf{D}(\mathbb{K}).$$

Next we pick full pretriangulated subcategories $K_1, K_2 \subseteq \mathbf{K}(A, \mathbf{M})$. In practice this choice would be by some boundedness conditions, for instance $K_2 := \mathbf{C}^+(\mathbf{M})$, cf. Corollary 11.4.10, or $K_1 := \mathbf{C}^-(\mathbf{M})$, cf. Corollary 11.2.14. We want to construct the right derived bifunctor of the triangulated bifunctor

$$F = \mathrm{Hom}_{A, \mathbf{M}}(-, -) : K_1^{\mathrm{op}} \times K_2 \rightarrow \mathbf{D}(\mathbb{K}).$$

This is done in the next theorem.

Theorem 13.6.1. *Let $K_1, K_2 \subseteq \mathbf{K}(A, \mathbf{M})$ be full pretriangulated subcategories, and let D_i denote the localization of K_i with respect to the quasi-isomorphisms in it. Assume either that K_1 has enough K -projectives, or that K_2 has enough K -injectives. Then the triangulated bifunctor*

$$\mathrm{Hom}_{A, \mathbf{M}}(-, -) : K_1^{\mathrm{op}} \times K_2 \rightarrow \mathbf{D}(\mathbb{K})$$

has a right derived bifunctor

$$\mathbf{RHom}_{A, \mathbf{M}}(-, -) : D_1^{\mathrm{op}} \times D_2 \rightarrow \mathbf{D}(\mathbb{K}).$$

Moreover, if $P_1 \in K_1$ is K -projective, or if $I_2 \in K_2$ is K -injective, then the morphism

$$\eta_{P_1, I_2} : \mathrm{Hom}_{A, \mathbf{M}}(P_1, I_2) \rightarrow \mathbf{RHom}_{A, \mathbf{M}}(P_1, I_2)$$

in $\mathbf{D}(\mathbb{K})$ is an isomorphism.

Proof. If \mathbf{K}_2 has enough K-injectives, then we can take $J_2 := \mathbf{K}_{2,\text{inj}}$, the full subcategory on the K-injectives inside \mathbf{K}_2 . And we take $J_1 := \mathbf{K}_1$. We claim that the conditions of Theorem 13.3.6 are satisfied. Condition (b) is simply the assumption that \mathbf{K}_2 has enough K-injectives. As for condition (a): this is Lemma 13.6.2 below.

On the other hand, if \mathbf{K}_1 has enough K-projectives, then we can take $J_1^{\text{op}} := \mathbf{K}_{1,\text{prj}}^{\text{op}}$, where $\mathbf{K}_{1,\text{prj}}$ is the full subcategory on the K-projectives inside \mathbf{K}_1 . And we take $J_2 := \mathbf{K}_2$. We claim that the conditions of Theorem 13.3.6 are satisfied for $J_1^{\text{op}} \subseteq \mathbf{K}_1^{\text{op}}$. Condition (b) is simply the assumption that \mathbf{K}_1 has enough K-projectives: a quasi-isomorphism $\rho : P \rightarrow M$ in \mathbf{K}_1 becomes a quasi-isomorphism $\rho^{\text{op}} : M^{\text{op}} \rightarrow P^{\text{op}}$ in \mathbf{K}_1^{op} . As for condition (a): this is Lemma 13.6.2 below.

The last assertion also follows from 13.6.2. \square

Lemma 13.6.2. *Suppose $\phi_1 : Q_1 \rightarrow P_1$ and $\phi_2 : I_2 \rightarrow J_2$ are quasi-isomorphisms in $\mathbf{C}(A, M)$, and either Q_1, P_1 are both K-projective, or I_2, J_2 are both K-injective. Then the homomorphism*

$$\text{Hom}_{A,M}(\phi_1, \phi_2) : \text{Hom}_{A,M}(P_1, I_2) \rightarrow \text{Hom}_{A,M}(Q_1, J_2)$$

in $\mathbf{C}(\mathbb{K})$ is a quasi-isomorphism.

Proof. We will only prove the case where Q_1, P_1 are both K-projective; the other case is very similar.

The homomorphism in question factors as follows:

$$\text{Hom}_{A,M}(\phi_1, \phi_2) = \text{Hom}_{A,M}(\phi_1, \text{id}_{J_2}) \circ \text{Hom}_{A,M}(\text{id}_{P_1}, \phi_2).$$

It suffices to prove that each of the factors is a quasi-isomorphism. This can be done by a messy direct calculation, but we will provide an indirect proof that relies on properties of the homotopy category $\mathbf{K} := \mathbf{K}(A, M)$ that were already established.

Let K_2 be the cone on the homomorphism $\phi_2 : I_2 \rightarrow J_2$. So K_2 is acyclic. Because P_1 is K-projective it follows that $\text{Hom}_{A,M}(P_1, K_2)$ is acyclic. Thus for every integer l we have

$$(13.6.3) \quad \text{Hom}_{\mathbf{K}}(\mathbb{T}^{-l}(P_1), K_2) \cong H^l(\text{Hom}_{A,M}(P_1, K_2)) = 0.$$

Next, there is a distinguished triangle

$$(13.6.4) \quad I_2 \xrightarrow{\phi_2} J_2 \xrightarrow{\beta_2} K_2 \xrightarrow{\gamma_2} \mathbb{T}(I_2)$$

in \mathbf{K} . Applying the cohomological functor $\text{Hom}_{\mathbf{K}}(\mathbb{T}^{-l}(P_1), -)$ to the distinguished triangle (13.6.4) yields a long exact sequence, as explained in Subsection 6.3. From it we deduce that the homomorphisms

$$\text{Hom}_{\mathbf{K}}(\mathbb{T}^{-l}(P_1), I_2) \rightarrow \text{Hom}_{\mathbf{K}}(\mathbb{T}^{-l}(P_1), J_2)$$

are bijective for all l . Using the isomorphisms like (13.6.3) for I_2 and J_2 we see that

$$\text{Hom}_{A,M}(\text{id}_{P_1}, \phi_2) : \text{Hom}_{A,M}(P_1, I_2) \rightarrow \text{Hom}_{A,M}(P_1, J_2)$$

is a quasi-isomorphism.

According to Corollary 10.2.12 the homomorphism $\phi_1 : Q_1 \rightarrow P_1$ is a homotopy equivalence; so it is an isomorphism in \mathbf{K} . Therefore for any integer l the homomorphism

$$\text{Hom}_{\mathbf{K}}(Q_1, \mathbb{T}^l(J_2)) \rightarrow \text{Hom}_{\mathbf{K}}(P_1, \mathbb{T}^l(J_2))$$

is bijective. As above we conclude that

$$\text{Hom}_{A,M}(\phi_1, \text{id}_{J_2}) : \text{Hom}_{A,M}(Q_1, J_2) \rightarrow \text{Hom}_{A,M}(P_1, J_2)$$

is a quasi-isomorphism. □

Remark 13.6.5. Theorem 13.6.1 should be viewed as a template. It has a variant for $\mathbf{C}(A)$ where A is a commutative ring, as in Example 13.1.10. There are bimodule variants as in Example 13.1.11 and Section 19. And there are geometric versions where the source and target are categories of sheaves – see Section 17.

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We end this section with the connection between \mathbf{RHom} and morphisms in the derived category.

Definition 13.6.6. Under the assumptions of Theorem 13.6.1, for DG modules $M_1 \in \mathbf{K}_1$ and $M_2 \in \mathbf{K}_2$, and for an integer i , we write

$$\mathrm{Ext}_{A,\mathbf{M}}^i(M_1, M_2) := \mathbf{H}^i(\mathbf{RHom}_{A,\mathbf{M}}(M_1, M_2)) \in \mathbf{M}(\mathbb{K}).$$

Exercise 13.6.7. Let A be a ring. Prove that for modules $M_1, M_2 \in \mathbf{M}(A)$ the \mathbb{K} -module $\mathrm{Ext}_A^i(M_1, M_2)$ defined above is canonically isomorphic to the classical definition.

Corollary 13.6.8. *Under the assumptions of Theorem 13.6.1, there is an isomorphism*

$$\mathrm{Ext}_{A,\mathbf{M}}^0(-, -) \xrightarrow{\cong} \mathrm{Hom}_{\mathbf{D}(A,\mathbf{M})}(-, -)$$

of additive bifunctors

$$\mathbf{D}_1^{\mathrm{op}} \times \mathbf{D}_2 \rightarrow \mathbf{M}(\mathbb{K}).$$

Exercise 13.6.9. Prove Corollary 13.6.8.

13.7. Left Derived Bifunctors. The material here is opposite (left vs. right) to that in Subsection 13.3. Because of the similarity, we give only a few details.

The assumptions in the next definition are identical to those in Setup 13.3.1.

Definition 13.7.1. Assume the following are given:

- (1) Pretriangulated categories $\mathbf{K}_1, \mathbf{K}_2$ and \mathbf{E} .
- (2) A triangulated bifunctor $F : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{E}$.
- (3) Denominator sets of cohomological origin $\mathbf{S}_1 \subseteq \mathbf{K}_1$ and $\mathbf{S}_2 \subseteq \mathbf{K}_2$.

A *left derived bifunctor* of F is a pair $(\mathbf{L}F, \eta)$, where

$$\mathbf{L}F : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{E}$$

is a triangulated bifunctor, and

$$\eta : \mathbf{L}F \circ (\mathbf{Q}_1 \times \mathbf{Q}_2) \Rightarrow F$$

is a morphism of triangulated bifunctors, such that the following universal property holds:

- (L) Given any pair (G, θ) , consisting of a triangulated bifunctor

$$G : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{E}$$

and a morphism of triangulated bifunctors

$$\theta : G \circ (\mathbf{Q}_1 \times \mathbf{Q}_2) \Rightarrow F,$$

there is a unique morphism of triangulated functors $\mu : G \Rightarrow LF$ such that

$$\theta = \eta * (\mu \circ \text{id}_{Q_1 \times Q_2}).$$

Proposition 13.7.2. *If a left derived bifunctor exists, then it is unique up to a unique isomorphism.*

Proof. This is the opposite of Proposition 13.3.4, and we leave it to the reader to make the adjustments. \square

Definition 13.7.3. Let K be a pretriangulated category, let $S \subseteq K$ be a denominator set of cohomological origin, and let $P \subseteq K$ be a full pretriangulated subcategory.

- (1) Let $M \in K$. A *left P-resolution* of M is a morphism $\rho : P \rightarrow M$ in S from an object $P \in P$.
- (2) We say that K *has enough left P-resolutions* if every object $M \in K$ admits a left P-resolution.

cmnt: this def should be moved to Sec 8

Theorem 13.7.4. *In the situation of Definition 13.7.1, assume there are full pretriangulated subcategories $P_1 \subseteq K_1$ and $P_2 \subseteq K_2$ with these two properties:*

- (a) *Acyclicity: if $\phi_1 : P_1 \rightarrow Q_1$ is a morphism in $P_1 \cap S_1$ and $\phi_2 : P_2 \rightarrow Q_2$ is a quasi-isomorphism in $P_2 \cap S_2$, then*

$$F(\phi_1, \phi_2) : F(P_1, P_2) \rightarrow F(Q_1, Q_2)$$

is an isomorphism in E .

- (b) *Abundance: K_1 has enough left P_1 -resolutions, and K_2 has enough left P_2 -resolutions.*

Then the left derived bifunctor

$$(LF, \eta) : D_1 \times D_2 \rightarrow E$$

exists. Moreover, for any objects $P_1 \in P_1$ and $P_2 \in P_2$ the morphism

$$\eta_{P_1, P_2} : LF(P_1, P_2) \rightarrow F(P_1, P_2)$$

in E is an isomorphism.

Proof. This is the opposite of Theorem 13.3.6, and we leave it to the reader to make the necessary changes in direction. \square

In applications we will see that either $P_1 = K_1$ or $P_2 = K_2$; namely we will only need to resolve in the second or in the first argument, respectively.

Proposition 13.7.5. *If a right derived bifunctor exists, then it is unique up to a unique isomorphism.*

Proof. This is just like the proof of Proposition 9.3.2. We leave the small changes up to the reader. \square

Existence in general is like Theorem 9.4.3, but more complicated.

Definition 13.7.6. Let K be a pretriangulated category, let $S \subseteq K$ be a denominator set of cohomological origin, and let $P \subseteq K$ be a full pretriangulated subcategory.

- (1) Let $M \in \mathbf{K}$. A *left P-resolution* of M is a quasi-isomorphism $\rho : P \rightarrow M$ in \mathbf{S} from an object $P \in \mathbf{P}$.
- (2) We say that \mathbf{K} *has enough left P-resolutions* if every object $M \in \mathbf{K}$ admits a left P-resolution.

cmnt: this def should be moved to Sec 8

Theorem 13.7.7. *In the situation of Definition 13.7.1, assume there are full pretriangulated subcategories $\mathbf{P}_1 \subseteq \mathbf{K}_1$ and $\mathbf{P}_2 \subseteq \mathbf{K}_2$ with these two properties:*

- (a) *Acyclicity: if $\phi_1 : P_1 \rightarrow Q_1$ is a morphism in $\mathbf{P}_1 \cap \mathbf{S}_1$ and $\phi_2 : P_2 \rightarrow Q_2$ is a morphism in $\mathbf{P}_2 \cap \mathbf{S}_2$, then*

$$F(\phi_1, \phi_2) : F(P_1, P_2) \rightarrow F(Q_1, Q_2)$$

is an isomorphism in \mathbf{E} .

- (b) *Abundance: \mathbf{K}_1 has enough left \mathbf{P}_1 -resolutions, and \mathbf{K}_2 has enough left \mathbf{P}_2 -resolutions.*

Then the left derived bifunctor

$$(\mathbf{L}F, \eta) : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{E}$$

exists. Moreover, for any objects $P_1 \in \mathbf{P}_1$ and $P_2 \in \mathbf{P}_2$ the morphism

$$\eta_{P_1, P_2} : \mathbf{L}F(P_1, P_2) \rightarrow F(P_1, P_2)$$

in \mathbf{E} is an isomorphism.

In applications we will see that either $\mathbf{P}_1 = \mathbf{K}_1$ or $\mathbf{P}_2 = \mathbf{K}_2$; namely we will only need to resolve in the second or in the first argument, respectively.

Proof. Like that of Theorem 13.3.6. We leave the side changes to the reader. \square

13.8. The Bifunctor $\otimes^{\mathbf{L}}$. Consider a DG ring A . Like in Example 13.1.9 we get a DG bifunctor

$$F := (- \otimes_A -) : \mathbf{C}(A^{\text{op}}) \times \mathbf{C}(A) \rightarrow \mathbf{C}(\mathbb{K}).$$

Passing to homotopy categories, and postcomposing with $\mathbf{Q} : \mathbf{K}(\mathbb{K}) \rightarrow \mathbf{D}(\mathbb{K})$, we obtain a triangulated bifunctor

$$F = (- \otimes_A -) : \mathbf{K}(A^{\text{op}}) \times \mathbf{K}(A) \rightarrow \mathbf{D}(\mathbb{K}).$$

Next we pick full pretriangulated subcategories $\mathbf{K}_1 \subseteq \mathbf{K}(A^{\text{op}})$ and $\mathbf{K}_2 \subseteq \mathbf{K}(A)$. In practice this choice would be by some boundedness conditions, for instance $\mathbf{K}_1 := \mathbf{C}^-(A^{\text{op}})$ or $\mathbf{K}_2 := \mathbf{C}^-(A)$, cf. Corollary 11.2.14. We want to construct the left derived bifunctor of the triangulated bifunctor

$$F = (- \otimes_A -) : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{D}(\mathbb{K}).$$

This is done in the next theorem.

Theorem 13.8.1. *Let $\mathbf{K}_1 \subseteq \mathbf{K}(A^{\text{op}})$ and $\mathbf{K}_2 \subseteq \mathbf{K}(A)$ be full pretriangulated subcategories, and let \mathbf{D}_i denote the localization of \mathbf{K}_i with respect to the quasi-isomorphisms in it. Assume that either \mathbf{K}_1 or \mathbf{K}_2 has enough K-flat objects.*

Then the triangulated bifunctor

$$(- \otimes_A -) : \mathbf{K}_1 \times \mathbf{K}_2 \rightarrow \mathbf{D}(\mathbb{K})$$

has a left derived bifunctor

$$(- \otimes_A^L -) : \mathbf{D}_1 \times \mathbf{D}_2 \rightarrow \mathbf{D}(\mathbb{K}).$$

Moreover, if either $P_1 \in \mathbf{K}_1$ or $P_2 \in \mathbf{K}_2$ is K -flat, then the morphism

$$\eta_{P_1, P_2} : P_1 \otimes_A^L P_2 \rightarrow P_1 \otimes_A P_2$$

in $\mathbf{D}(\mathbb{K})$ is an isomorphism.

Note that a DG module $P_1 \in \mathbf{K}_1$ is checked for K -flatness as a right DG A -module; and a DG module $P_2 \in \mathbf{K}_2$ is checked for K -flatness as a left DG A -module.

Proof. If \mathbf{K}_2 has enough K -flats, then we can take $\mathbf{P}_2 := \mathbf{K}_{2, \text{flat}}$, the full subcategory on the K -flats inside \mathbf{K}_2 . And we take $\mathbf{P}_1 := \mathbf{K}_1$. We claim that the conditions of Theorem 13.7.4 are satisfied. Condition (b) is simply the assumption that \mathbf{K}_2 has enough K -flats. As for condition (a): this is Lemma 13.8.2 below.

The other case is proved the same way (but replacing sides). The last assertion also follows from 13.8.2. \square

Lemma 13.8.2. *Suppose $\phi_1 : P_1 \rightarrow Q_1$ and $\phi_2 : P_2 \rightarrow Q_2$ are quasi-isomorphisms in $\mathbf{C}(A^{\text{op}})$ and $\mathbf{C}(A)$ respectively, and either of the conditions below holds:*

- (i) Q_1 and P_1 are both K -flat.
- (ii) P_2 and Q_2 are both K -flat.

Then the homomorphism

$$\phi_1 \otimes \phi_2 : P_1 \otimes_A P_2 \rightarrow Q_1 \otimes_A Q_2$$

in $\mathbf{C}(\mathbb{K})$ is a quasi-isomorphism.

Proof. We will only prove the lemma under condition (i); the other case is very similar. The homomorphism in question factors as follows:

$$\phi_1 \otimes \phi_2 = (\phi_1 \otimes \text{id}_{P_2}) \circ (\text{id}_{P_1} \otimes \phi_2).$$

It suffices to prove that each of the factors is a quasi-isomorphism. This can be done by a messy direct calculation, but we will provide an indirect proof that relies on properties of the DG categories $\mathbf{C}(A^{\text{op}})$ and $\mathbf{C}(A)$ that were already established.

First we shall prove that $\text{id}_{P_1} \otimes \phi_2$ is a quasi-isomorphism. Let R_2 be the standard cone on the strict homomorphism $\phi_2 : P_2 \rightarrow Q_2$. So there is a standard triangle

$$(13.8.3) \quad P_2 \xrightarrow{\phi_2} Q_2 \rightarrow R_2 \rightarrow T(P_2)$$

in $\mathbf{C}_{\text{str}}(A)$, and R_2 is acyclic. Applying the DG functor $P_1 \otimes_A -$ to the triangle (13.8.3), and using Theorem 5.3.7, we see that there is a standard triangle

$$(13.8.4) \quad P_1 \otimes_A P_2 \xrightarrow{\text{id}_{P_1} \otimes \phi_2} P_1 \otimes_A Q_2 \rightarrow P_1 \otimes_A R_2 \rightarrow T(P_1 \otimes_A P_2)$$

in $\mathbf{C}(\mathbb{K})$. This becomes a distinguished triangle in the pretriangulated category $\mathbf{K}(\mathbb{K})$. Thus there is a long exact sequence in cohomology associated to (13.8.4). Because P_1 is K -flat it follows that $P_1 \otimes_A R_2$ is acyclic. We conclude that $H^i(\text{id}_{P_1} \otimes \phi_2)$ is bijective for all i .

Now we shall prove that $\phi_1 \otimes \text{id}_{P_2}$ is a quasi-isomorphism. Let $R_1 \in \mathbf{C}(A^{\text{op}})$ be the cone on the homomorphism $\phi_1 : P_1 \rightarrow Q_1$. It is both acyclic and K -flat. Using standard triangles like (13.8.3) and (13.8.4) we reduce the problem to showing that $R_1 \otimes_A P_2$ is acyclic. According to Corollary 11.3.27 and Proposition 10.3.2 there is

a quasi-isomorphism $\tilde{P}_2 \rightarrow P_2$ in $\mathbf{C}(A)$ from some K-flat DG module \tilde{P}_2 . As already proved in the previous paragraph, since R_1 is K-flat, the homomorphism

$$R_1 \otimes_A \tilde{P}_2 \rightarrow R_1 \otimes_A P_2$$

is a quasi-isomorphism. But R_1 is acyclic and \tilde{P}_2 is K-flat, and therefore $R_1 \otimes_A \tilde{P}_2$ is acyclic. We conclude that $R_1 \otimes_A P_2$ is acyclic, as required. \square

Remark 13.8.5. Theorem 13.8.1 should be viewed as a template. It has a variant for $\mathbf{C}(A)$ where A is a commutative ring, as in Example 13.1.8. There are bimodule variants as in Example 13.1.9 and Section 19. And there are geometric versions where the source and target are categories of sheaves – see Section 17.

14. DUALIZING COMPLEXES OVER COMMUTATIVE RINGS

In this section we finally explain what was outlined, as a motivating discussing, in Subsection 0.1. Dualizing complexes are perhaps the most compelling reason to study derived categories. In the commutative setting of the current section the technicalities are milder than in the geometric setting (Section 18) and the noncommutative setting (Section 19).

We will start with some more technical facts on functors.

cmnt: move them to an earlier location,

Then we will learn about *dualizing complexes* and *residue complexes* over commutative rings, as defined by Grothendieck in [RD] in the 1960's.

The initial plan was to also talk about *Local Duality*, *MGM Equivalence* and *perfect complexes* in this section; but for lack of time and space, these topics will be confined to short remarks. See Remark 14.4.25, ???

cmnt: finish

14.1. Cohomological Dimension of Functors. The material here is a refinement of the notion of “way-out functors” from [RD, Section II.7]. It is taken from [Ye10]. As always, there is a fixed base ring \mathbb{K} .

cmnt: maybe move this material to an earlier location?

By *generalized integers* we mean elements of the ordered set $\mathbb{Z} \cup \{\pm\infty\}$. Recall that for a subset $S \subseteq \mathbb{Z}$, its infimum is $\inf(S) \in \mathbb{Z} \cup \{\pm\infty\}$, where $\inf(S) = +\infty$ iff $S = \emptyset$. Likewise the supremum is $\sup(S) \in \mathbb{Z} \cup \{\pm\infty\}$, where $\sup(S) = -\infty$ iff $S = \emptyset$. For $i, j \in \mathbb{Z} \cup \{\infty\}$, the expressions $i + j$ and $-i - j$ have obvious values in $\mathbb{Z} \cup \{\pm\infty\}$. And for $i, j \in \mathbb{Z} \cup \{\pm\infty\}$, the expression $i \leq j$ has an obvious meaning.

Let $M = \bigoplus_{i \in \mathbb{Z}} M^i$ be a graded \mathbb{K} -module. We write

$$(14.1.1) \quad \inf(M) := \inf \{i \mid M^i \neq 0\} \quad \text{and} \quad \sup(M) := \sup \{i \mid M^i \neq 0\}.$$

The amplitude of M is

$$(14.1.2) \quad \text{amp}(M) := \sup(M) - \inf(M) \in \mathbb{N} \cup \{\pm\infty\}.$$

(For $M = 0$ this reads $\inf(M) = \infty$, $\sup(M) = -\infty$ and $\text{amp}(M) = -\infty$.) Thus M is bounded (resp. bounded above, resp. bounded below) iff $\text{amp}(M) < \infty$ (resp. $\sup(M) < \infty$, resp. $\inf(M) > -\infty$).

Given $i_0 \leq i_1$ in $\mathbb{Z} \cup \{\pm\infty\}$, the *integer interval* with these endpoints is the set of integers

$$(14.1.3) \quad [i_0, i_1] := \{i \in \mathbb{Z} \mid i_0 \leq i \leq i_1\}.$$

There is also the empty integer interval \emptyset .

A nonempty integer interval $[i_0, i_1]$ is said to be bounded (resp. bounded above, resp. bounded below) if $i_0, i_1 \in \mathbb{Z}$ (resp. $i_1 \in \mathbb{Z}$, resp. $i_0 \in \mathbb{Z}$). The *length* of this interval is $i_1 - i_0 \in \mathbb{N} \cup \{\infty\}$. Of course the interval has finite length iff it is bounded.

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We write $-[i_0, i_1] := [-i_1, -i_0]$. Given a second nonempty integer interval $[j_0, j_1]$, we let

$$[i_0, i_1] + [j_0, j_1] := [i_0 + j_0, i_1 + j_1].$$

The empty integer interval \emptyset is bounded, and its length is $-\infty$. If S is any integer interval, then the sum is the integer interval $S + \emptyset := \emptyset$. And $-\emptyset := \emptyset$.

Definition 14.1.4. Let $M = \bigoplus_{i \in \mathbb{Z}} M^i$ be a graded \mathbb{K} -module.

- (1) We say that M is concentrated in an integer interval $[i_0, i_1]$ if

$$\{i \in \mathbb{Z} \mid M^i \neq 0\} \subseteq [i_0, i_1].$$

- (2) The *concentration* of M is the smallest integer interval $\text{con}(M)$ in which M is concentrated.

In other words, if $M \neq 0$ then

$$i_0 = \inf(M) \leq i_1 = \sup(M),$$

the concentration of M is the interval $\text{con}(M) = [i_0, i_1]$, and the amplitude $\text{amp}(M)$ is the length of $\text{con}(M)$. Furthermore, $\text{con}(M) = \emptyset$ iff $M = 0$.

The next definition is in conflict with Definitions 8.3.3 and 8.3.4; but we already warned that this change will take place (see Remark 8.3.9). The reason for the change: the new definition is more practical.

Definition 14.1.5. Let A be a DG ring and \mathbf{M} an abelian category. The expression $\mathbf{D}^*(A, \mathbf{M})$, where “ \star ” is either “+”, “-” or “b”, refers to the full subcategory of $\mathbf{D}(A, \mathbf{M})$ on the DG modules with bounded below (resp. bounded above, resp. bounded) cohomologies.

Thus, for example, a DG module M belongs to $\mathbf{D}^b(A, \mathbf{M})$ iff $\text{con}(\mathbf{H}(M))$ is a bounded integer interval.

Definition 14.1.6. Let A be a DG ring and \mathbf{M} an abelian category. For a DG module $M \in \mathbf{C}(A, \mathbf{M})$ and an integer i , we write

$$M[i] := \mathbf{T}^i(M),$$

the i -th translation of M . This notation applies also to the homotopy category $\mathbf{K}(A, \mathbf{M})$, the derived category $\mathbf{D}(A, \mathbf{M})$, and any other T-additive category.

The notation $M[i]$ makes it difficult to use the little t operator and to talk about translation isomorphisms, but hopefully we won't require them anymore.

Definition 14.1.7. Let A, B be DG rings, let \mathbf{M}, \mathbf{N} be abelian categories, and let $\mathbf{C} \subseteq \mathbf{D}(A, \mathbf{M})$ be a full additive subcategory.

- (1) Let

$$F : \mathbf{C} \rightarrow \mathbf{D}(B, \mathbf{N})$$

be an additive functor, and let S be an integer interval. We say that F has *cohomological displacement at most S* if

$$\text{con}(\mathbf{H}(F(M))) \subseteq \text{con}(\mathbf{H}(M)) + S$$

for every $M \in \mathbf{C}$.

(2) Let

$$F : \mathbf{C}^{\text{op}} \rightarrow \mathbf{D}(B, \mathbf{N})$$

be an additive functor, and let S be an integer interval. We say that F has *cohomological displacement at most S* if

$$\text{con}(\mathbf{H}(F(M))) \subseteq -\text{con}(\mathbf{H}(M)) + S$$

for every $M \in \mathbf{C}$.

- (3) Let F be as in item (1) or (2). The *cohomological displacement of F* is the smallest integer interval S for which F has cohomological displacement at most S .
- (4) Let S be the cohomological displacement of F . The *cohomological dimension* of F is defined to be the length of the integer interval S .

To emphasize the most important case: *the functor F has finite cohomological dimension iff its cohomological displacement is bounded.*

Example 14.1.8. The functor F is the zero functor iff it has cohomological displacement \emptyset and cohomological dimension $-\infty$.

Example 14.1.9. Consider a commutative ring $A = B$, and the abelian categories $\mathbf{M} = \mathbf{N} := \mathbf{M}(\mathbb{K})$. So $\mathbf{D}(A, \mathbf{M}) = \mathbf{D}(B, \mathbf{N}) = \mathbf{D}(A)$. Take $\mathbf{C} := \mathbf{D}(A)$. For the covariant case (item (1) in Definition 14.1.7) take a nonzero projective module P , and let

$$F := \text{RHom}_A(P \oplus P[1], -) : \mathbf{D}(A) \rightarrow \mathbf{D}(A).$$

Then F has cohomological displacement $[0, 1]$. For the contravariant case (item (2)) take a nonzero injective module I , and let

$$F := \text{RHom}_A(-, I \oplus I[1]) : \mathbf{D}(A)^{\text{op}} \rightarrow \mathbf{D}(A).$$

Then F has cohomological displacement $[-1, 0]$. In both cases the cohomological dimension of F is 1.

Example 14.1.10. Suppose A and B are rings and $F : \mathbf{M}(A) \rightarrow \mathbf{M}(B)$ is a left exact additive functor. We get a triangulated functor

$$\text{RF} : \mathbf{D}(A) \rightarrow \mathbf{D}(B),$$

and $\mathbf{H}^i(\text{RF}(M)) = \text{R}^i F(M)$ for all $M \in \mathbf{M}(A)$. Taking $\mathbf{C} := \mathbf{M}(A)$, with its canonical embedding into $\mathbf{D}(A)$, we get an additive functor

$$(\text{RF})|_{\mathbf{M}(A)} : \mathbf{M}(A) \rightarrow \mathbf{D}(A).$$

The cohomological dimension of $(\text{RF})|_{\mathbf{M}(A)}$ equals the usual cohomological dimension of the functor F .

Remark 14.1.11. Assume that in Definition 14.1.7 we take $\mathbf{M} = \mathbf{M}(\mathbb{K})$, $\mathbf{C} = \mathbf{D}(A)$ and F is a triangulated functor. The functor F has bounded below (resp. above) cohomological displacement iff it is way-out right (resp. left), in the sense of [RD, Section I.7].

Definition 14.1.12. Let \star, Δ be boundedness conditions, and assume the right derived bifunctor

$$\text{RHom}_{A, \mathbf{M}} : \mathbf{D}^{\star}(A, \mathbf{M})^{\text{op}} \times \mathbf{D}^{\Delta}(A, \mathbf{M}) \rightarrow \mathbf{D}(\mathbb{K})$$

exists. Let S be an integer interval of length $i \in \mathbb{N} \cup \{\pm\infty\}$.

- (1) Let $M \in \mathbf{D}^*(A, \mathbf{M})$, and let $\mathbf{C} \subseteq \mathbf{D}^\Delta(A, \mathbf{M})$ be a full additive subcategory. We say that M has *projective concentration* S and *projective dimension* i relative to \mathbf{C} if the functor

$$\mathrm{RHom}_{A, \mathbf{M}}(M, -)|_{\mathbf{C}} : \mathbf{C} \rightarrow \mathbf{D}(\mathbb{K})$$

has cohomological displacement $-S$.

- (2) Let $M \in \mathbf{D}^\Delta(A, \mathbf{M})$, and let $\mathbf{C} \subseteq \mathbf{D}^*(A, \mathbf{M})$ be a full additive subcategory. We say that M has *injective concentration* S and *injective dimension* i relative to \mathbf{C} if the functor

$$\mathrm{RHom}_{A, \mathbf{M}}(-, M)|_{\mathbf{C}^{\mathrm{op}}} : \mathbf{C}^{\mathrm{op}} \rightarrow \mathbf{D}(\mathbb{K})$$

has cohomological displacement S .

- (3) If $\mathbf{C} = \mathbf{D}(A, \mathbf{M})$, then we omit the “relative to \mathbf{C} ” clause.

Example 14.1.13. Continuing with the setup of Example 14.1.9, the DG module $P \oplus P[1]$ (resp. $I \oplus I[1]$) has projective (resp. injective) concentration $[-1, 0]$.

Example 14.1.14. Let A be a DG ring, and consider the free DG module $P := A \in \mathbf{D}(A)$. The functor

$$F := \mathrm{RHom}_A(P, -) : \mathbf{D}(A) \rightarrow \mathbf{D}(\mathbb{K})$$

is isomorphic to the forgetful functor, so it has cohomological displacement $[0, 0]$ and cohomological dimension 0. Thus the DG module P has projective concentration $[0, 0]$ and projective dimension 0. Note however that the cohomology $H(P)$ could be unbounded!

cmnt: next prop should move to Sec 7

Proposition 14.1.15. *Let*

$$0 \rightarrow L \xrightarrow{\phi} M \xrightarrow{\psi} N \rightarrow 0$$

be a short exact sequence in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$. Then there is a morphism $\theta : N \rightarrow L[1]$ in $\mathbf{D}(A, \mathbf{M})$ such that

$$L \xrightarrow{\mathrm{Q}(\phi)} M \xrightarrow{\mathrm{Q}(\psi)} N \xrightarrow{\theta} L[1]$$

is a distinguished triangle in $\mathbf{D}(A, \mathbf{M})$.

Proof. We are following the proof of [KaSc1, Proposition 1.7.5]. Let \tilde{N} be the standard cone on ϕ . In matrix notation as in Definition 4.2.1, we have

$$\tilde{N} = \begin{bmatrix} M \\ \mathrm{T}(L) \end{bmatrix} \quad \text{and} \quad \mathrm{d}_{\tilde{N}} = \begin{bmatrix} \mathrm{d}_M & \phi \circ \mathrm{t}^{-1} \\ 0 & \mathrm{d}_{\mathrm{T}(L)} \end{bmatrix}.$$

The object \tilde{N} sits inside the standard triangle

$$L \xrightarrow{\phi} M \xrightarrow{\tilde{\psi}} \tilde{N} \xrightarrow{\tilde{\chi}} \mathrm{T}(L)$$

in $\mathbf{C}_{\mathrm{str}}(A, \mathbf{M})$, where

$$\tilde{\psi} := \begin{bmatrix} \mathrm{id} \\ 0 \end{bmatrix} \quad \text{and} \quad \tilde{\chi} := [0 \quad \mathrm{id}]$$

in matrix notation. Define the morphism $\gamma = \tilde{N} \rightarrow N$ to be $\gamma := [\psi \ 0]$. We get a commutative diagram

$$\begin{array}{ccccccc} L & \xrightarrow{\phi} & M & \xrightarrow{\tilde{\psi}} & \tilde{N} & \xrightarrow{\tilde{\chi}} & \mathbf{T}(L) \\ & & & \searrow \psi & \downarrow \gamma & & \\ & & & & N & & \end{array}$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. We will prove below that γ is a quasi-isomorphism. Then the morphism $\theta := \mathbf{Q}(\tilde{\chi}) \circ \mathbf{Q}(\gamma)^{-1}$ will work.

It remains to prove that γ is a quasi-isomorphism. Let \tilde{K} be the standard cone on id_L , and let $\tilde{\beta} : \tilde{K} \rightarrow \tilde{N}$ be the matrix morphism

$$\begin{bmatrix} \phi & 0 \\ 0 & \text{id} \end{bmatrix} : \begin{bmatrix} L \\ \mathbf{T}(L) \end{bmatrix} \rightarrow \begin{bmatrix} M \\ \mathbf{T}(L) \end{bmatrix}.$$

This fits into a short exact sequence

$$0 \rightarrow \tilde{K} \xrightarrow{\tilde{\beta}} \tilde{N} \xrightarrow{\gamma} N \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(A, \mathbf{M})$. But the DG module \tilde{K} is acyclic, and therefore γ is a quasi-isomorphism. \square

The next proposition pertains only to the ring case. To prove it we shall require the following truncation operations. For any complex $M \in \mathbf{C}(A)$ its *stupid truncations* at an integer q are

$$(14.1.16) \quad \text{stt}^{\leq q}(M) := (\dots \rightarrow M^{q-1} \rightarrow M^q \rightarrow 0 \rightarrow 0 \rightarrow \dots)$$

and

$$(14.1.17) \quad \text{stt}^{\geq q}(M) := (\dots \rightarrow 0 \rightarrow 0 \rightarrow M^q \rightarrow M^{q+1} \rightarrow \dots).$$

They fit into an exact sequence

$$(14.1.18) \quad 0 \rightarrow \text{stt}^{\geq q}(M) \rightarrow M \rightarrow \text{stt}^{\leq q-1}(M) \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(A)$.

cmnt: move all truncation stuff to Sec 3?

Proposition 14.1.19. *Let A be a ring. The following are equivalent for $M \in \mathbf{D}(A)$:*

- (i) M has finite injective dimension.
- (ii) M has finite injective dimension relative to $\mathbf{M}(A)$.
- (iii) There is a quasi-isomorphism $M \rightarrow I$ in $\mathbf{C}_{\text{str}}(A)$ to a bounded complex of injective A -modules I .

Proof. (i) \Rightarrow (ii): This is trivial.

(ii) We may assume that $\mathbf{H}(M)$ is nonzero. Let $[q_0, q_1]$ be the injective concentration of the complex M relative to $\mathbf{M}(A)$, as in Definition 14.1.12; this is a bounded integer interval. Since $M \cong \mathbf{RHom}_A(A, M)$ in $\mathbf{D}(\mathbb{K})$, we see that

$$q_0 = \inf(\mathbf{H}(M)) \leq \sup(\mathbf{H}(M)) \leq q_1.$$

According to Corollary 11.4.12 there is quasi-isomorphism $M \rightarrow J$, where J is a complex of injective A -modules and $\inf(J) = q_0$. Take $I := \text{smt}^{\leq q_1}(J)$, the smart

truncation from (8.3.6). Then the canonical homomorphism $I \rightarrow J$ is a quasi-isomorphism. The complex I is concentrated in the integer interval $[q_0, q_1]$, and $I^q = J^q$ is injective for all $q < q_1$.

Let us prove that $I^{q_1} = Z^{q_1}(J)$ is also an injective module. Classically we would use a cosyzygy argument. Here we use another trick. Define $I' := \text{stt}^{\leq q_1-1}(I)$, so

$$I' = (\dots 0 \rightarrow I^{q_0} \rightarrow \dots \rightarrow I^{q_1-1} \rightarrow 0 \rightarrow \dots).$$

This is a bounded complex of injectives. Consider the short exact sequence

$$0 \rightarrow I^{q_1}[-q_1] \rightarrow I \rightarrow I' \rightarrow 0$$

in $\mathbf{C}_{\text{str}}(A)$. According to Proposition 14.1.15 this gives a distinguished triangle

$$(14.1.20) \quad I^{q_1}[-q_1] \rightarrow I \rightarrow I' \rightarrow I^{q_1}[-q_1+1]$$

in $\mathbf{D}(A)$. Take any A -module N . Applying $\text{RHom}_A(N, -)$ to the distinguished triangle (14.1.20) and then taking cohomologies, we get a long exact sequence

$$(14.1.21) \quad \dots \rightarrow \text{Ext}_A^{q+q_1-1}(N, I') \rightarrow \text{Ext}_A^q(N, I^{q_1}) \rightarrow \text{Ext}_A^{q+q_1}(N, I) \rightarrow \dots$$

in $\mathbf{M}(\mathbb{K})$. For any $q > 0$ the module $\text{Ext}_A^{q+q_1-1}(N, I')$ vanishes trivially. By the definition of the interval $[q_0, q_1]$ and the existence of an isomorphism $M \cong I$ in $\mathbf{D}(A)$, for any $q > 0$ the module $\text{Ext}_A^{q+q_1}(N, I)$ is zero. Hence $\text{Ext}_A^q(N, I^{q_1}) = 0$ for all $q > 0$. This proves that the module I^{q_1} is injective.

We have quasi-isomorphisms $M \rightarrow J$ and $I \rightarrow J$. Since I is K-injective, there is a quasi-isomorphism $M \rightarrow I$.

(iii) \Rightarrow (i): This is also trivial. \square

Exercise 14.1.22. State and prove the analogous result for finite projective dimension of complexes.

In the next definition, A is again a DG ring.

Definition 14.1.23. Let \star, Δ be boundedness conditions, and assume the left derived bifunctor

$$(- \otimes_A^{\mathbf{L}} -) : \mathbf{D}^{\star}(A^{\text{op}}) \times \mathbf{D}^{\Delta}(A) \rightarrow \mathbf{D}(\mathbb{K})$$

exists. Let S be an integer interval of length $i \in \mathbb{N} \cup \{\pm\infty\}$.

- (1) Let $M \in \mathbf{D}^{\Delta}(A)$, and let $\mathbf{C} \subseteq \mathbf{D}^{\star}(A^{\text{op}})$ be a full additive subcategory. We say that M has *flat concentration* S and *flat dimension* i relative to \mathbf{C} if the functor

$$(- \otimes_A^{\mathbf{L}} M)|_{\mathbf{C}} : \mathbf{C} \rightarrow \mathbf{D}(\mathbb{K})$$

has cohomological displacement S .

- (2) If $\mathbf{C} = \mathbf{D}(A^{\text{op}})$, then we omit the “relative to \mathbf{C} ” clause.

Proposition 14.1.24. Let A be a ring. The following are equivalent for $M \in \mathbf{D}(A)$:

- (i) M has finite flat dimension.
- (ii) M has finite flat dimension relative to $\mathbf{M}(A^{\text{op}})$.
- (iii) There is a quasi-isomorphism $P \rightarrow M$ in $\mathbf{C}_{\text{str}}(A)$ from a bounded complex of flat A -modules P .

Exercise 14.1.25. Prove Proposition 14.1.24. (The proof is similar to that of Proposition 14.1.19.)

Definition 14.1.26. Suppose the ring A is left noetherian.

- (1) We denote by $\mathbf{M}_f(A)$ the full subcategory of $\mathbf{M}(A) = \text{Mod } A$ on the finitely generated modules.
- (2) We denote by $\mathbf{D}_f(A)$ the full subcategory of $\mathbf{D}(A) = \mathbf{D}(\text{Mod } A)$ on the complexes with finitely generated cohomology modules.

Because A is left noetherian, the category $\mathbf{M}_f(A)$ is a thick abelian subcategory of $\mathbf{M}(A)$, and the category $\mathbf{D}_f(A)$ is a pretriangulated subcategory of $\mathbf{D}(A)$. When viewed as a left module, $A \in \mathbf{M}_f(A) \subseteq \mathbf{D}_f^b(A)$.

Theorem 14.1.27. *Let A be a left noetherian ring, let \mathbf{N} be an abelian category, let*

$$F, G : \mathbf{D}_f(A) \rightarrow \mathbf{D}(\mathbf{N})$$

be triangulated functors, and let $\eta : F \rightarrow G$ be a morphism of triangulated functors. Assume that the morphism

$$\eta_A : F(A) \rightarrow G(A)$$

in $\mathbf{D}(\mathbf{N})$ is an isomorphism.

- (1) *If F and G have bounded above cohomological displacements, then*

$$\eta_M : F(M) \rightarrow G(M)$$

is an isomorphism for every $M \in \mathbf{D}_f^-(A)$.

- (2) *If F and G have bounded cohomological displacements, then η_M is an isomorphism for every $M \in \mathbf{D}_f(A)$.*

We shall require the next lemmas for the proof of the theorem.

Lemma 14.1.28. *Let \mathbf{D} be a pretriangulated category, let $F, G : \mathbf{D} \rightarrow \mathbf{D}(\mathbf{N})$ be triangulated functors, let $\eta : F \rightarrow G$ be a morphism of triangulated functors, and let*

$$L \xrightarrow{\phi} M \rightarrow N \rightarrow L[1]$$

be a distinguished triangle in \mathbf{D} .

- (1) *If the morphisms η_L and η_M are both isomorphisms, then η_N is an isomorphism.*
- (2) *Let j be an integer. If $H^{j-1}(F(N)), H^{j-1}(G(N)), H^j(F(N))$ and $H^j(G(N))$ are all zero, and if $H^j(\eta_L)$ is an isomorphism, then $H^j(\eta_M)$ is an isomorphism.*

Proof. (1) In $\mathbf{D}(\mathbf{N})$ we get the commutative diagram

$$(14.1.29) \quad \begin{array}{ccccccc} F(L) & \longrightarrow & F(M) & \longrightarrow & F(N) & \longrightarrow & F(L)[1] \\ \downarrow \eta_L & & \downarrow \eta_M & & \downarrow \eta_N & & \downarrow \eta_{L[1]} \\ G(L) & \longrightarrow & G(M) & \longrightarrow & G(N) & \longrightarrow & G(L)[1] \end{array}$$

with horizontal distinguished triangles. According to Proposition 6.3.5, η_N is an isomorphism.

(2) passing to cohomologies in (14.1.29) we have a commutative diagram

$$\begin{array}{ccccccc}
 \mathrm{H}^{j-1}(F(N)) & \longrightarrow & \mathrm{H}^j(F(L)) & \xrightarrow{\mathrm{H}^j(F(\phi))} & \mathrm{H}^j(F(M)) & \longrightarrow & \mathrm{H}^j(F(N)) \\
 \downarrow \mathrm{H}^{j-1}(\eta_N) & & \downarrow \mathrm{H}^j(\eta_L) & & \downarrow \mathrm{H}^j(\eta_M) & & \downarrow \mathrm{H}^j(\eta_N) \\
 \mathrm{H}^{j-1}(G(N)) & \longrightarrow & \mathrm{H}^j(G(L)) & \xrightarrow{\mathrm{H}^j(G(\phi))} & \mathrm{H}^j(G(M)) & \longrightarrow & \mathrm{H}^j(G(N))
 \end{array}$$

The vanishing assumption implies that $\mathrm{H}^j(F(\phi))$ and $\mathrm{H}^j(G(\phi))$ are isomorphisms. Hence $\mathrm{H}^j(\eta_M)$ is an isomorphism. \square

Lemma 14.1.30. *Let \mathbf{D} be a pretriangulated category, let $F, G : \mathbf{D} \rightarrow \mathbf{D}(\mathbf{N})$ be triangulated functors, and let $\eta : F \rightarrow G$ be a morphism of triangulated functors. The following conditions are equivalent for $M \in \mathbf{D}$:*

- (i) η_M is an isomorphism.
- (ii) $\eta_{M[i]}$ is an isomorphism for every integer i .
- (iii) The morphism

$$\mathrm{H}^j(\eta_M) : \mathrm{H}^j(F(M)) \rightarrow \mathrm{H}^j(G(M))$$

is an isomorphism for every integer j .

Proof. The equivalence (i) \Leftrightarrow (ii) is because both F and G are triangulated functors. The equivalence (i) \Leftrightarrow (iii) is because the functor $\mathbf{H} : \mathbf{D}(\mathbf{N}) \rightarrow \mathbf{G}(\mathbf{N})$ is conservative; see Corollary 8.1.8. \square

Proof of Theorem 14.1.27. (1) First assume P is a bounded complex of finitely generated free A -modules. Then P is obtained from A by finitely many standard cones and translations. By Lemmas 14.1.28(1) and 14.1.30 it follows that η_P is an isomorphism.

Next let P be a bounded above complex of finitely generated free A -modules. Choose some integer j . Let i_1 be an integer such that the integer interval $[-\infty, i_1]$ contains the cohomological displacements of F and G . Define $P' := \mathrm{stt}^{\leq j-i_1-2}(P)$, the stupid truncation of P below $j - i_1 - 2$; and let $P'' := \mathrm{stt}^{\geq j-i_1-1}(P)$, the complementary stupid truncation. See formulas (14.1.16) and (14.1.17). According to Proposition 14.1.15, the short exact sequence (14.1.18) gives a distinguished triangle

$$(14.1.31) \quad P'' \rightarrow P \rightarrow P' \rightarrow P''[1]$$

in $\mathbf{D}_f(A)$. The complex P'' is a bounded complex of finitely generated free A -modules, so we already know that $\eta_{P''}$ is an isomorphism. Hence $\mathrm{H}^j(\eta_{P''})$ is an isomorphism. On the other hand $\mathbf{H}(P')$ is concentrated in the interval $[-\infty, j - i_1 - 2]$. Therefore $\mathrm{H}^k(F(P')) = \mathrm{H}^k(G(P')) = 0$ for all $k \geq j - 1$. By Lemma 14.1.28(2), $\mathrm{H}^j(\eta_P)$ is an isomorphism. Because j is arbitrary, Lemma 14.1.30 says that η_P is an isomorphism.

Now take an arbitrary $M \in \mathbf{D}_f^-(A)$. By Corollary 11.3.32 and Example 11.3.33 there is a resolution $P \rightarrow M$, where P is a bounded above complex of finitely generated free A -modules. Since η_P is an isomorphism, so is η_M .

(2) Now we assume that the functors F and G have finite cohomological dimensions. Take any complex $M \in \mathbf{D}_f(A)$. By Lemma 14.1.30 it suffices to prove that $\mathrm{H}^j(\eta_M)$ is an isomorphism for any integer j .

Let $[i_0, i_1]$ be a bounded integer interval that contains the cohomological displacements of the functors F and G . Define $M'' := \text{smt}^{\leq j-i_0}(M)$, the smart truncation of M below $j - i_0$; and let $M' := \text{smt}^{\geq j-i_0+1}(M)$, the complementary smart truncation. See formulas (8.3.6) and (8.3.7).

cmnt: maybe move the material on smart truncation from Sec 7 to Sec 3...

We obtain a short exact sequence

$$0 \rightarrow M'' \rightarrow M \rightarrow M' \rightarrow 0$$

of complexes. The cohomologies satisfy $H^i(M'') = H^i(M)$ and $H^i(M') = 0$ for $i \leq j - i_0$; and $H^i(M'') = 0$ and $H^i(M') = H^i(M)$ for $i \geq j - i_0 + 1$. Therefore we have a distinguished triangle

$$(14.1.32) \quad M'' \rightarrow M \rightarrow M' \rightarrow M''[1]$$

in $\mathbf{D}_f(A)$, and $M'' \in \mathbf{D}_f^-(A)$. By part (1) we know that $\eta_{M''}$ is an isomorphism, and therefore also $H^j(\eta_{M''})$ is an isomorphism. The cohomology $H(M')$ is concentrated in the interval $[j - i_0 + 1, \infty]$, and therefore the cohomologies $H(F(M'))$ and $H(G(M'))$ are concentrated in the interval $[j + 1, \infty]$. In particular the objects $H^{j-1}(F(M'))$, $H^{j-1}(G(M'))$, $H^j(F(M'))$ and $H^j(G(M'))$ are zero. By Lemma 14.1.28(2), $H^j(\eta_M)$ is an isomorphism. \square

Next we give a similar theorem. Recall that if $\mathbf{N}_0 \subseteq \mathbf{N}$ is a thick abelian subcategory, then $\mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$, the full subcategory of $\mathbf{D}(\mathbf{N})$ on the complexes whose cohomologies lie inside \mathbf{N}_0 , is a pretriangulated subcategory.

Theorem 14.1.33. *Let A be a left noetherian ring, let \mathbf{N} be an abelian category, let $\mathbf{N}_0 \subseteq \mathbf{N}$ be a thick abelian subcategory, and let*

$$F : \mathbf{D}_f(A)^{\text{op}} \rightarrow \mathbf{D}(\mathbf{N})$$

be a triangulated functor. Assume that $F(A)$ belongs to $\mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$.

- (1) *If F has bounded below cohomological displacement, then $F(M)$ belongs to $\mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$ for every $M \in \mathbf{D}_f^-(A)$.*
- (2) *If F has bounded cohomological displacement, then $F(M)$ belongs to $\mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$ for every $M \in \mathbf{D}_f(A)$.*

Proof. (1) First assume P is a bounded complex of finitely generated free A -modules. Then P is obtained from A by finitely many standard cones and translations. Since $\mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$ is a pretriangulated subcategory and F is a triangulated functor, it follows that $F(P) \in \mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$.

Next let P be a bounded above complex of finitely generated free A -modules. Choose some integer j . We want to prove that $H^j(F(P)) \in \mathbf{N}_0$. Let i_0 be an integer such that the integer interval $[i_0, \infty]$ contains the cohomological displacement of F . Define $P' := \text{stt}^{\leq -j-1+i_0}(P)$, the stupid truncation of P below $-j - 1 + i_0$; and let $P'' := \text{stt}^{\geq j+i_0}(P)$, the complementary stupid truncation. We get a distinguished triangle (14.1.31) in $\mathbf{D}_f(A)$. The complex P'' is a bounded complex of finitely generated free A -modules, so we already know that $F(P'') \in \mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$, and in particular $H^j(F(P'')) \in \mathbf{N}_0$. On the other hand $H(P')$ is concentrated in the interval $[-\infty, -j - 1 + i_0]$. Therefore $H(F(P'))$ is concentrated in the interval $[j + 1, \infty]$, and in particular $H^{j-1}(F(P')) = H^j(F(P')) = 0$. As we saw in the proof

of Lemma 14.1.28(2), $H^j(F(P'')) \rightarrow H^j(F(P))$ is an isomorphism. The conclusion is that $H^j(F(P)) \in \mathbf{N}_0$.

Now take an arbitrary $M \in \mathbf{D}_f^-(A)$. There is a quasi-isomorphism $P \rightarrow M$, where P is a bounded above complex of finitely generated free A -modules. So $F(M) \cong F(P)$, and thus $F(M) \in \mathbf{D}_{\mathbf{N}_0}(\mathbf{N})$.

(2) Now we assume that the functor F has finite cohomological dimension. Take any complex $M \in \mathbf{D}_f(A)$. We want to prove that for any $j \in \mathbb{Z}$ the object $H^j(F(M))$ lies in \mathbf{N}_0 .

Let $[i_0, i_1]$ be a bounded integer interval that contains the cohomological displacement of the functor F . Define $M'' := \text{smt}^{\leq -j+1+i_1}(M)$, the smart truncation of M below $-j+1+i_1$; and let $M' := \text{smt}^{\geq -j+2+i_1}(M)$, the complementary smart truncation. As we already noted in the proof of Theorem 14.1.27, there is a distinguished triangle (14.1.32) in $\mathbf{D}_f(A)$. The cohomology of M' is concentrated in the interval $[-j+2+i_1, \infty]$, and therefore the cohomology of $F(M')$ is concentrated in the interval $[-\infty, j-2]$. In particular the objects $H^{j-1}(F(M'))$ and $H^j(F(M'))$ are zero. By the proof of Lemma 14.1.28(2), the morphism $H^j(F(M'')) \rightarrow H^j(F(M))$ is an isomorphism. But $M'' \in \mathbf{D}_f^-(A)$, so as we proved in part (1), its cohomologies are inside \mathbf{N}_0 . \square

Theorems 14.1.27 and 14.1.33 have several obvious modifications, for instance changing the variance of the functor F (replacing the source category by its opposite).

14.2. Dualizing Complexes. From here on in this section all rings are commutative noetherian by default.

Let A be a noetherian ring. We have the abelian categories $\mathbf{M}_f(A) \subseteq \mathbf{M}(A)$ as before. But because A is commutative, the Hom bifunctor has another target:

$$\text{Hom}_A(-, -) : \mathbf{M}(A)^{\text{op}} \times \mathbf{M}(A) \rightarrow \mathbf{M}(A).$$

Likewise for the right derived bifunctor:

$$\text{RHom}_A(-, -) : \mathbf{D}(A)^{\text{op}} \times \mathbf{D}(A) \rightarrow \mathbf{D}(A).$$

When we fix the second argument M , we get an A -linear triangulated functor:

$$\text{RHom}_A(-, M) : \mathbf{D}(A)^{\text{op}} \rightarrow \mathbf{D}(A).$$

This is the sort of functor with which we will be concerned.

Let $M \in \mathbf{C}(A)$. The DG A -module

$$\text{Hom}_A(M, M) = \text{End}_A(M)$$

is a central noncommutative DG A -ring; there is a ring homomorphism

$$(14.2.1) \quad \alpha_M : A \rightarrow \text{Hom}_A(M, M).$$

When we forget the ring structure, α_M becomes a homomorphism in $\mathbf{C}_{\text{str}}(A)$.

Definition 14.2.2. Given a complex $M \in \mathbf{D}(A)$, the *derived homothety morphism*

$$\alpha_M^{\text{R}} : A \rightarrow \text{RHom}_A(M, M)$$

is the morphism in $\mathbf{D}(A)$ with this formula:

$$\alpha_M^{\text{R}} := \eta_{M, M} \circ \mathbf{Q}(\alpha_M).$$

Namely the diagram

$$\begin{array}{ccccc}
 & & \alpha_M^R & & \\
 & \curvearrowright & & \curvearrowleft & \\
 A & \xrightarrow{Q(\alpha_M)} & \text{Hom}_A(M, M) & \xrightarrow{\eta_{M,M}} & \text{RHom}_A(M, M)
 \end{array}$$

in $\mathbf{D}(A)$ is commutative.

Exercise 14.2.3. Prove that if $\rho : M \rightarrow I$ is a K-injective resolution, then the diagram

$$\begin{array}{ccccc}
 A & \xrightarrow{Q(\alpha_I)} & \text{Hom}_A(I, I) & \xrightarrow[\cong]{\eta_{I,I}} & \text{RHom}_A(I, I) \\
 & \searrow \alpha_M^R & & & \downarrow \cong \\
 & & & & \text{RHom}(Q(\rho), Q(\rho)^{-1}) \\
 & & & & \downarrow \\
 & & & & \text{RHom}_A(R, R)
 \end{array}$$

in $\mathbf{D}(A)$ is commutative.

Exercise 14.2.4. Formulate and prove a version of the previous exercise with a K-projective resolution of M .

Definition 14.2.5. A complex $M \in \mathbf{D}(A)$ is said to have the *derived Morita property* if the derived homothety morphism

$$\alpha_M^R : A \rightarrow \text{RHom}_A(M, M)$$

in $\mathbf{D}(A)$ is an isomorphism.

Proposition 14.2.6. *The following conditions are equivalent for a complex $M \in \mathbf{D}(A)$:*

- (i) M has the derived Morita property.
- (ii) The canonical ring homomorphism

$$A \rightarrow \text{End}_{\mathbf{D}(A)}(M)$$

is a bijection, and

$$\text{Hom}_{\mathbf{D}(A)}(M, M[i]) = 0$$

for all $i \neq 0$.

Exercise 14.2.7. Prove Proposition 14.2.6. (Hint: see Corollary 13.6.8 and the preceding material.)

Remark 14.2.8. In some texts, a complex M with the derived Morita property is called a *semi-dualizing complex*. This name is only partly justified, because this property occurs in the definition of a dualizing complexes – see Definition 14.2.9 below. However, there is a whole other class of complexes with the derived Morita property – these are the *tilting complexes*. Often these two classes of complexes are disjoint. More on these notions, and their noncommutative variants, will be in Section 19 of the book.

The next definition first appeared in [RD, Section V.2]. The injective dimension of a complex was defined in Definition 14.1.12.

Definition 14.2.9. Let A be a noetherian commutative ring. A complex of A -modules R is called a *dualizing complex* if it has the following three properties:

- (i) $R \in \mathbf{D}_f^b(A)$.
- (ii) R has finite injective dimension.
- (iii) R has the derived Morita property.

Recall that in the traditional literature (e.g. [Mats]), a noetherian ring A is called *regular* if all its local rings $A_{\mathfrak{p}}$ are regular local rings. The *Krull dimension* of A is the dimension of the scheme $\text{Spec } A$; namely the supremum of the lengths of strictly ascending chains of prime ideals in A . In practice we never see regular rings that are not finite dimensional (there are only pretty exotic examples of them). The following convention will simplify matters for us:

Convention 14.2.10. We shall say that a noetherian commutative ring A is *regular* if it has finite Krull dimension, and all its local rings $A_{\mathfrak{p}}$ are regular local rings.

Any field \mathbb{K} , and the ring of integers \mathbb{Z} , are regular rings. If A is regular, then so is the polynomial ring $A[t_1, \dots, t_n]$ in $n < \infty$ variables, and also the localization of A at any multiplicatively closed set. See [Mats, Chapter 7].

Example 14.2.11. As prove by Serre, see [Mats, Theorem 19.2], a regular ring A has *finite global cohomological dimension*. This means that there is a number $d \in \mathbb{N}$ such that for any modules $M, N \in \mathbf{M}(A)$ and any $q > d$, the Ext module $\text{Ext}_A^q(M, N)$ vanishes. This implies that any module N has injective dimension $\leq d$ (and also projective dimension $\leq d$).

Taking $R := A$ we see that R satisfies condition (ii) of Definition 14.2.9. The other two conditions hold regardless of the regularity of A . Thus $R = A$ is a dualizing complex over the ring A .

In the Introduction, Subsection 0.1, we used this fact for $A = \mathbb{Z}$.

Definition 14.2.12. Given a dualizing complex $R \in \mathbf{D}(A)$, the *duality functor* associated to it is the triangulated functor

$$D : \mathbf{D}(A)^{\text{op}} \rightarrow \mathbf{D}(A), \quad D := \text{RHom}_A(-, R).$$

Let $I, M \in \mathbf{C}(A)$. There is a homomorphism

$$\tilde{\theta}_{M,I} : M \rightarrow \text{Hom}_A(\text{Hom}_A(M, I), I)$$

in $\mathbf{C}_{\text{str}}(A)$ with formula

$$\tilde{\theta}_{M,I}(m)(\phi) := (-1)^{p \cdot q} \cdot \phi(m)$$

for $m \in M^p$ and $\phi \in \text{Hom}_A(M, I)^q$.

Lemma 14.2.13. *Let R be a dualizing complex over A , with associated duality functor D . There is a unique morphism*

$$\theta : \text{Id} \rightarrow D \circ D$$

of triangulated functors from $\mathbf{D}(A)$ to itself, such that if $\rho : R \rightarrow I$ is a K -injective resolution, then for any complex $M \in \mathbf{D}(A)$ the diagram

$$\begin{array}{ccccc} M & \xrightarrow{Q(\tilde{\theta}_{M,I})} & \text{Hom}_A(\text{Hom}_A(M, I), I) & \longrightarrow & \text{RHom}_A(\text{RHom}_A(M, I), I) \\ \theta_M \downarrow & & & & \downarrow \\ D(D(M)) & \xrightarrow{\text{id}} & & \longrightarrow & \text{RHom}_A(\text{RHom}_A(M, R), R) \end{array}$$

in $\mathbf{D}(A)$, in which the unlabeled morphisms are

$$\mathrm{RHom}(\eta_{M,I}^{-1}, \mathrm{id}) \circ \eta_{\mathrm{Hom}_A(M,I),I}$$

and

$$\mathrm{RHom}(\mathrm{RHom}(\mathrm{id}, \mathrm{Q}(\rho)), \mathrm{Q}(\rho)^{-1}),$$

is commutative.

Exercise 14.2.14. Prove Lemma 14.2.13.

Here is the first important result regarding dualizing complexes.

Theorem 14.2.15. *Suppose R is a dualizing complex over the noetherian commutative ring A , with associated duality functor D . Then for any complex $M \in \mathbf{D}_f(A)$ the following hold:*

- (1) *The complex $D(M)$ belongs to $\mathbf{D}_f(A)$.*
- (2) *The morphism*

$$\theta_M : M \rightarrow D(D(M))$$

in $\mathbf{D}(A)$ is an isomorphism.

Proof. (1) Condition (b) of Definition 14.2.9 says that the functor D has finite cohomological dimension. Condition (a) says that $D(A) \in \mathbf{D}_f(A)$. The assertion follows from Theorem 14.1.33, with $\mathbf{N}_0 := \mathbf{M}_f(A)$.

(2) The composition $D \circ D$ is a functor with finite cohomological dimension (at most twice the injective dimension of R). The cohomological dimension of the identity functor is 0 (if $A \neq 0$). By condition (c) of Definition 14.2.9 we know that θ_A is an isomorphism. Now we can use Theorem 14.1.27. \square

Corollary 14.2.16. *Under the assumptions of Theorem 14.2.15, let \star be one of the boundedness conditions \mathbf{b} , $+$, $-$ or “empty”, and let $-\star$ be the reverse boundedness condition, namely \mathbf{b} , $-$, $+$ or “empty”, respectively. Then the functor*

$$D : \mathbf{D}_f^\star(A)^{\mathrm{op}} \rightarrow \mathbf{D}_f^{-\star}(A)$$

is an equivalence of pretriangulated categories.

Proof. The previous theorem tells us that D is its own quasi-inverse. The claim about the boundedness holds because D has finite cohomological dimension. \square

We saw that dualizing complexes exists over regular rings. This fact is used for the very general existence result below. First a definition and some lemmas.

Definition 14.2.17. Let $f : A \rightarrow B$ be a ring homomorphism. We say that f is an *essentially finite type homomorphism* (EFT) if it factors as $A \rightarrow B' \rightarrow B$, where $A \rightarrow B'$ is finite type, and $B' \rightarrow B$ is a localization at some multiplicatively closed set. In this case we also say that B is an *essentially finite type A -ring*.

Example 14.2.18. Let X be a finite type scheme over A , and let $x \in X$ be a point. Then the local ring $\mathcal{O}_{X,x}$ is essentially finite type over A .

A ring homomorphism $A \rightarrow B$ gives rise to a forgetful functor $\mathrm{Rest} : \mathbf{M}(B) \rightarrow \mathbf{M}(A)$, that in turn determines a DG functor $\mathrm{Rest} : \mathbf{C}(B) \rightarrow \mathbf{C}(A)$ and a triangulated functor $\mathrm{Rest} : \mathbf{D}(B) \rightarrow \mathbf{D}(A)$. These functors are going to be implicit in the discussion below.

Lemma 14.2.19. *Let $A \rightarrow B$ be a ring homomorphism.*

- (1) If $I \in \mathbf{C}(A)$ is K -injective, then $J := \mathrm{Hom}_A(B, I) \in \mathbf{C}(B)$ is K -injective.
 (2) Given $M \in \mathbf{D}(A)$, let us define

$$N := \mathrm{RHom}_A(B, M) \in \mathbf{D}(B).$$

Then there is an isomorphism

$$\mathrm{RHom}_B(-, N) \cong \mathrm{RHom}_A(-, M)$$

of triangulated functors $\mathbf{D}(B) \rightarrow \mathbf{D}(B)$.

Proof. (1) This is an adjunction calculation. Suppose $L \in \mathbf{C}(B)$ is acyclic. There are isomorphisms

$$(14.2.20) \quad \mathrm{Hom}_B(L, J) \cong \mathrm{Hom}_B(L, \mathrm{Hom}_A(B, I)) \cong \mathrm{Hom}_A(L, I)$$

in $\mathbf{C}(B)$. Since I is K -injective over A , this complex is acyclic.

(2) Choose a K -injective resolution $M \rightarrow I$ in $\mathbf{C}(A)$. Let J be as above. Then $N \rightarrow J$ is a K -injective resolution in $\mathbf{C}(B)$. There are isomorphisms of triangulated functors

$$(14.2.21) \quad \mathrm{RHom}_A(-, M) \cong \mathrm{Hom}_A(-, I)$$

and

$$(14.2.22) \quad \mathrm{RHom}_B(-, N) \cong \mathrm{Hom}_B(-, J),$$

where the first functors (14.2.21) are from $\mathbf{D}(A)$ to itself, and the functors (14.2.22) are from $\mathbf{D}(B)$ to itself. But given $L \in \mathbf{C}(B)$ we can view $\mathrm{Hom}_A(L, I)$ as a complex of B -modules, and in this way the functors (14.2.21) become triangulated functors from $\mathbf{D}(B)$ to itself. Formula (14.2.20) shows that the functors (14.2.21) and (14.2.22) are isomorphic. \square

Lemma 14.2.23. *Let $A \rightarrow B$ be a flat ring homomorphism, let $M \in \mathbf{D}_f^-(A)$, and let $N \in \mathbf{D}^+(A)$. Then there is an isomorphism*

$$\mathrm{RHom}_A(M, N) \otimes_A B \cong \mathrm{RHom}_B(B \otimes_A M, B \otimes_A N)$$

in $\mathbf{D}(B)$. This isomorphism is functorial in M and N .

Proof. First we note that since B is a flat A -module, the functor $- \otimes_A B$ is triangulated (it is its own left derived functor), and it goes $\mathbf{D}(A) \rightarrow \mathbf{D}(B)$.

Let's choose a resolution $P \rightarrow M$ where P is a bounded above complex of finitely generated free A -modules. After possibly truncating the complex N from below, we can assume it is a bounded below complex of A -modules. There is an isomorphism

$$(14.2.24) \quad \mathrm{RHom}_A(M, N) \otimes_A B \cong \mathrm{Hom}_A(P, N) \otimes_A B$$

in $\mathbf{D}(B)$. We claim that the canonical homomorphism

$$(14.2.25) \quad \mathrm{Hom}_A(P, N) \otimes_A B \rightarrow \mathrm{Hom}_A(P, N \otimes_A B)$$

in $\mathbf{C}(B)$ is bijective. This is because of finiteness. To be explicit, in each degree i we have

$$\mathrm{Hom}_A(P, N)^i = \prod_j \mathrm{Hom}_A(P^j, N^{i+j}).$$

This is actually a finite product, because $P^j = 0$ for $j \gg 0$, and $N^{i+j} = 0$ for $j \ll 0$. And for each pair (i, j) the module $\mathrm{Hom}_A(P^j, N^{i+j})$ is a finite product of copies of N^{i+j} , because P^j is a finitely generated free A -module. This shows that

$$\mathrm{Hom}_A(P^j, N^{i+j}) \otimes_A B \cong \mathrm{Hom}_A(P^j, N^{i+j} \otimes_A B).$$

Taking the product on all j we conclude that (14.2.25) is indeed bijective.

Next we apply the usual change of ring adjunction to get the isomorphism

$$(14.2.26) \quad \mathrm{Hom}_A(P, B \otimes_A N) \cong \mathrm{Hom}_B(B \otimes_A P, B \otimes_A N)$$

in $\mathbf{C}(B)$. Since $B \otimes_A P \rightarrow B \otimes_A M$ is a K-projective resolution over B , there is an isomorphism

$$(14.2.27) \quad \mathrm{Hom}_B(B \otimes_A P, B \otimes_A N) \cong \mathrm{RHom}_B(B \otimes_A M, B \otimes_A N)$$

in $\mathbf{D}(B)$.

Combining the isomorphisms (14.2.24), (14.2.25), (14.2.26) and (14.2.27) gives us the desired isomorphism. The functoriality is clear. \square

Lemma 14.2.28. *Let I be an A -module. The following conditions are equivalent:*

- (i) I is injective.
- (ii) For any finitely generated A -module M the module $\mathrm{Ext}_A^1(M, I)$ is zero.

Exercise 14.2.29. Prove Lemma 14.2.28. (Hint: use the Baer criterion Theorem 2.6.10.)

Lemma 14.2.30. *The injective dimension of a complex $N \in \mathbf{D}(A)$ equals the cohomological dimension of the functor*

$$\mathrm{RHom}_A(-, N)|_{\mathbf{M}_f(A)^{\mathrm{op}}} : \mathbf{M}_f(A)^{\mathrm{op}} \rightarrow \mathbf{D}(A).$$

Proof. By definition the injective dimension of N , say d , is the cohomological dimension of the functor

$$\mathrm{RHom}_A(-, N) : \mathbf{D}(A)^{\mathrm{op}} \rightarrow \mathbf{D}(A).$$

Let d' be the cohomological dimension of the functor $\mathrm{RHom}_A(-, N)|_{\mathbf{M}_f(A)^{\mathrm{op}}}$. Obviously the inequality $d \geq d'$ holds. For the reverse inequality we may assume that $H(N)$ is nonzero and $d' < \infty$. This implies that there are integers $q_1 = q_0 + d'$ such that for any $M \in \mathbf{M}_f(A)$ there is an inclusion

$$\mathrm{con}(\mathrm{RHom}_A(M, N)) \subseteq [q_0, q_1].$$

In particular, for $M = A$, we get $\mathrm{con}(H(N)) \subseteq [q_0, q_1]$. Let $N \rightarrow J$ be an injective resolution in $\mathbf{C}(A)$ with $\mathrm{inf}(J) = q_0$. Take $I := \mathrm{smt}^{\leq q_1}(J)$, the smart truncation from (8.3.6). The proof of Proposition 14.1.19, plus Lemma 14.2.28, show that $N \rightarrow I$ is an injective resolution. But then

$$\mathrm{RHom}_A(-, N) \cong \mathrm{Hom}_A(-, I),$$

so this functor has cohomological displacement in the interval $[q_0, q_1]$, that has length d' . \square

Recall that a ring homomorphism $A \rightarrow B$ is called *finite* if it makes B into a finitely generated A -module.

Proposition 14.2.31. *Let $A \rightarrow B$ be a finite ring homomorphism, and let R_A be a dualizing complex over A . Then the complex*

$$R_B := \mathrm{RHom}_A(B, R_A) \in \mathbf{D}(B)$$

is a dualizing complex over B .

Proof. Consider the functors $D_A := \mathrm{RHom}_A(-, R_A)$ and $D_B := \mathrm{RHom}_B(-, R_B)$. As explained in the proof of Lemma 14.2.19(2), they are isomorphic as functors from $\mathbf{D}(B)$ to itself. Since $R_B = D_A(B)$ and $B \in \mathbf{D}_f^b(A)$, by Corollary 14.2.16 we have $R_B \in \mathbf{D}_f^b(A)$. But then also $R_B \in \mathbf{D}_f^b(B)$. Next, because $D_B(L) \cong D_A(L)$ for any $L \in \mathbf{D}(B)$, this implies that the cohomological dimension of D_B is at most that of D_A , which is finite. We see that the injective dimension of the complex R_B is finite. Lastly, there is an isomorphism $D_B \circ D_B \cong D_A \circ D_A$ as functors from $\mathbf{D}_f^b(B)$ to itself, and hence $\theta : \mathrm{Id} \rightarrow D_B \circ D_B$ is an isomorphism. Applying this to the object $B \in \mathbf{D}_f^b(B)$ we see that

$$\alpha = \theta_B : B \rightarrow (D_B \circ D_B)(B)$$

is an isomorphism. So R_B has the derived Morita property. The conclusion is that R_B is a dualizing complex over B . \square

Proposition 14.2.32. *Let $A \rightarrow B$ be a localization ring homomorphism, and let R_A be a dualizing complex over A . Then the complex*

$$R_B := B \otimes_A R_A \in \mathbf{D}(B)$$

is a dualizing complex over B .

Proof. It is clear that $R_B \in \mathbf{D}_f^b(B)$. By Lemma 14.2.30, to compute the injective dimension of R_B it is enough to look at $\mathrm{RHom}_B(M, R_B)$ for $M \in \mathbf{M}_f(B)$. We can find a finitely generated A -submodule $M' \subseteq M$ such that $B \cdot M' = M$; and then $M \cong B \otimes_A M'$. Lemma 14.2.23 tells us that

$$\mathrm{RHom}_B(M, R_B) \cong \mathrm{RHom}_A(M', R_A) \otimes_A B.$$

We conclude that the injective dimension of R_B is at most that of R_A , which is finite. Lastly, by the same lemma we get an isomorphism

$$\mathrm{RHom}_B(R_B, R_B) \cong \mathrm{RHom}_A(R_A, R_A) \otimes_A B,$$

and it is compatible with the morphisms from B . Thus R_B has the derived Morita property. \square

Theorem 14.2.33. *Let \mathbb{K} be a regular ring, and let A be an essentially finite type \mathbb{K} -ring. Then A has a dualizing complex.*

Proof. The ring homomorphism $\mathbb{K} \rightarrow A$ can be factored as $\mathbb{K} \rightarrow A_{\mathrm{pl}} \rightarrow A_{\mathrm{ft}} \rightarrow A$, where $A_{\mathrm{pl}} = \mathbb{K}[t_1, \dots, t_n]$ is a polynomial ring, $A_{\mathrm{pl}} \rightarrow A_{\mathrm{ft}}$ is surjective, and $A_{\mathrm{ft}} \rightarrow A$ is a localization. (The subscripts stand for “polynomial” and “finite type” respectively.) According to [Mats, Theorem 19.5] the ring A_{pl} is regular; so, as shown in Example 14.2.18, the complex $R_{\mathrm{pl}} := A_{\mathrm{pl}}$ is a dualizing complex over A_{pl} .

Define

$$R_{\mathrm{ft}} := \mathrm{RHom}_{A_{\mathrm{pl}}}(A_{\mathrm{ft}}, R_{\mathrm{pl}}) \in \mathbf{D}(A_{\mathrm{ft}}).$$

By Proposition 14.2.31 this is a dualizing complex over A_{ft} . Finally define

$$R := A \otimes_{A_{\mathrm{ft}}} R_{\mathrm{ft}} \in \mathbf{D}_f^b(A).$$

By Proposition 14.2.32 this is dualizing complex over A . \square

The proof of Theorem 14.2.33 might give the impression that A could have a lot of nonisomorphic dualizing complexes. This is not quite true, as we now prove.

Theorem 14.2.34. *Let A be a noetherian ring with connected spectrum, and let R and R' be dualizing complexes over A . Then there is a rank 1 projective A -module L and an integer d , such that $R' \cong R \otimes_A L[d]$ in $\mathbf{D}(A)$.*

Some lemmas first.

Lemma 14.2.35 (Künneth Trick). *Let $M, M' \in \mathbf{D}^-(A)$, and let $i, i' \in \mathbb{Z}$ be such that $\sup(\mathbf{H}(M)) \leq i$ and $\sup(\mathbf{H}(M')) \leq i'$. Then*

$$\mathbf{H}^{i+i'}(M \otimes_A^L M') \cong \mathbf{H}^i(M) \otimes_A \mathbf{H}^{i'}(M').$$

Exercise 14.2.36. Prove Lemma 14.2.35.

Lemma 14.2.37 (Projective Truncation Trick). *Let $M \in \mathbf{D}(A)$, with $i_1 := \sup(\mathbf{H}(M)) \in \mathbb{Z}$. Assume the A -module $P := \mathbf{H}^{i_1}(M)$ is projective. Then there is an isomorphism*

$$M \cong \text{smt}^{\leq i_1-1}(M) \oplus P[-i_1]$$

in $\mathbf{D}(A)$.

Exercise 14.2.38. Prove Lemma 14.2.37. (Hint: first replace M with $\text{smt}^{\leq i_1}(M)$. Then prove that P is a direct summand of M^{i_1} .)

By a *principal open set* in $\text{Spec } A$ we mean a set of the form $\text{Spec } A_s$, where A_s is the localization of A at the element $s \in A$. Note that

$$\text{Spec } A_s = \{\mathfrak{p} \in \text{Spec } A \mid s \notin \mathfrak{p}\}.$$

Lemma 14.2.39. *Let $M, M' \in \mathbf{M}_f(A)$, and let $\mathfrak{p} \subseteq A$ be a prime ideal.*

- (1) *If $M_{\mathfrak{p}} \neq 0$ and $M'_{\mathfrak{p}} \neq 0$ then $M_{\mathfrak{p}} \otimes_{A_{\mathfrak{p}}} M'_{\mathfrak{p}} \neq 0$.*
- (2) *If $M_{\mathfrak{p}} \otimes_{A_{\mathfrak{p}}} M'_{\mathfrak{p}} \cong A_{\mathfrak{p}}$ then $M_{\mathfrak{p}} \cong M'_{\mathfrak{p}} \cong A_{\mathfrak{p}}$.*
- (3) *If $M_{\mathfrak{p}} \cong A_{\mathfrak{p}}$, then there is a principal open neighborhood $\text{Spec } A_s$ of \mathfrak{p} in $\text{Spec } A$ such that $M_s \cong A_s$ as A_s -modules.*

Exercise 14.2.40. Prove Lemma 14.2.39. (Hint: use the Nakayama Lemma.)

Here is a pretty difficult technical lemma.

Lemma 14.2.41. *In the situation of the theorem, let $M, M' \in \mathbf{D}_f^-(A)$ satisfy $M \otimes_A^L M' \cong A$ in $\mathbf{D}(A)$. Then $M \cong L[d]$ in $\mathbf{D}(A)$ for some rank 1 projective A -module L and an integer d .*

Proof. For any prime $\mathfrak{p} \subseteq A$ let $M_{\mathfrak{p}} := A_{\mathfrak{p}} \otimes_A M$, and define

$$e_{\mathfrak{p}} := \sup(\mathbf{H}(M_{\mathfrak{p}})) \in \mathbb{Z} \cup \{-\infty\}.$$

Define the number $e'_{\mathfrak{p}}$ similarly.

Fix one prime \mathfrak{p} . Since

$$(14.2.42) \quad M_{\mathfrak{p}} \otimes_{A_{\mathfrak{p}}}^L M'_{\mathfrak{p}} \cong A_{\mathfrak{p}}$$

is nonzero, it follows that $\mathbf{H}(M_{\mathfrak{p}}) \neq 0$ and $\mathbf{H}(M'_{\mathfrak{p}}) \neq 0$. So $e_{\mathfrak{p}}, e'_{\mathfrak{p}} \in \mathbb{Z}$, and $\mathbf{H}^{e_{\mathfrak{p}}}(M_{\mathfrak{p}}), \mathbf{H}^{e'_{\mathfrak{p}}}(M'_{\mathfrak{p}})$ are nonzero finite $A_{\mathfrak{p}}$ -modules. By Lemma 14.2.39(1) we know that

$$\mathbf{H}^{e_{\mathfrak{p}}}(M_{\mathfrak{p}}) \otimes_{A_{\mathfrak{p}}} \mathbf{H}^{e'_{\mathfrak{p}}}(M'_{\mathfrak{p}}) \neq 0.$$

According to Lemma 14.2.35 we have

$$\mathbf{H}^{e_{\mathfrak{p}}}(M_{\mathfrak{p}}) \otimes_{A_{\mathfrak{p}}} \mathbf{H}^{e'_{\mathfrak{p}}}(M'_{\mathfrak{p}}) \cong \mathbf{H}^{(e_{\mathfrak{p}}+e'_{\mathfrak{p}})}(M_{\mathfrak{p}} \otimes_{A_{\mathfrak{p}}}^L M'_{\mathfrak{p}}) \cong \mathbf{H}^{(e_{\mathfrak{p}}+e'_{\mathfrak{p}})}(A_{\mathfrak{p}}).$$

But $A_{\mathfrak{p}}$ is concentrated in degree 0; this forces $e_{\mathfrak{p}} + e'_{\mathfrak{p}} = 0$ and

$$H^{e_{\mathfrak{p}}}(M_{\mathfrak{p}}) \otimes_{A_{\mathfrak{p}}} H^{e'_{\mathfrak{p}}}(M'_{\mathfrak{p}}) \cong A_{\mathfrak{p}}$$

in $\mathbf{D}(A_{\mathfrak{p}})$. By Lemma 14.2.39(2) we now see that

$$(14.2.43) \quad H^{e_{\mathfrak{p}}}(M_{\mathfrak{p}}) \cong H^{e'_{\mathfrak{p}}}(M'_{\mathfrak{p}}) \cong A_{\mathfrak{p}}.$$

According to Lemma 14.2.37 there are isomorphisms

$$(14.2.44) \quad M_{\mathfrak{p}} \cong A_{\mathfrak{p}}[-e_{\mathfrak{p}}] \oplus \text{smt}^{\leq e_{\mathfrak{p}}-1}(M_{\mathfrak{p}})$$

and

$$M'_{\mathfrak{p}} \cong A_{\mathfrak{p}}[-e'_{\mathfrak{p}}] \oplus \text{smt}^{\leq e'_{\mathfrak{p}}-1}(M'_{\mathfrak{p}})$$

in $\mathbf{D}(A_{\mathfrak{p}})$. These, with (14.2.42), give an isomorphism

$$(14.2.45) \quad (A_{\mathfrak{p}}[-e_{\mathfrak{p}}] \oplus \text{smt}^{\leq e_{\mathfrak{p}}-1}(M_{\mathfrak{p}})) \otimes_{A_{\mathfrak{p}}} (A_{\mathfrak{p}}[-e'_{\mathfrak{p}}] \oplus \text{smt}^{\leq e'_{\mathfrak{p}}-1}(M'_{\mathfrak{p}})) \cong A_{\mathfrak{p}}.$$

The left side of (14.2.45) is the direct sum of four objects. Passing to the cohomology of (14.2.45) we see that

$$N := H(\text{smt}^{\leq e_{\mathfrak{p}}-1}(M_{\mathfrak{p}})[-e'_{\mathfrak{p}}])$$

is a direct summand of $A_{\mathfrak{p}}$. But, since $e'_{\mathfrak{p}} + e_{\mathfrak{p}} = 0$, the graded module N is concentrated in the degree interval $[\infty, -1]$. It follows that $N = 0$. Therefore, by (14.2.44), we deduce that

$$(14.2.46) \quad M_{\mathfrak{p}} \cong A_{\mathfrak{p}}[-e_{\mathfrak{p}}].$$

The calculation above works for any prime \mathfrak{p} . From (14.2.46) we get

$$(14.2.47) \quad A_{\mathfrak{p}} \otimes_A H^i(M) \cong H^i(M_{\mathfrak{p}}) \cong \begin{cases} A_{\mathfrak{p}} & \text{if } i = e_{\mathfrak{p}}, \\ 0 & \text{otherwise.} \end{cases}$$

We now use Lemma 14.2.39(3) to deduce that for any prime \mathfrak{p} there is an open neighborhood $U_{\mathfrak{p}}$ of \mathfrak{p} in $\text{Spec } A$ such that $H^{e_{\mathfrak{q}}}(M_{\mathfrak{q}}) \cong A_{\mathfrak{q}}$ for all $\mathfrak{q} \in U_{\mathfrak{p}}$. This implies, by equation (14.2.47), that $e_{\mathfrak{q}} = e_{\mathfrak{p}}$. Therefore $\mathfrak{p} \mapsto e_{\mathfrak{p}}$ is a locally constant function $\text{Spec } A \rightarrow \mathbb{Z}$. We assumed that $\text{Spec } A$ is connected, and this implies that this is a constant function, say $e_{\mathfrak{p}} = -d$ for some integer d .

Define $L := H^{-d}(M) \in \mathbf{M}_f(A)$. Using truncation we see that $M \cong L[d]$ in $\mathbf{D}(A)$. We know that $L_{\mathfrak{p}} \cong A_{\mathfrak{p}}$ for all primes \mathfrak{p} . Finally, Lemma 14.2.23 says that the A -module L is projective. \square

Remark 14.2.48. Lemma 14.2.41 is actually true in much greater generality: the ring A does not have to be noetherian, and we do not have to assume that the complexes M and M' have bounded above or finite cohomology. The proof is harder. See [Ye10, Theorem 6.13].

Proof of Theorem 14.2.34. Define the duality functors $D := \text{RHom}_A(-, R)$ and $D' := \text{RHom}_A(-, R')$; these are finite dimensional contravariant triangulated functors from $\mathbf{D}_f(A)$ to itself. And define $F := D' \circ D$ and $F' := D \circ D'$, that are finite dimensional covariant triangulated functors from $\mathbf{D}_f(A)$ to itself. Let

$$(14.2.49) \quad M := F(A) = (D'(D(A)) = \text{RHom}_A(R, R')$$

and

$$M' := F'(A) = (D(D'(A)) = \text{RHom}_A(R', R).$$

These are objects of $\mathbf{D}_f^b(A)$.

For any object $N \in \mathbf{D}(A)$ there is a morphism

$$\psi_N : N \otimes_A^L \mathrm{RHom}_A(R, R') \rightarrow \mathrm{RHom}_A(\mathrm{RHom}_A(N, R), R')$$

defined as follows: we choose a K-projective resolution $P \rightarrow N$ and a K-injective resolution $R' \rightarrow I'$. Then ψ_N is represented by the obvious homomorphism of complexes

$$P \otimes_A \mathrm{Hom}_A(R, I') \rightarrow \mathrm{Hom}_A(\mathrm{Hom}_A(P, R), I').$$

As N changes, ψ_N is a morphism of triangulated functors

$$\psi : - \otimes_A^L M \rightarrow D' \circ D = F.$$

For $N = A$ the morphism ψ_A is an isomorphism, by equation (14.2.49). The functor F has finite cohomological dimension, and the functor $- \otimes_A^L M$ has bounded above cohomological displacement. According to Theorem 14.1.27, the morphism ψ_N is an isomorphism for any $N \in \mathbf{D}_f^-(A)$. In particular this is true for $N := M'$. So, using Theorem 14.2.15, we obtain

$$M' \otimes_A^L M \cong (D' \circ D)(M') \cong (D' \circ D \circ D \circ D')(A) \cong A.$$

According to Lemma 14.2.41 there is an isomorphism $M \cong L[d]$. Finally, using the isomorphism ψ_R , we get

$$R \otimes_A L[d] \cong F(R) = D'(D(R)) \cong D'(A) = R'.$$

□

What if $\mathrm{Spec} A$ has more than one connected component? A decomposition of $\mathrm{Spec} A$ into open-closed subschemes

$$\mathrm{Spec} A = \mathrm{Spec} A_1 \sqcup \cdots \sqcup \mathrm{Spec} A_r$$

corresponds to a decomposition of A into a product of rings:

$$(14.2.50) \quad A = A_1 \times \cdots \times A_r.$$

The noetherian property implies that $\mathrm{Spec} A$ has only finitely many connected components. If each $\mathrm{Spec} A_i$ in (14.2.50) is connected and nonempty, then this is called the *connected component decomposition of A* .

Let $\mathbf{K}_1, \dots, \mathbf{K}_r$ be pretriangulated categories. The product category $\mathbf{K} := \prod_{i=1}^r \mathbf{K}_i$ has a pretriangulated structure such that the functors $\mathbf{K}_i \rightarrow \mathbf{K} \rightarrow \mathbf{K}_i$ are triangulated.

Proposition 14.2.51. *Given a ring isomorphism $A \cong \prod_{i=1}^r A_i$, the functor*

$$M \mapsto \prod_i A_i \otimes_A M$$

is an equivalence of pretriangulated categories

$$\mathbf{D}(A) \rightarrow \prod_i \mathbf{D}(A_i).$$

Exercise 14.2.52. Prove Proposition 14.2.51.

Corollary 14.2.53. *Let R and R' be dualizing complexes over A , and let (14.2.50) be the connected component decomposition of A . Then there is an isomorphism*

$$R' \cong R \otimes_A (L_1[d_1] \oplus \cdots \oplus L_r[d_r])$$

in $\mathbf{D}(A)$, where each L_i is a rank 1 projective A_i -module, and each d_i is an integer. Furthermore, the modules L_i are unique up to isomorphism, and the integers d_i are unique.

Exercise 14.2.54. Prove Corollary 14.2.53.

Remark 14.2.55. A rank 1 projective A -module L is also called an *invertible A -module*. This is because L is invertible for the tensor product. Recall that the group of isomorphism classes of invertible A -modules is the *commutative Picard group* $\text{Pic}_A(A)$.

The *commutative derived Picard group* $\text{DPic}_A(A)$ is the abelian group $\text{Pic}_A(A) \times \mathbb{Z}^r$ that classifies dualizing complexes over A , as in Corollary 14.2.53.

Now assume that A is *noncommutative*, and flat central over a commutative ring \mathbb{K} . There are noncommutative versions of dualizing complexes and of “invertible” complexes, that are called *tilting complexes*. The latter form the nonabelian group $\text{DPic}_{\mathbb{K}}(A)$, and it classifies noncommutative dualizing complexes. See [Ric1], [Ric2], [Kel], [Ye4] and [RoZi]. We hope to get to this material in Section 19 of the book.

Remark 14.2.56. The lack of uniqueness of dualizing complexes has always been a source of difficulty. A certain uniqueness or functoriality is needed, already for proving existence of dualizing complexes on schemes.

In [RD] Grothendieck utilized local and global duality in order to formulate a suitable uniqueness of dualizing complexes. This approach was very cumbersome (even without providing details!)

Since then there have been a few approaches in the literature to attack this difficulty. Generally speaking, these approaches came in two flavors:

- Representability: this started with Deligne’s Appendix to [RD], and continued most notably in the work of Neeman, and of Lipman et al. See [Ne2], [Li1] and their references.
- Explicit Constructions: mostly in the early work of Lipman et al., including [Li1] and [LNS], and in the work of Yekutieli [Ye2], and [Ye3] and [Ye6]. references.

In the Section ??? of the book we will present *rigid dualizing complexes*, for which there is a built-in functoriality.

14.3. More on Injective Resolutions. We start with a few facts about injective modules over rings that are neither commutative nor noetherian. Sources for this material are [Rot] and [Lam].

Definition 14.3.1.

- (1) Let M be an A -module. A submodule $N \subseteq M$ is called an *essential submodule* if for every nonzero submodule $L \subseteq M$, the intersection $N \cap L$ is nonzero. In this case we also say that M is an *essential extension* of N .
- (2) An *essential monomorphism* is a monomorphism $\phi : N \rightarrow M$ whose image is an essential submodule of M .
- (3) Let M be an A -module. An *injective hull* (or *injective envelope*) of M is an injective module I , together with an essential monomorphism $M \rightarrow I$.

Proposition 14.3.2. Any A -module M admits an injective hull.

Proof. See [Lam, Section 3.D]. □

There is a weak uniqueness result for injective hulls.

Proposition 14.3.3. *Let M be an A -module, and suppose $\phi : M \hookrightarrow I$ and $\phi' : M \hookrightarrow I'$ are monomorphisms into injective modules.*

- (1) *If ϕ is essential, then there is a monomorphism $\psi : I \xrightarrow{\cong} I'$ such that $\psi \circ \phi = \phi'$.*
- (2) *If ϕ' is also essential, then ψ above is an isomorphism.*

Exercise 14.3.4. Prove Proposition 14.3.3.

In classical homological algebra we talk about the minimal injective resolution of a module. Let us recall it. We start with taking the injective hull $M \hookrightarrow I^0$. This gives an exact sequence

$$0 \rightarrow M \rightarrow I^0 \rightarrow M^1 \rightarrow 0,$$

where M^1 is the cokernel. Then we take the injective hull $M^1 \hookrightarrow I^1$, and this gives a longer exact sequence

$$0 \rightarrow M \rightarrow I^0 \rightarrow I^1 \rightarrow M^2 \rightarrow 0,$$

etc. We want to generalize this idea to complexes.

Definition 14.3.5.

- (1) A *minimal injective complex* of A -modules is a bounded below complex of injective modules I , such that for every integer q the submodule of cocycles $Z^q(I) \subseteq I^q$ is essential.
- (2) Let $M \in \mathbf{D}^+(A)$. A *minimal injective resolution* of M is a quasi-isomorphism $M \rightarrow I$ into a minimal injective complex I .

Proposition 14.3.6. *Let $M \in \mathbf{D}^+(A)$.*

- (1) *There exists a minimal injective resolution $\phi : M \rightarrow I$.*
- (2) *If $\phi' : M \rightarrow I'$ is another minimal injective resolution, then there is an isomorphism $\psi : I \rightarrow I'$ in $\mathbf{C}_{\text{str}}(A)$ such that $\phi' = \psi \circ \phi$.*
- (3) *If M has finite injective dimension, then it has a bounded minimal injective resolution I .*

Proof. We know that there is a quasi-isomorphism $M \rightarrow J$ where J is a bounded below complex of injective modules. For any q let E^q be an injective hull of $Z^q(I)$. By Proposition 14.3.3(1) we can assume that E^q sits inside J^q like this: $Z^q(I) \subseteq E^q \subseteq J^q$. Since E^q is injective, we can decompose J^q into a direct sum: $J^q \cong E^q \oplus K^q$. The homomorphism $d_J^q : K^q \rightarrow J^{q+1}$ is a monomorphism since $K^q \cap Z^q(I) = 0$. And the image $d_J^q(K^q)$ is contained in E^{q+1} . Thus $d_J^q(K^q)$ is a direct summand of E^{q+1} , and this shows that the quotient

$$I^{q+1} := E^{q+1}/d_J^q(K^q) \cong J^{q+1}/(K^{q+1} \oplus d_J^q(K^q))$$

is an injective module. The canonical surjection of graded modules $\pi : J \rightarrow I$ is a homomorphism of complexes, with kernel the acyclic complex

$$\bigoplus_q (K^q[-q] \xrightarrow{d_J^q} d_J^q(K^q)[-q-1]).$$

Therefore π is a quasi-isomorphism. A short calculation shows that I is a minimal injective complex, i.e. $Z^q(I) \subseteq I^q$ is essential.

- (2) See next exercise. (We will not need this fact.)

(3) According to Proposition 14.1.19, the complex J that appears in item (1) can be chosen to be bounded. \square

Exercise 14.3.7. Prove Proposition 14.3.6(2).

Remark 14.3.8. There is a more general version of minimal injective complex: it is a K -injective complex I consisting of injective modules, such that each $Z^q(I) \subseteq I^q$ is essential. See [Kr, Appendix B].

Remark 14.3.9. Important: the isomorphisms ψ in Propositions 14.3.3 and 14.3.6 are not unique (see next exercise). We will see below (in Subsection ????) that a rigid residue complex is a minimal injective complex that has no nontrivial rigid automorphisms.

Exercise 14.3.10. Take $A := \mathbb{K}[[t]]$, the power series ring over a field \mathbb{K} . Let $M := A/(t)$, the trivial module (the residue field viewed as an A -module).

(1) Find the minimal injective resolution

$$0 \rightarrow M \rightarrow I^0 \rightarrow I^1 \rightarrow 0.$$

(2) Find nontrivial automorphisms of the complex I in $\mathbf{C}_{\text{str}}(A)$ that fix the submodule $M \subseteq I^0$.

Now we add the noetherian condition.

Proposition 14.3.11. Assume A is a left noetherian ring. Let $\{I_z\}_{z \in Z}$ be a collection of injective A -modules. Then $I = \bigoplus_{z \in Z} I_z$ is an injective A -module.

Exercise 14.3.12. Prove Proposition 14.3.11. (Hint: use the Baer criterion.)

From here all rings here are noetherian commutative. For them much more can be said.

Recall that a module M is called *indecomposable* if it is not the direct sum of two nonzero modules.

Definition 14.3.13. Let $\mathfrak{a} \subseteq A$ be an ideal.

(1) Let M be an A -module. The \mathfrak{a} -torsion submodule of M is the submodule $\Gamma_{\mathfrak{a}}(M)$ consisting of the elements that are annihilated by powers of \mathfrak{a} . Thus

$$\Gamma_{\mathfrak{a}}(M) = \lim_{i \rightarrow} \text{Hom}_A(A/\mathfrak{a}^i, M) \subseteq M.$$

(2) If $\Gamma_{\mathfrak{a}}(M) = M$ then M is called an \mathfrak{a} -torsion module.

Perhaps the most important theorem about injective modules over noetherian commutative rings is the following structural result due to Matlis [Matl] from 1958. See also [Ste, Section IV.4], [Lam, Sections 3.F and 3.I], [Mats, Section 18] and [BrSh].

Theorem 14.3.14 (Matlis). Let A be a noetherian commutative ring.

- (1) Let $\mathfrak{p} \subseteq A$ be a prime ideal, and let $J(\mathfrak{p})$ be the injective hull of the $A_{\mathfrak{p}}$ -module $\mathfrak{k}(\mathfrak{p})$. Then, as an A -module, $J(\mathfrak{p})$ is injective, indecomposable and \mathfrak{p} -torsion.
- (2) Suppose I is an indecomposable injective A -module. Then $I \cong J(\mathfrak{p})$ for a unique prime ideal $\mathfrak{p} \subseteq A$.
- (3) Every injective A module I is a direct sum of indecomposable injective A -modules.

Theorem 14.3.14 tells us that any injective A -module I can be written as a direct sum

$$(14.3.15) \quad I \cong \bigoplus_{\mathfrak{p} \in \operatorname{Spec} A} J(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}}}$$

for a collection of cardinal numbers $\{\mu_{\mathfrak{p}}\}_{\mathfrak{p} \in \operatorname{Spec} A}$, called the *Bass numbers*. General counting tricks can show that the multiplicity $\mu_{\mathfrak{p}}$ is an invariant of I . But we can be more precise:

Proposition 14.3.16. *Assume A is a noetherian commutative ring. Let I be an injective A -module, with decomposition (14.3.15). Then for any \mathfrak{p} there is equality*

$$\mu_{\mathfrak{p}} = \operatorname{rank}_{\mathbf{k}(\mathfrak{p})}(\operatorname{Hom}_{A_{\mathfrak{p}}}(J(\mathfrak{p}), A_{\mathfrak{p}} \otimes_A I)).$$

Proof. Consider another prime \mathfrak{q} . If $\mathfrak{q} \not\subseteq \mathfrak{p}$ then there is an element $a \in \mathfrak{q} - \mathfrak{p}$, and then a is both invertible and locally nilpotent on $A_{\mathfrak{p}} \otimes_A J(\mathfrak{q})$. This implies that $A_{\mathfrak{p}} \otimes_A J(\mathfrak{q}) = 0$. On the other hand, if $\mathfrak{q} \subseteq \mathfrak{p}$, then $A_{\mathfrak{p}} \otimes_A J(\mathfrak{q}) \cong J(\mathfrak{q})$. Therefore

$$A_{\mathfrak{p}} \otimes_A I \cong \bigoplus_{\mathfrak{q} \subseteq \mathfrak{p}} J(\mathfrak{q})^{\oplus \mu_{\mathfrak{q}}}.$$

Next, if $\mathfrak{q} \subsetneq \mathfrak{p}$, then there is an element $b \in \mathfrak{p} - \mathfrak{q}$, and it is both invertible and zero on the module

$$\operatorname{Hom}_{A_{\mathfrak{p}}}(J(\mathfrak{q}), J(\mathfrak{p})).$$

The implication is that this module is zero.

Finally, if $\mathfrak{q} = \mathfrak{p}$ then we have

$$\operatorname{Hom}_{A_{\mathfrak{p}}}(J(\mathfrak{p}), J(\mathfrak{p})) \cong \operatorname{Hom}_{A_{\mathfrak{p}}}(J(\mathfrak{p}), \mathbf{k}(\mathfrak{p})) \cong \mathbf{k}(\mathfrak{p}),$$

because the inclusion $J(\mathfrak{p}) \subseteq \mathbf{k}(\mathfrak{p})$ is essential.

Putting all these cases together we see that

$$\operatorname{Hom}_{A_{\mathfrak{p}}}(J(\mathfrak{p}), A_{\mathfrak{p}} \otimes_A I) \cong \mathbf{k}(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}}}$$

as $\mathbf{k}(\mathfrak{p})$ -modules. □

14.4. Residue Complexes. In this subsection A is a noetherian commutative ring. Here we introduce residue complexes (called residual complexes in [RD]). Most of the material is taken from the original [RD]. In Example 14.4.12 we will see the relation between the geometry of $\operatorname{Spec} A$ and the structure of dualizing complexes over A (continuing Example 0.1.8 from the Introduction). Example 14.4.23 will explain the relation to residues in the classical sense.

Lemma 14.4.1. *Let R be a dualizing complex over A and let $\mathfrak{p} \subseteq A$ be a prime ideal. There is an integer d such that*

$$\operatorname{Ext}_{A_{\mathfrak{p}}}^i(\mathbf{k}(\mathfrak{p}), R_{\mathfrak{p}}) \cong \begin{cases} \mathbf{k}(\mathfrak{p}) & \text{if } i = -d, \\ 0 & \text{otherwise.} \end{cases}$$

Proof. By Proposition 14.2.32, $R_{\mathfrak{p}}$ is a dualizing complex over the local ring $A_{\mathfrak{p}}$. And by Proposition 14.2.31,

$$S := \operatorname{RHom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), R_{\mathfrak{p}})$$

is a dualizing complex over the residue field $\mathbf{k}(\mathfrak{p})$. Since $\mathbf{k}(\mathfrak{p})$ is a regular ring, it is also a dualizing complex over itself. Theorem 14.2.34 tells us that $S \cong \mathbf{k}(\mathfrak{p})[d]$ in $\mathbf{D}(\mathbf{k}(\mathfrak{p}))$ for some integer d . □

Definition 14.4.2. The number d in Lemma 14.4.1 is called the *dimension of \mathfrak{p} relative to R* , and is denoted by $\dim_R(\mathfrak{p})$.

In this way we obtain a function

$$\dim_R : \text{Spec } A \rightarrow \mathbb{Z},$$

called the *dimension function associated to R* .

Let us recall a few notions regarding the combinatorics of prime ideals in a ring A . A prime ideal \mathfrak{q} is an *immediate specialization* of another prime \mathfrak{p} if $\mathfrak{p} \subsetneq \mathfrak{q}$, and there is no other prime \mathfrak{p}' such that $\mathfrak{p} \subsetneq \mathfrak{p}' \subsetneq \mathfrak{q}$. In other words, if the dimension of the local ring $A_{\mathfrak{q}}/\mathfrak{p}_{\mathfrak{q}}$ is 1.

A *chain of prime ideals* in A is a sequence $(\mathfrak{p}_0, \dots, \mathfrak{p}_n)$ of primes such that $\mathfrak{p}_i \subsetneq \mathfrak{p}_{i+1}$ for all i . The number n is the *length* of the chain. The chain is called *saturated* if for each i the prime \mathfrak{p}_{i+1} is an immediate specialization of \mathfrak{p}_i .

Theorem 14.4.3. *Let R be a dualizing complex over A and let $\mathfrak{p}, \mathfrak{q} \subseteq A$ be prime ideals. Assume that \mathfrak{q} is an immediate specialization of \mathfrak{p} . Then*

$$\dim_R(\mathfrak{q}) = \dim_R(\mathfrak{p}) - 1.$$

To prove this theorem we need a baby version of local cohomology: codimension 1 only.

Let \mathfrak{a} be an ideal in A . The torsion functor $\Gamma_{\mathfrak{a}}$ has a right derived functor $\mathbf{R}\Gamma_{\mathfrak{a}}$. For any complex $M \in \mathbf{D}(A)$, the module $H_{\mathfrak{a}}^p(M) := H^p(\mathbf{R}\Gamma_{\mathfrak{a}}(M))$ is called the *p -th cohomology of M with supports in \mathfrak{a}* . In case A is a local ring and \mathfrak{m} is its maximal ideal, then $H_{\mathfrak{m}}^p(M)$ is also called the *local cohomology of M* .

Now suppose \mathfrak{a} is a principal ideal in A , generated by an element a . Let $A_a = A[a^{-1}]$ be the localized ring. For any A -module M we write $M_a = A_a \otimes_A M$. There is a canonical exact sequence

$$(14.4.4) \quad 0 \rightarrow \Gamma_{\mathfrak{a}}(M) \rightarrow M \rightarrow M_a.$$

Lemma 14.4.5. *Let $\mathfrak{a} = (a)$ be a principal ideal in A .*

(1) *For any injective module I the sequence*

$$0 \rightarrow \Gamma_{\mathfrak{a}}(I) \rightarrow I \rightarrow I_a \rightarrow 0$$

is exact.

(2) *For any $M \in \mathbf{D}^+(A)$ and any there is a long exact sequence of A -modules*

$$\cdots \rightarrow H_{\mathfrak{a}}^p(M) \rightarrow H^p(M) \rightarrow H^p(M_a) \rightarrow H_{\mathfrak{a}}^{p+1}(M) \rightarrow \cdots$$

Proof. (1) Let $J(\mathfrak{q})$ be an indecomposable injective A -module. According to Theorem 14.3.14(1), if $a \in \mathfrak{q}$ then $\Gamma_{\mathfrak{a}}(J(\mathfrak{q})) = J(\mathfrak{q})$ and $J(\mathfrak{q})_a = 0$. But if $a \notin \mathfrak{q}$ then $J(\mathfrak{q}) = J(\mathfrak{q})_a$ and $\Gamma_{\mathfrak{a}}(J(\mathfrak{q})) = 0$. By Theorem 14.3.14 we see that any injective module I breaks up into a direct sum $I = \Gamma_{\mathfrak{a}}(I) \oplus I_a$, and this proves that the sequence is split exact.

(2) Choose a resolution $M \rightarrow I$ by a bounded below complex of injectives. We obtain an exact sequence of complexes as in item (1). The long exact sequence in cohomology

$$\cdots \rightarrow H^p(\Gamma_{\mathfrak{a}}(I)) \rightarrow H^p(I) \rightarrow H^p(I_a) \rightarrow H^{p+1}(\Gamma_{\mathfrak{a}}(I)) \rightarrow \cdots$$

is what we want. □

Lemma 14.4.6. *Suppose A is an integral domain, with fraction field K , such that $A \neq K$. Then K is not a finitely generated A -module.*

Proof. Let $a \in A$ be a nonzero element that is not invertible. Then

$$A \subsetneq a^{-1} \cdot A \subsetneq a^{-2} \cdot A \subsetneq \cdots \subseteq K$$

is an infinite ascending sequence of A -submodules in K . □

Lemma 14.4.7. *For any ideal \mathfrak{a} and any $M \in \mathbf{D}(A)$ there is an isomorphism of A -modules*

$$H_{\mathfrak{a}}^p(M) \cong \lim_{k \rightarrow} \text{Ext}_A^p(A/\mathfrak{a}^k, M).$$

Proof. Choose a K -injective resolution $M \rightarrow I$. Then, using the fact that cohomology commutes with direct limits, we have

$$\begin{aligned} H_{\mathfrak{a}}^p(M) &\cong H^p(\Gamma_{\mathfrak{a}}(I)) \cong H^p(\lim_{k \rightarrow} \text{Hom}_A(A/\mathfrak{a}^k, I)) \\ &\cong \lim_{k \rightarrow} H^p(\text{Hom}_A(A/\mathfrak{a}^k, I)) \cong \lim_{k \rightarrow} \text{Ext}_A^p(A/\mathfrak{a}^k, M). \end{aligned}$$

□

Lemma 14.4.8. *Assume A is local, with maximal ideal \mathfrak{m} . Let R be a dualizing complex over A , and let $d := \dim_R(\mathfrak{m})$. Then for any $i \neq -d$ the local cohomology $H_{\mathfrak{m}}^i(R)$ vanishes.*

See Remark 14.4.25 for more about $H_{\mathfrak{m}}^{-d}(R)$.

Proof. We know that

$$\text{Ext}_A^i(\mathbf{k}(\mathfrak{m}), R) \cong \begin{cases} \mathbf{k}(\mathfrak{m}) & \text{if } i = -d, \\ 0 & \text{otherwise.} \end{cases}$$

Let N be a finite length A -module. Since N is gotten from the residue field $\mathbf{k}(\mathfrak{m})$ by finitely many extensions, induction on the length of N shows that $\text{Ext}_A^i(N, R) = 0$ for all $i \neq -d$. This holds in particular for $N := A/\mathfrak{m}^k$. Now use Lemma 14.4.7. □

Proof of Theorem 14.4.3. After replacing A with $A_{\mathfrak{q}}/\mathfrak{p}_{\mathfrak{q}}$, we can assume that $\mathfrak{p} = 0$ and $A = A_{\mathfrak{q}}$. Thus A is a 1-dimensional local integral domain, with only two primes ideals: $0 = \mathfrak{p}$ and the maximal ideal \mathfrak{q} . Take any nonzero element $a \in \mathfrak{q}$. Then the localization $A_{\mathfrak{a}}$ is the field of fractions of A , i.e. $A_{\mathfrak{a}} = \mathbf{k}(\mathfrak{p})$. On the other hand, letting $\mathfrak{a} := (a) \subseteq A$, the quotient A/\mathfrak{a} is a finite length A -module, so the ideal \mathfrak{a} is \mathfrak{q} -primary, and $\Gamma_{\mathfrak{a}} = \Gamma_{\mathfrak{q}}$.

Define $d := \dim_R(\mathfrak{q})$ and $e := \dim_R(\mathfrak{p})$. By Lemma 14.4.5 there is an exact sequence of A -modules

$$\cdots \rightarrow H_{\mathfrak{a}}^{-e}(R) \rightarrow H^{-e}(R) \xrightarrow{\phi} H^{-e}(R_{\mathfrak{a}}) \rightarrow H_{\mathfrak{a}}^{-e+1}(R) \rightarrow \cdots .$$

Since $a \neq 0$ there are equalities $A_{\mathfrak{a}} = A_{\mathfrak{p}} = \text{Frac}(A) = \mathbf{k}(\mathfrak{p})$. Then $H^{-e}(R_{\mathfrak{a}}) \cong \mathbf{k}(\mathfrak{p})$, and this is not a finitely generated A -module by Lemma 14.4.6. On the other hand the A -module $H^{-e}(R)$ is finitely generated. We conclude that homomorphism ϕ is not surjective, and thus $H_{\mathfrak{a}}^{-e+1}(R) \neq 0$. But $H_{\mathfrak{a}}^{-e+1}(R) = H_{\mathfrak{q}}^{-e+1}(R)$, so according to Lemma 14.4.8 we must have $-e + 1 = -d$. Thus $e = d + 1$ as claimed. □

Corollary 14.4.9. *If A has a dualizing complex, then the Krull dimension of A is finite. More precisely, if R is a dualizing complex over A , then $\dim(A)$ is at most the injective dimension of R .*

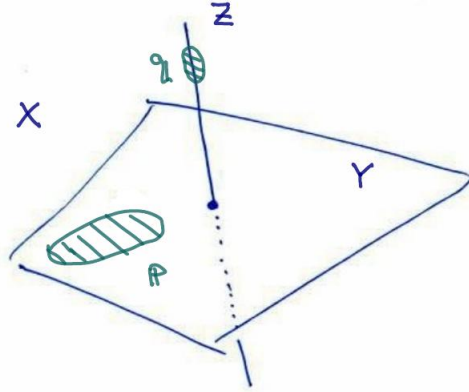


FIGURE 8. An algebraic variety X that is connected but not equidimensional: it has irreducible components Y and Z of dimensions 2 and 1 respectively. The generic points $\mathfrak{p} \in Y$ and $\mathfrak{q} \in Z$ are shown.

Proof. Let $[i_0, i_1]$ be the injective concentration of the complex R . See Definition 14.1.12. This is a bounded interval. Since

$$\text{Ext}_{A_{\mathfrak{p}}}^i(\mathbf{k}(\mathfrak{p}), R_{\mathfrak{p}}) \cong \text{Ext}_A^i(A/\mathfrak{p}, R)_{\mathfrak{p}},$$

we see that the number $\dim_R(\mathfrak{p}) \in [i_0, i_1]$.

Let $(\mathfrak{p}_0, \dots, \mathfrak{p}_n)$ be a chain of prime ideals in A . Because A is noetherian, we can squeeze more primes into this chain, until after finitely many steps it becomes saturated. According to Theorem 14.4.3 we have

$$n = \dim_R(\mathfrak{p}_0) - \dim_R(\mathfrak{p}_n).$$

Therefore $n \leq i_1 - i_0$. □

Definition 14.4.10. The ring A is called *catenary* if for any pair of primes $\mathfrak{p} \subseteq \mathfrak{q}$ there is a number $n_{\mathfrak{p}, \mathfrak{q}}$ such that for any saturated chain $(\mathfrak{p}_0, \dots, \mathfrak{p}_n)$ with $\mathfrak{p}_0 = \mathfrak{p}$ and $\mathfrak{p}_n = \mathfrak{q}$, there is equality $n = n_{\mathfrak{p}, \mathfrak{q}}$.

Corollary 14.4.11. *If A has a dualizing complex, then it is catenary.*

Proof. Let R be a dualizing complex over A . The proof of the previous corollary shows that the number

$$n_{\mathfrak{p}, \mathfrak{q}} = \dim_R(\mathfrak{p}) - \dim_R(\mathfrak{q})$$

has the desired property. □

Example 14.4.12. This is a continuation of Example 0.1.8 from the Introduction. Consider the ring

$$A = \mathbb{R}[t_1, t_2, t_3]/(t_3 \cdot t_1, t_3 \cdot t_2).$$

The affine algebraic variety

$$X = \text{Spec } A \subseteq \mathbf{A}_{\mathbb{R}}^3$$

is shown in figure 8. It is the union of a plane Y and a line Z , meeting at the origin.

Since the ring A is finite type over the field \mathbb{R} , it has a dualizing complex R . We will now prove that there is some integer i s.t. $H^i(R)$ and $H^{i+1}(R)$ are nonzero.

Define the prime ideals $\mathfrak{m} := (t_1, t_2, t_3)$, $\mathfrak{q} := (t_1, t_2)$ and $\mathfrak{p} := (t_3)$. Thus \mathfrak{m} is the origin, \mathfrak{q} is the generic point of the line $Z = \text{Spec } A/\mathfrak{q}$, and \mathfrak{p} is the generic point of the plane $Y = \text{Spec } A/\mathfrak{p}$. By translating R as needed, we can assume that $\dim_R(\mathfrak{m}) = 0$. Since \mathfrak{m} is an immediate specialization of \mathfrak{q} , Theorem 14.4.3 tells us that $\dim_R(\mathfrak{q}) = 1$. Similarly, since any line in Y passing through the origin gives rise to a saturated chain $(\mathfrak{p}, \mathfrak{q}', \mathfrak{m})$, we see that $\dim_R(\mathfrak{p}) = 2$.

Since \mathfrak{q} is the generic point of Z , its local ring is the residue field: $A_{\mathfrak{q}} = \mathbf{k}(\mathfrak{q})$. We know that $\dim_R(\mathfrak{q}) = 1$. Hence

$$\mathbf{k}(\mathfrak{q}) \cong \text{Ext}_{A_{\mathfrak{q}}}^{-1}(\mathbf{k}(\mathfrak{q}), R_{\mathfrak{q}}) = \text{Ext}_{A_{\mathfrak{q}}}^{-1}(A_{\mathfrak{q}}, R_{\mathfrak{q}}) \cong \text{Ext}_A^{-1}(A, R)_{\mathfrak{q}} \cong H^{-1}(R)_{\mathfrak{q}}.$$

Therefore $H^{-1}(R) \neq 0$. A similar calculation involving \mathfrak{p} shows that $H^{-2}(R) \neq 0$.

Example 14.4.13. Let A be a local ring, with maximal ideal \mathfrak{m} and residue field $\mathbf{k}(\mathfrak{m})$. Recall that A is called *Gorenstein* if the free module A has finite injective dimension. The ring A is called *Cohen-Macaulay* if its depth is equal to its dimension, where the depth of A is the minimal integer i such that $\text{Ext}_A^i(\mathbf{k}(\mathfrak{m}), A) \neq 0$. It is known that Gorenstein implies Cohen-Macaulay. See [Mats] for details.

As is our usual practice (cf. Convention 14.2.10) we shall say that a noetherian commutative ring A is Cohen-Macaulay (resp. Gorenstein) if it has finite Krull dimension, and all its local rings $A_{\mathfrak{p}}$ are Cohen-Macaulay (resp. Gorenstein) local rings, as defined above.

Assume A has a connected spectrum, and let R be a dualizing complex over A . Grothendieck showed in [RD, Section V.9] that A is a Cohen-Macaulay ring iff $R \cong L[d]$ for some finitely generated module L and some integer d ; the proof is not easy. It is however pretty easy to prove (using Theorem 14.2.34) that A is a Gorenstein ring iff $R \cong L[d]$ for some invertible module L and some integer d .

There is a lot more to say about the relation between the CM (Cohen-Macaulay) property and duality. See Remark 14.4.27

Recall that for any $\mathfrak{p} \in \text{Spec } A$ we denote by $J(\mathfrak{p})$ the corresponding indecomposable injective module.

Definition 14.4.14. A *residue complex* over A is a complex of A -module \mathcal{K} having these properties:

- (i) \mathcal{K} is a dualizing complex.
- (ii) For any integer d there is an isomorphism of A -modules

$$\mathcal{K}^{-d} \cong \bigoplus_{\substack{\mathfrak{p} \in \text{Spec } A \\ \dim_{\mathcal{K}}(\mathfrak{p})=d}} J(\mathfrak{p}).$$

The reason we like residue complexes is this:

Theorem 14.4.15. *Suppose \mathcal{K} and \mathcal{K}' are residue complexes over A that have the same dimension function. Then the homomorphism*

$$Q : \text{Hom}_{\mathbf{C}_{\text{str}}(A)}(\mathcal{K}, \mathcal{K}') \rightarrow \text{Hom}_{\mathbf{D}(A)}(\mathcal{K}, \mathcal{K}')$$

is bijective.

In more words: for any morphism $\psi : \mathcal{K} \rightarrow \mathcal{K}'$ in $\mathbf{D}(A)$ there is a unique strict homomorphism of complexes $\phi : \mathcal{K} \rightarrow \mathcal{K}'$ such that $\psi = Q(\phi)$.

Proof. Since the complex \mathcal{K}' is \mathbf{K} -injective, by Theorem ????

cmnt: creat new thm just before Cor 9.1.13

we know that the homomorphism

$$Q : \text{Hom}_{\mathbf{K}(A)}(\mathcal{K}, \mathcal{K}') \rightarrow \text{Hom}_{\mathbf{D}(A)}(\mathcal{K}, \mathcal{K}')$$

is bijective. And by definition the homomorphism

$$P : \text{Hom}_{\mathbf{C}_{\text{str}}(A)}(\mathcal{K}, \mathcal{K}') \rightarrow \text{Hom}_{\mathbf{K}(A)}(\mathcal{K}, \mathcal{K}')$$

is surjective. It remains to prove that

$$\text{Hom}_A(\mathcal{K}, \mathcal{K}')^{-1} = 0,$$

i.e. here are no nonzero degree -1 homomorphisms $\gamma : \mathcal{K} \rightarrow \mathcal{K}'$.

The residue complexes \mathcal{K} and \mathcal{K}' decompose into indecomposable summands by the formula in property (ii) of Definition 14.4.14. A homomorphism $\gamma : \mathcal{K} \rightarrow \mathcal{K}'$ of degree -1 is nonzero iff at least one of its components

$$\gamma_{\mathfrak{p}, \mathfrak{q}} : J(\mathfrak{p}) \rightarrow J(\mathfrak{q})$$

is nonzero, for some $J(\mathfrak{p}) \subseteq \mathcal{K}^{-i}$ and $J(\mathfrak{q}) \subseteq \mathcal{K}'^{-i-1}$. Denoting by \dim the dimension function of both these dualizing complexes, we have $\dim(\mathfrak{p}) = i$ and $\dim(\mathfrak{q}) = i + 1$. But the lemma below says that \mathfrak{q} has to be a specialization of \mathfrak{p} . Therefore, as in the proof of Corollary 14.4.9, there is an inequality in the opposite direction: $\dim(\mathfrak{p}) \geq \dim(\mathfrak{q})$. We see that it is impossible to have a nonzero degree -1 homomorphism $\gamma : \mathcal{K} \rightarrow \mathcal{K}'$. \square

Lemma 14.4.16. *Let $\mathfrak{p}, \mathfrak{q}$ be prime ideals. If there is a nonzero homomorphism $\gamma : J(\mathfrak{p}) \rightarrow J(\mathfrak{q})$, then \mathfrak{q} is a specialization of \mathfrak{p} .*

Proof. Assume \mathfrak{q} is not a specialization of \mathfrak{p} ; i.e. $\mathfrak{p} \not\subseteq \mathfrak{q}$. So there is an element $a \in \mathfrak{p} - \mathfrak{q}$. Let $\gamma : J(\mathfrak{p}) \rightarrow J(\mathfrak{q})$ be a homomorphism, and consider the module $N := \gamma(J(\mathfrak{p})) \subseteq J(\mathfrak{q})$. Since $J(\mathfrak{p})$ is \mathfrak{p} -torsion, the element a acts on N locally-nilpotently. On the other hand, $J(\mathfrak{q})$ is a module over $A_{\mathfrak{q}}$, so a acts invertibly on $J(\mathfrak{q})$, and hence it has zero annihilator in N . The conclusion is that $N = 0$. \square

Here is a general existence theorem.

Theorem 14.4.17. *Suppose the ring A has a dualizing complex R . Let $R \rightarrow \mathcal{K}$ be a minimal injective resolution of R . Then \mathcal{K} is a residue complex over A .*

The proof is after two lemmas.

Lemma 14.4.18. *Let $S \subseteq A$ be a multiplicatively closed set, with localization A_S . For any A -module M we write $M_S := A_S \otimes_A M$.*

- (1) *If I is an injective A -module, then I_S is an injective A_S -module.*
- (2) *If I is an injective A -module and $M \subseteq I$ is an essential A -submodule, then $M_S \subseteq I_S$ is an essential A_S -submodule.*
- (3) *If I is a minimal injective complex of A -modules, then I_S is a minimal injective complex of A_S -modules,*

Proof. (1) By Theorem 14.3.14 there is a direct sum decomposition $I \cong I' \oplus I''$, where

$$I' \cong \bigoplus_{\mathfrak{p} \cap S = \emptyset} J(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}}} \quad \text{and} \quad I'' \cong \bigoplus_{\mathfrak{p} \cap S \neq \emptyset} J(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}}}.$$

If $\mathfrak{p} \cap S = \emptyset$ then $J(\mathfrak{p}) \cong J(\mathfrak{p})_S$ is an injective A_S -module; and if $\mathfrak{p} \cap S \neq \emptyset$ then $J(\mathfrak{p})_S = 0$. We see that $I_S \cong I'$ is an injective A_S -module.

(2) Denote by $\lambda : I \rightarrow I_S$ the canonical homomorphism. Under the decomposition $I \cong I' \oplus I''$ above, $\lambda|_{I'} : I' \rightarrow I_S$ is an isomorphism.

Let L be a nonzero A_S -submodule of I_S . Since λ is split, we can lift it to a submodule $L' \subseteq I' \subseteq I$, such that $\lambda : L' \rightarrow L$ is bijective. Because $M \subseteq I$ is essential, we know that $M \cap L'$ is nonzero. But $M \cap L' \subseteq I'$, so $\lambda(M \cap L')$ is a nonzero submodule of L . Yet $M \cap L' \subseteq M$, so $\lambda(M \cap L') \subseteq \lambda(M) \subseteq M_S$. Therefore $M_S \cap L \neq 0$.

(3) By part (1) the complex I_S is a bounded below complex of injective A_S -modules. Exactness of localization shows that $Z^n(I_S) = Z^n(I)_S$ inside I_S^n ; so by part (2) the inclusion $Z^n(I_S) \hookrightarrow I_S^n$ is essential. \square

Lemma 14.4.19. *Let $\mathfrak{a} \subseteq A$ be an ideal, and define $B := A/\mathfrak{a}$.*

- (1) *If I is an injective A -module, then $J := \text{Hom}_A(B, I)$ is an injective B -module.*
- (2) *Let I and J be as above. If $M \subseteq I$ is an essential A -submodule, then $N := \text{Hom}_A(B, M)$ is an essential B -submodule of J .*
- (3) *If I is a minimal injective complex of A -modules, then $J := \text{Hom}_A(B, I)$ is a minimal injective complex of B -modules,*

Proof. (1) This is immediate from adjunction.

(2) We identify J and N with the submodules of I and M respectively that are the annihilators of \mathfrak{a} . Let $L \subseteq J$ be a nonzero B -submodule. Then L is a nonzero A -submodule of I . Because M is essential, the intersection $L \cap M$ is nonzero. But $L \cap M$ is annihilated by \mathfrak{a} , so it sits inside N , and in fact $L \cap M = L \cap N$.

(3) By part (1) the complex J is a bounded below complex of injective B -modules. Left exactness of $\text{Hom}_A(B, -)$ shows that $Z^n(J) = \text{Hom}_A(B, Z^n(I))$ inside J^n ; so by part (2) the inclusion $Z^n(J) \hookrightarrow J^n$ is essential. \square

Proof of Theorem 14.4.17. Since $\mathcal{K} \cong R$ in $\mathbf{D}(A)$ it follows that \mathcal{K} is a dualizing complex. To show that \mathcal{K} has property (ii) of Definition 14.4.14 we have to count multiplicities. For any \mathfrak{p} and d let $\mu_{\mathfrak{p}, d}$ be the multiplicity of $J(\mathfrak{p})$ in \mathcal{K}^{-d} , so that

$$\mathcal{K}^{-d} \cong \bigoplus_{\mathfrak{p} \in \text{Spec } A} J(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}, d}}.$$

We have to prove that

$$(14.4.20) \quad \mu_{\mathfrak{p}, d} = \begin{cases} 1 & \text{if } \dim_{\mathcal{K}}(\mathfrak{p}) = d, \\ 0 & \text{otherwise.} \end{cases}$$

Now by Lemma 14.4.18(3) the complex $\mathcal{K}_{\mathfrak{p}} = A_{\mathfrak{p}} \otimes_A \mathcal{K}$ is a minimal injective complex of $A_{\mathfrak{p}}$ -modules. Because $\mathcal{K}_{\mathfrak{p}}$ is K -injective over $A_{\mathfrak{p}}$ we get

$$\text{Ext}_{A_{\mathfrak{p}}}^{-d}(\mathbf{k}(\mathfrak{p}), R_{\mathfrak{p}}) \cong H^{-d}(\text{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), \mathcal{K}_{\mathfrak{p}}))$$

as $\mathbf{k}(\mathfrak{p})$ -modules. By Lemma 14.4.19(3) the complex $\text{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), \mathcal{K}_{\mathfrak{p}})$ is a minimal injective complex of $\mathbf{k}(\mathfrak{p})$ -modules. It is easy to see (and we leave this verification to the reader) that a minimal injective complex over a field must have trivial

differential. Therefore

$$H^d(\mathrm{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), \mathcal{K}_{\mathfrak{p}})) \cong \mathrm{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), \mathcal{K}_{\mathfrak{p}}^{-d}).$$

Now by arguments like in the proof of Lemma 14.4.18(1) we know that

$$\mathrm{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), J(\mathfrak{q})_{\mathfrak{p}}) \cong \begin{cases} \mathbf{k}(\mathfrak{p}) & \text{if } \mathfrak{q} = \mathfrak{p}, \\ 0 & \text{otherwise.} \end{cases}$$

It follows that

$$\mathrm{Hom}_{A_{\mathfrak{p}}}(\mathbf{k}(\mathfrak{p}), \mathcal{K}_{\mathfrak{p}}^{-d}) \cong \mathbf{k}(\mathfrak{p})^{\oplus \mu_{\mathfrak{p}, d}}.$$

We see that

$$\mathrm{rank}_{\mathbf{k}(\mathfrak{p})}(\mathrm{Ext}_{A_{\mathfrak{p}}}^{-d}(\mathbf{k}(\mathfrak{p}), R_{\mathfrak{p}})) = \mu_{\mathfrak{p}, d}.$$

But by Definition 14.4.2 this number satisfies (14.4.20). □

Corollary 14.4.21. *If \mathcal{K} is a residue complex over A then it is a minimal injective complex.*

Proof. Let $\phi : \mathcal{K} \rightarrow \mathcal{K}'$ be a minimal injective resolution of \mathcal{K} . According to Theorem 14.4.17, \mathcal{K}' is also a residue complex. Now $Q(\phi) : \mathcal{K} \rightarrow \mathcal{K}'$ is an isomorphism in $\mathbf{D}(A)$, so by Theorem 14.4.15 we know that $\phi : \mathcal{K} \rightarrow \mathcal{K}'$ is an isomorphism in $\mathbf{C}_{\mathrm{str}}(A)$. □

Exercise 14.4.22. Find a direct proof of Corollary 14.4.21, without resorting to Theorems 14.4.17 and 14.4.15. (Hint: look at the proof of Proposition 14.3.6.)

We end this section with an example and two remarks.

Example 14.4.23. Take an algebraically closed field \mathbb{K} (e.g. $\mathbb{K} = \mathbb{C}$), and let $A := \mathbb{K}[t]$, the ring of polynomials in a variable t . So $\mathrm{Spec} A = \mathbf{A}_{\mathbb{K}}^1$, the affine line over \mathbb{K} .

Grothendieck’s full duality theory from [RD], or alternatively the theory of *rigid complexes*, that we will talk about later in the book, both say that the “correct” dualizing complex over A is $R_A := \Omega_{A/\mathbb{K}}^1[1]$. Here $\Omega_{A/\mathbb{K}}^1$ is the module of differential 1-forms, which is a free A -module of rank 1 with basis dt . The corresponding residue complex (the minimal injective resolution of the complex R_A , see Theorem 14.4.17) is the *rigid residue complex* \mathcal{K}_A of A .

There is a very explicit way to write the complex \mathcal{K}_A , and it relies on the notion of *algebraic residues*. This is, presumably, the source of the name “residue complex”.

Consider a maximal ideal $\mathfrak{m} \subseteq A$. It is generated by $t - \lambda$ for some $\lambda \in \mathbb{K}$. The \mathfrak{m} -adic completion of the local ring $A_{\mathfrak{m}}$ is denoted by $\widehat{A}_{\mathfrak{m}}$, and it a power series ring: $\widehat{A}_{\mathfrak{m}} = \mathbb{K}[[t - \lambda]]$.

Let L denote the field of fractions of A , so $L = \mathbb{K}(t)$, the field of rational functions. The completion $\widehat{L}_{\mathfrak{m}}$ of L at a maximal ideal $\mathfrak{m} = (t - \lambda)$ is the Laurent series field $\mathbb{K}((t - \lambda))$.

A rational differential form is an element

$$\alpha = f(t) \cdot dt \in \Omega_{L/\mathbb{K}}^1 = L \otimes_A \Omega_{A/\mathbb{K}}^1,$$

where $f(t) \in L$. Any maximal ideal $\mathfrak{m} = (t - \lambda) \subseteq A$ determines a residue functional

$$\mathrm{Res}_{\mathfrak{m}} : \Omega_{L/\mathbb{K}}^1 \rightarrow \mathbb{K}.$$

The formula is this: for $\alpha = f(t) \cdot dt$ we express $f(t)$ as a Laurent series in $\widehat{L}_{\mathfrak{m}}$, say

$$f(t) = \sum_j \mu_j \cdot (t - \lambda)^j,$$

with coefficients $\mu_j \in \mathbb{K}$. Then

$$\text{Res}_{\mathfrak{m}}(\alpha) := \mu_{-1}.$$

More on this can be found in [Har, Theorem III.7.14.1].

The rational differential form $\alpha \in \Omega_{L/\mathbb{K}}^1$ defines a continuous functional

$$\partial_{\mathfrak{m}}(\alpha) : \widehat{A}_{\mathfrak{m}} \rightarrow \mathbb{K}, \quad \partial_{\mathfrak{m}}(\alpha)(a) := \text{Res}_{\mathfrak{m}}(a \cdot \alpha).$$

We get an A -linear homomorphism

$$\partial_{\mathfrak{m}} : \Omega_{L/\mathbb{K}}^1 \rightarrow \text{Hom}_{\mathbb{K}}^{\text{cont}}(\widehat{A}_{\mathfrak{m}}, \mathbb{K}).$$

By Matlis theory the module

$$J(\mathfrak{m}) := \text{Hom}_{\mathbb{K}}^{\text{cont}}(\widehat{A}_{\mathfrak{m}}, \mathbb{K})$$

is the indecomposable injective A -module associated to \mathfrak{m} . And, letting $\mathfrak{p} := (0)$, the module $J(\mathfrak{p}) := \Omega_{L/\mathbb{K}}^1$ is the generic indecomposable injective module.

A careful calculation shows that the sequence of A -modules

$$0 \rightarrow \Omega_{A/\mathbb{K}}^1 \rightarrow \Omega_{L/\mathbb{K}}^1 \xrightarrow{\sum_{\mathfrak{m}} \partial_{\mathfrak{m}}} \bigoplus_{\mathfrak{m}} \text{Hom}_{\mathbb{K}}^{\text{cont}}(\widehat{A}_{\mathfrak{m}}, \mathbb{K}) \rightarrow 0$$

is exact. Therefore the rigid residue complex of A is

$$\mathcal{K}_A = (\mathcal{K}_A^{-1} \xrightarrow{\partial} \mathcal{K}_A^0) = \left(\Omega_{L/\mathbb{K}}^1 \xrightarrow{\sum_{\mathfrak{m}} \partial_{\mathfrak{m}}} \bigoplus_{\mathfrak{m}} \text{Hom}_{\mathbb{K}}^{\text{cont}}(\widehat{A}_{\mathfrak{m}}, \mathbb{K}) \right).$$

A similar (but much more complicated) description is possible for any finite type \mathbb{K} -scheme; this was done in [Ye2].

Remark 14.4.24. Here is a brief explanation of *Matlis duality*. For more details see [RD, Section V.5], [Mats, Theorem 18.6] or [BrSh, Section 10.2]. Assume A is a complete local ring with maximal ideal \mathfrak{m} . As usual, the category of finitely generated A -modules is $\mathbf{M}_f(A)$. There is also the category $\mathbf{M}_a(A)$ of artinian A -modules. These are full abelian subcategories of $\mathbf{M}(A)$. Note that these subcategories are characterized by dual properties: the objects of $\mathbf{M}_f(A)$ are noetherian, i.e. they satisfy the ascending chain condition; and the objects of $\mathbf{M}_a(A)$ satisfy the descending chain condition.

Consider the indecomposable injective module $J(\mathfrak{m})$. The functor $D := \text{Hom}_A(-, J(\mathfrak{m}))$ is exact of course. Matlis duality asserts that

$$D : \mathbf{M}_f(A)^{\text{op}} \rightarrow \mathbf{M}_a(A)$$

is an equivalence, with quasi-inverse D .

Remark 14.4.25. We now provide a brief discussion of *local duality*, based on [RD, Section V.6]. (There is a weaker variant of this result, for modules instead of complexes, that can be found in [BrSh, Theorem 11.2.6].) Again A is local, with maximal ideal \mathfrak{m} . Let R be a dualizing complex over A . By translating R we can assume that $\dim_R(\mathfrak{m}) = 0$. Lemma 14.4.8 tells us that $H_{\mathfrak{m}}^i(R) = 0$ for all $i \neq 0$. A calculation, that relies on Matlis duality, shows that $H_{\mathfrak{m}}^0(R) \cong J(\mathfrak{m})$, the indecomposable injective corresponding to \mathfrak{m} .

Let us fix an isomorphism $\beta : H_{\mathfrak{m}}^0(R) \xrightarrow{\cong} J(\mathfrak{m})$. This induces a morphism

$$(14.4.26) \quad \theta_M : R\Gamma_{\mathfrak{m}}(M) \rightarrow \mathrm{Hom}_A(\mathrm{RHom}_A(M, R), J(\mathfrak{m})),$$

functorial in $M \in \mathbf{D}^+(A)$. The Local Duality Theorem [RD, Theorem V.6.2] says that θ_M is an isomorphism if $M \in \mathbf{D}_f^+(A)$.

Here is a modern take on this theorem: we can construct the morphism θ_M for any $M \in \mathbf{D}(A)$. Let's replace R by the residue complex \mathcal{K} (the minimal injective resolution of R). Then β is just a module isomorphism $\beta : \mathcal{K}^0 \xrightarrow{\cong} J(\mathfrak{m})$. For any complex M we choose a \mathbf{K} -injective resolution $M \rightarrow I(M)$. Then θ_M is represented by the homomorphism

$$\Gamma_{\mathfrak{m}}(I(M)) \rightarrow \mathrm{Hom}_A(\mathrm{Hom}_A(I(M), \mathcal{K}), \mathcal{K}^0)$$

in $\mathbf{C}_{\mathrm{str}}(A)$ that sends an element $u \in \Gamma_{\mathfrak{m}}(I(M))^p$ and a homomorphism

$$\phi \in \mathrm{Hom}_A(I(M), \mathcal{K})^{-p}$$

to $\phi(u) \in \mathcal{K}^0$.

We know that the functors appearing in equation (14.4.26) have finite cohomological dimensions. Since $A \in \mathbf{D}_f^+(A)$, the local duality theorem from [RD] tells us that θ_A is an isomorphism. Now we can apply Theorem 14.1.27 to conclude that θ_M is an isomorphism for any $M \in \mathbf{D}_f(A)$.

Remark 14.4.27. Here is more on the CM property and duality. Let A be a noetherian ring with connected spectrum. Assume A has a dualizing complex R , and corresponding dimension function \dim_R .

Consider a complex $M \in \mathbf{D}_f^b(A)$. In [RD] Grothendieck defines M to be a *CM complex with respect to R* if for any prime ideal $\mathfrak{p} \subseteq A$ and every $i \neq -\dim_R(\mathfrak{p})$ the local cohomology satisfies $H_{\mathfrak{p}}^i(M_{\mathfrak{p}}) = 0$. Notice that this is a property of the sheaf \mathcal{M} (the sheafification of the module M) on the topological space $X := \mathrm{Spec} A$.

It is proved in [RD] that when A is a regular ring, $R = A$, and M is a finitely generated A -module, then M is a CM module (in the conventional sense) iff it is a CM complex.

Let $\mathbf{D}_f^0(A)$ be the full subcategory of $\mathbf{D}_f^b(A)$ on the complexes M such that $H^i(M) = 0$ for all $i \neq 0$. We know that $\mathbf{D}_f^0(A)$ is equivalent to $\mathbf{M}_f(A) = \mathrm{Mod}_f A$. In [YeZh2] it was proved that the following are equivalent for a complex $M \in \mathbf{D}_f^b(A)$:

- (i) The complex M is CM w.r.t. R .
- (ii) The complex $\mathrm{RHom}_A(M, R)$ belongs to $\mathbf{D}_f^0(A)$.

It follows that the CM complexes form an abelian subcategory of $\mathbf{D}_f^b(A)$, dual to $\mathbf{M}_f(A)$. In fact, they are the heart of a perverse t-structure on $\mathbf{D}_f^b(A)$, and hence they deserve to be called *perverse finitely generated A -modules*. Geometrically, on the scheme $X := \mathrm{Spec} A$, the CM complexes inside $\mathbf{D}_c^b(X)$ form a stack of abelian categories, and so they are *perverse coherent sheaves*. All this is explained in [YeZh2, Section 6].

Current Material

cmnt: Current material of course.

cmnt: Start of course IV

15. RIGID COMPLEXES OVER COMMUTATIVE RINGS

As we saw in the previous section, a dualizing complex R over a noetherian commutative ring A is not unique. This was the source of major difficulties in [RD], first for gluing dualizing complexes on schemes, and then for producing the trace morphisms.

In 1997, M. Van den Bergh [VdB] discovered the idea of *rigidity* for dualizing complexes. This was done in the context of noncommutative ring theory: A is a noncommutative noetherian ring, central over a base field \mathbb{K} . The theory of noncommutative rigid dualizing complexes was developed further in several papers of Zhang and Yekutieli, among them [YeZh1] and [YeZh2]. Some of this material will be discussed in Section 19 of the book.

Here we will deal with the commutative side only, which turns out to be extremely powerful. Before explaining it, let us first observe that this is one of the rare cases in which an idea originating from noncommutative algebra had significant impact in commutative algebra.

In this section we define rigid dualizing complexes, and prove their existence and uniqueness, in the following context: \mathbb{K} is a regular noetherian commutative ring (e.g. a field or the ring of integers \mathbb{Z}), and A is a flat essentially finite type commutative \mathbb{K} -ring. We then introduce the functorial properties of rigid dualizing complexes: rigid traces and rigid localization morphisms. After that we pass to rigid residue complexes. For them we also define the ind-rigid trace morphisms. These concepts will allow us (in Section 18) to geometrize all the above – namely to produce rigid residue complexes of essentially finite type \mathbb{K} -schemes, and to manipulate them effectively. The material here is based on several papers of Zhang and Yekutieli, including them [YeZh1], [YeZh2], [YeZh3], [YeZh4], [Ye11] and [Ye13].

The theory of rigid dualizing complexes does not really require the flatness assumption (of A over \mathbb{K}). In the papers [YeZh3] and [YeZh4] the authors had already developed this theory without flatness, using flat DG ring resolutions. This is a much more difficult theory, and in fact there were a few crucial mistakes in these two papers. These mistakes were discovered by Avramov, Iyengar, Lipman and Nayak in the paper [AILN], and one error was corrected there. The remaining mistakes have since been rectified (in [Ye11] and [Ye13]). See Remark 15.1.26 below.

15.1. The Squaring Operation and Rigid Complexes. In this subsection we work in the following setup:

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Setup 15.1.1. A is a nonzero commutative ring, and B is a flat commutative A -ring.

Consider the enveloping ring $B \otimes_A B$. It comes equipped with a few ring homomorphisms:

$$(15.1.2) \quad B \xrightarrow{\eta_i} B \otimes_A B \xrightarrow{\epsilon} B,$$

where $\eta_0(b) := b \otimes 1$, $\eta_1(b) := 1 \otimes b$, and $\epsilon(b_0 \otimes b_1) := b_0 \cdot b_1$. We view B as a module over $B \otimes_A B$ via ϵ . Of course $\epsilon \circ \eta_i = \text{id}_B$.

Remark 15.1.3. It will be helpful to consider a $(B \otimes_A B)$ -module M as an A -central B - B -bimodule, where the left B -action on M is through η_0 , and the right action is through η_1 . This is the noncommutative point of view. To be precise, if B had been a noncommutative central A -ring, then the enveloping ring would have been $B \otimes_A B^{\text{op}}$. More on this in Section 19.

Suppose we are given B -modules M_0 and M_1 . Then the tensor product $M_0 \otimes_A M_1$ is a $(B \otimes_A B)$ -module. In this way we get an additive bifunctor

$$(- \otimes_A -) : \mathbf{M}(B) \times \mathbf{M}(B) \rightarrow \mathbf{M}(B \otimes_A B).$$

Passing to complexes, and then to homotopy categories, we obtain a triangulated bifunctor

$$(15.1.4) \quad (- \otimes_A -) : \mathbf{K}(B) \times \mathbf{K}(B) \rightarrow \mathbf{K}(B \otimes_A B).$$

Lemma 15.1.5. *The bifunctor (15.1.4) has a left derived bifunctor*

$$(- \otimes_A^{\mathbf{L}} -) : \mathbf{D}(B) \times \mathbf{D}(B) \rightarrow \mathbf{D}(B \otimes_A B).$$

If either M_0 or M_1 is a complex of B -modules that is K -flat over A , then the morphism

$$\eta_{M_0, M_1} : M_0 \otimes_A^{\mathbf{L}} M_1 \rightarrow M_0 \otimes_A M_1$$

in $\mathbf{D}(B \otimes_A B)$ is an isomorphism.

Proof. This is a variant of Theorem 13.8.1. We know by Corollary 11.3.27 and Proposition 10.3.2 that any complex $M \in \mathbf{C}(B)$ admits a K -flat resolution $P \rightarrow M$. Because B is flat over A , the complex P is also K -flat over A . By Theorem 13.7.7 the left derived functor $- \otimes_A^{\mathbf{L}} -$ exists, and the condition on η_{M_0, M_1} holds. \square

Remark 15.1.6. The innocuous looking Lemma 15.1.5 is actually of tremendous importance. Without the flatness of $A \rightarrow B$ we could do very little homological algebra of bimodules. Getting around the lack of flatness requires the use of flat DG ring resolutions, as explained in Remark 15.1.26.

Any module $L \in \mathbf{M}(B)$ has an action by $B \otimes_A B$ coming from the homomorphism ϵ in (15.1.2). Consider now a module $N \in \mathbf{M}(B \otimes_A B)$. The abelian group N has two possible B -module structures, coming from the homomorphisms η_i . Thus the abelian group $\text{Hom}_{B \otimes_A B}(L, N)$ has three possible B -module structures: there is one action from the B -module structure on L , and there are two from the B -module structures on N . The next easy lemma is crucial.

Lemma 15.1.7. *The three B -module structures on $\text{Hom}_{B \otimes_A B}(L, N)$ coincide.*

Exercise 15.1.8. Prove the lemma.

We are mostly interested in the B -module $L = B$. As the module N changes, we get an additive functor

$$\mathrm{Hom}_{B \otimes_A B}(B, -) : \mathbf{M}(B \otimes_A B) \rightarrow \mathbf{M}(B).$$

Passing to complexes, and then to homotopy categories, we get a triangulated functor

$$\mathrm{Hom}_{B \otimes_A B}(B, -) : \mathbf{K}(B \otimes_A B) \rightarrow \mathbf{K}(B).$$

This has a right derived functor

$$(15.1.9) \quad \mathrm{RHom}_{B \otimes_A B}(B, -) : \mathbf{D}(B \otimes_A B) \rightarrow \mathbf{D}(B),$$

that is calculated by K-injective resolutions. Namely if $N \in \mathbf{C}(B \otimes_A B)$ is a K-injective complex, then the morphism

$$\eta_N : \mathrm{Hom}_{B \otimes_A B}(B, N) \rightarrow \mathrm{RHom}_{B \otimes_A B}(B, N)$$

in $\mathbf{D}(B)$ is an isomorphism.

By composing the bifunctor $(- \otimes_A^L -)$ from Lemma 15.1.5 and the functor $\mathrm{RHom}_{B \otimes_A B}(B, -)$ from (15.1.9) we obtain a triangulated bifunctor

$$(15.1.10) \quad \mathrm{RHom}_{B \otimes_A B}(B, - \otimes_A^L -) : \mathbf{D}(B) \times \mathbf{D}(B) \rightarrow \mathbf{D}(B).$$

Definition 15.1.11. Under Setup 15.1.1, the *squaring operation* is the functor

$$\mathrm{Sq}_{B/A} : \mathbf{D}(B) \rightarrow \mathbf{D}(B)$$

defined as follows:

- (1) For a complex $M \in \mathbf{D}(B)$, its square is the complex

$$\mathrm{Sq}_{B/A}(M) := \mathrm{RHom}_{B \otimes_A B}(B, M \otimes_A^L M) \in \mathbf{D}(B).$$

- (2) For a morphism $\phi : M \rightarrow N$ in $\mathbf{D}(B)$, its square is the morphism

$$\mathrm{Sq}_{B/A}(\phi) := \mathrm{RHom}_{B \otimes_A B}(B, \phi \otimes_A^L \phi) : \mathrm{Sq}_{B/A}(M) \rightarrow \mathrm{Sq}_{B/A}(N)$$

in $\mathbf{D}(B)$.

It will be good to have an explicit formulation of the squaring operation. Let us first choose a K-projective resolution $\sigma : P \rightarrow M$ in $\mathbf{C}(B)$. Note that P is unique up to homotopy equivalence. Since B is flat over A , the complex P is K-flat over A . We get an isomorphism

$$(15.1.12) \quad \mathrm{pres}_P : P \otimes_A P \xrightarrow{\cong} M \otimes_A^L M$$

in $\mathbf{D}(B \otimes_A B)$ that we call a *presentation*. It is uniquely characterized by the commutativity of the diagram

$$\begin{array}{ccc} M \otimes_A^L M & \xrightarrow{\eta_{M,M}} & M \otimes_A M \\ \uparrow \mathrm{Q}(\sigma) \otimes_A^L \mathrm{Q}(\sigma) \cong & \swarrow \mathrm{pres}_P \cong & \uparrow \mathrm{Q}(\sigma \otimes_A \sigma) \\ P \otimes_A^L P & \xrightarrow[\cong]{\eta_{P,P}} & P \otimes_A P \end{array}$$

in $\mathbf{D}(B \otimes_A B)$.

Next we choose a K-injective resolution $\rho : P \otimes_A P \rightarrow I$ in $\mathbf{C}(B \otimes_A B)$. It is unique up to homotopy equivalence. The resolution ρ gives rise to an isomorphism

$$(15.1.13) \quad \mathrm{pres}_I : \mathrm{Hom}_{B \otimes_A B}(B, I) \xrightarrow{\cong} \mathrm{RHom}_{B \otimes_A B}(B, P \otimes_A P)$$

in $\mathbf{D}(B)$ such that the diagram

$$\begin{array}{ccc}
 \mathrm{Hom}_{B \otimes_A B}(B, P \otimes_A P) & \xrightarrow{\eta_{M, P \otimes_A P}} & \mathrm{RHom}_{B \otimes_A B}(B, P \otimes_A P) \\
 \downarrow \mathrm{Q}(\mathrm{Hom}_{B \otimes_A B}(B, \rho)) & \nearrow \mathrm{pres}_I \cong & \downarrow \cong \\
 \mathrm{Hom}_{B \otimes_A B}(B, I) & \xrightarrow[\cong]{\eta_{M, I}} & \mathrm{RHom}_{B \otimes_A B}(B, I) \\
 & & \downarrow \cong \\
 & & \mathrm{RHom}_{B \otimes_A B}(B, \mathrm{Q}(\rho))
 \end{array}$$

is commutative.

The combination of the presentations pres_P and pres_I gives an isomorphism

$$(15.1.14) \quad \mathrm{pres}_{P, I} : \mathrm{Hom}_{B \otimes_A B}(B, I) \xrightarrow{\cong} \mathrm{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$, that we also call a presentation.

Let $\phi : M \rightarrow N$ be a morphism in $\mathbf{D}(B)$. The morphism $\mathrm{Sq}_{B/A}(\phi)$ can also be made explicit using presentations. For that we need to choose a K-projective resolution $\sigma_N : Q \rightarrow N$ in $\mathbf{C}(B)$, and a K-injective resolution $\rho_N : Q \otimes_A Q \rightarrow J$ in $\mathbf{C}(B \otimes_A B)$. These provide us with a presentation

$$\mathrm{pres}_{Q, J} : \mathrm{Hom}_{B \otimes_A B}(M, J) \xrightarrow{\cong} \mathrm{Sq}_{B/A}(N).$$

There are homomorphisms $\tilde{\phi} : P \rightarrow Q$ in $\mathbf{C}_{\mathrm{str}}(B)$, and $\chi : I \rightarrow J$ in $\mathbf{C}_{\mathrm{str}}(B \otimes_A B)$, both unique up to homotopy, such that the diagrams

$$\begin{array}{ccc}
 P & \xrightarrow[\cong]{\mathrm{Q}(\sigma)} & M \\
 \downarrow \mathrm{Q}(\tilde{\phi}) & & \downarrow \phi \\
 Q & \xrightarrow[\cong]{\mathrm{Q}(\sigma_N)} & N
 \end{array}
 \quad
 \begin{array}{ccccc}
 M \otimes_A^L M & \xleftarrow[\cong]{\mathrm{pres}_P} & P \otimes_A P & \xrightarrow[\cong]{\mathrm{Q}(\rho)} & I \\
 \downarrow \phi \otimes_A^L \phi & & \downarrow \mathrm{Q}(\tilde{\phi} \otimes_A \tilde{\phi}) & & \downarrow \mathrm{Q}(\chi) \\
 N \otimes_A^L N & \xleftarrow[\cong]{\mathrm{pres}_Q} & Q \otimes_A Q & \xrightarrow[\cong]{\mathrm{Q}(\rho_N)} & J
 \end{array}$$

in $\mathbf{D}(C)$ and $\mathbf{D}(B \otimes_A B)$ respectively are commutative. See Subsections 10.1 and 10.2. Then the diagram

$$(15.1.15) \quad
 \begin{array}{ccc}
 \mathrm{Hom}_{B \otimes_A B}(B, I) & \xrightarrow[\cong]{\mathrm{pres}_{P, I}} & \mathrm{Sq}_{B/A}(M) \\
 \downarrow \mathrm{Q}(\mathrm{Hom}_{B \otimes_A B}(\mathrm{id}_B, \chi)) & & \downarrow \mathrm{Sq}_{B/A}(\phi) \\
 \mathrm{Hom}_{B \otimes_A B}(B, J) & \xrightarrow[\cong]{\mathrm{pres}_{Q, J}} & \mathrm{Sq}_{B/A}(N)
 \end{array}$$

in $\mathbf{D}(B)$ is commutative.

The squaring operation is not an additive functor. In fact, it is a *quadratic functor*:

Theorem 15.1.16. *Let $\phi : M \rightarrow N$ be a morphism in $\mathbf{D}(B)$ and let $b \in B$. Then*

$$\mathrm{Sq}_{B/A}(b \cdot \phi) = b^2 \cdot \mathrm{Sq}_{B/A}(\phi),$$

as morphisms $\mathrm{Sq}_{B/A}(M) \rightarrow \mathrm{Sq}_{B/A}(N)$ in $\mathbf{D}(B)$.

Proof. We shall use presentations. Let $\tilde{\phi} : P \rightarrow Q$ be a homomorphism in $\mathbf{C}_{\text{str}}(B)$ that represents ϕ , as above. Then the homomorphism

$$b \cdot \tilde{\phi} : P \rightarrow Q$$

$\mathbf{C}_{\text{str}}(B)$ represents $b \cdot \phi$. Tensoring we get a homomorphism

$$(b \cdot \tilde{\phi}) \otimes_A (b \cdot \tilde{\phi}) : P \otimes_A P \rightarrow Q \otimes_A Q$$

$\mathbf{C}_{\text{str}}(B \otimes_A B)$. But

$$(b \cdot \tilde{\phi}) \otimes_A (b \cdot \tilde{\phi}) = (b \otimes b) \cdot (\tilde{\phi} \otimes_A \tilde{\phi}).$$

Hence on the K-injectives we get the homomorphism

$$(b \otimes b) \cdot \chi : I \rightarrow J$$

$\mathbf{C}_{\text{str}}(B \otimes_A B)$. We conclude that

$$\text{Hom}_{B \otimes_A B}(\text{id}_B, (b \otimes b) \cdot \chi) : \text{Hom}_{B \otimes_A B}(B, I) \rightarrow \text{Hom}_{B \otimes_A B}(B, J)$$

represents $\text{Sq}_{B/A}(b \cdot \phi)$. Finally, by Lemma 15.1.7 we know that

$$\text{Hom}_{B \otimes_A B}(\text{id}_B, (b \otimes b) \cdot \chi) = \text{Hom}_{B \otimes_A B}(b^2 \cdot \text{id}_B, \chi) = b^2 \cdot \text{Hom}_{B \otimes_A B}(\text{id}_B, \chi).$$

□

Definition 15.1.17. Let $M \in \mathbf{D}(B)$. A *rigidifying isomorphism* for M over B relative to A is an isomorphism

$$\rho : M \xrightarrow{\cong} \text{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$.

Definition 15.1.18. A *rigid complex* over B relative to A is a pair (M, ρ) , consisting of a complex $M \in \mathbf{D}(B)$ and a rigidifying isomorphism

$$\rho : M \xrightarrow{\cong} \text{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$.

Definition 15.1.19. Suppose (M, ρ) and (N, σ) are rigid complexes over B relative to A . A *morphism of rigid complexes*

$$\phi : (M, \rho) \rightarrow (N, \sigma)$$

is a morphism $\phi : M \rightarrow N$ in $\mathbf{D}(B)$, such that the diagram

$$\begin{array}{ccc} M & \xrightarrow{\rho} & \text{Sq}_{B/A}(M) \\ \phi \downarrow & & \downarrow \text{Sq}_{B/A}(\phi) \\ N & \xrightarrow{\sigma} & \text{Sq}_{B/A}(N) \end{array}$$

in $\mathbf{D}(B)$ is commutative.

The category of rigid complexes over B relative to A is denoted by $\mathbf{D}(B)_{\text{rig}/A}$.

Recall that a complex $M \in \mathbf{D}(B)$ has the derived Morita property if the derived homothety morphism

$$\alpha_M^{\text{R}} : B \rightarrow \text{RHom}_B(M, M)$$

in $\mathbf{D}(B)$ is an isomorphism.

Theorem 15.1.20. *Let (M, ρ) be a rigid complex over B relative to A . If M has the derived Morita property, then the only automorphism of (M, ρ) in $\mathbf{D}(B)_{\text{rig}/A}$ is the identity.*

Proof. Let

$$\phi : (M, \rho) \xrightarrow{\cong} (M, \rho)$$

be an automorphism in $\mathbf{D}(B)_{\text{rig}/A}$. By Proposition 14.2.6, there is a unique invertible element $b \in B$ such that $\phi = b \cdot \text{id}_M$, as morphisms $M \rightarrow M$ in $\mathbf{D}(B)$.

Next, according to Theorem 15.1.16, we have

$$\text{Sq}_{B/A}(\phi) = \text{Sq}_{B/A}(b \cdot \text{id}_M) = b^2 \cdot \text{Sq}_{B/A}(\text{id}_M).$$

Plugging this into the diagram in Definition 15.1.19 we get a commutative diagram

$$\begin{array}{ccc} M & \xrightarrow[\cong]{\rho} & \text{Sq}_{B/A}(M) \\ b \cdot \text{id}_M \downarrow & & \downarrow b^2 \cdot \text{id}_M \\ M & \xrightarrow[\cong]{\rho} & \text{Sq}_{B/A}(M) \end{array}$$

in $\mathbf{D}(B)$. Once more using Proposition 14.2.6 we see that $b^2 = b$. Because b is an invertible element, it follows that $b = 1$. Thus $\phi = \text{id}_M$. \square

Example 15.1.21. Assume $B = A$, and take $M := B$. Then $B \otimes_A B \cong B$, $M \otimes_A^L M \cong M$, and there are canonical isomorphisms

$$\text{Sq}_{B/A}(M) = \text{RHom}_{B \otimes_A B}(B, M \otimes_A^L M) \cong \text{Hom}_B(B, M) \cong M.$$

Thus the pair (M, id) belongs to $\mathbf{D}(B)_{\text{rig}/A}$. Furthermore, the complex M has the derived Morita property, so Theorem 15.1.20 applies.

To the reader who might object to this as being a ridiculously stupid example, we say that in all important situations, there is exactly one object in $\mathbf{D}(B)_{\text{rig}/A}$ (up to unique isomorphism, according to Theorem 15.1.20). And it is induced, in a suitable sense, from the one in the example above. See Subsection 15.4.

The next two exercises provide rigid complexes that are far from trivial. These exercises will reappear later, as steps to produce rigid complexes over A relative to \mathbb{K} , where \mathbb{K} is a regular ring and A is an essentially finite type \mathbb{K} -ring.

Exercise 15.1.22. Take $B := A[t_1, \dots, t_n]$, the polynomial ring in n variables.

(1) Prove that

$$\text{Ext}_{B \otimes_A B}^i(B, B \otimes_A B) \cong \begin{cases} B & \text{if } i = n \\ 0 & \text{if } i \neq n. \end{cases}$$

(Hint: Let I be the kernel of the multiplication homomorphism $B \otimes_A B \rightarrow B$. Show that I is generated by the sequence (c_1, \dots, c_n) , where $c_j := t_j \otimes 1 - 1 \otimes t_j$. Then show this is a regular sequence. Now use the Koszul complex associated to this sequence as a free resolution of B over $B \otimes_A B$.

(2) Conclude from (1) that the complex $B[n] \in \mathbf{D}(B)$ is rigid relative to A ; namely that there is a rigidifying isomorphism

$$\rho : B[n] \xrightarrow{\cong} \text{Sq}_{B/A}(B[n]).$$

Example 15.1.23. Let A be a noetherian ring, and let $B := A[t_1, \dots, t_n]$ as in the exercise above. Let $\Delta_{B/A} := \Omega_{B/A}^n$ be the module of degree n differential forms. It is the n -th exterior power of $\Omega_{B/A}^1$, so it is a free B module of rank 1, with basis $d(t_1) \wedge \dots \wedge d(t_n)$.

We will show later (in ???)

cmnt: fill

that the complex $\Delta_{B/A}[n]$ has a canonical rigidifying isomorphism relative to A . I.e. there is a rigidifying isomorphism

$$\rho : \Delta_{B/A}[n] \xrightarrow{\cong} \mathrm{Sq}_{B/A}(\Delta_{B/A}[n])$$

in $\mathbf{D}(B)$ that is invariant under A -ring automorphisms of B .

Example 15.1.24. Let A be a noetherian ring, and let $A \rightarrow B$ be a finite flat ring homomorphism. So B is a finitely generated projective A -module. Define

$$\Delta_{B/A} := \mathrm{Hom}_A(B, A) \in \mathbf{M}(B).$$

We will see later (in ???)

cmnt: fill

that the complex $\Delta_{B/A}$ has a canonical rigidifying isomorphism relative to A . I.e. there is a rigidifying isomorphism

$$\rho : \Delta_{B/A} \xrightarrow{\cong} \mathrm{Sq}_{B/A}(\Delta_{B/A})$$

in $\mathbf{D}(B)$ that is invariant under A -ring automorphisms of B .

Remark 15.1.25. The squaring operation is related to *Hochschild cohomology*. Assume for simplicity that A is a field and M is a B -module. Then for each i the cohomology

$$H^i(\mathrm{Sq}_{B/A}(M)) = \mathrm{Ext}_{B \otimes_A B}^i(B, M \otimes_A M)$$

is the i -th Hochschild cohomology with values in the B -bimodule $M \otimes_A M$. For more on this material see [AILN], [Sha1] and [Sha2].

Remark 15.1.26. It is possible to avoid the assumption that B is flat over A . This is done by choosing a DG ring \tilde{B} that is K -flat as a DG A -module, and a DG ring quasi-isomorphism $\tilde{B} \rightarrow B$ over A . Such resolutions always exist. Then we take

$$(15.1.27) \quad \mathrm{Sq}_{B/A}(M) := \mathrm{RHom}_{\tilde{B} \otimes_A \tilde{B}}(B, M \otimes_A^L M).$$

This was the construction used by Zhang and Yekutieli in the paper [YeZh3].

Unfortunately there was a serious error in [YeZh3]: we did not prove that formula (15.1.27) does not depend on the resolution \tilde{B} . This error was discovered, and corrected, by Avramov, Iyengar, Lipman and Nayak in their paper [AILN].

There were ensuing errors in [YeZh3] regarding the functoriality of the squaring operation in the ring B (this will be studied in Subsection 15.3 below). The paper [AILN] did not treat such functoriality at all, and the construction and proofs were corrected only in our recent paper [Ye11]. It is worthwhile to mention that the correct proofs (both in [AILN] and [Ye11]) rely on *noncommutative DG rings* and DG bimodules over them.

Because the non-flat case is so much more complicated, we have decided not to reproduce it in the book. The interested reader can look up the research papers

[Ye11], [Ye13], [Ye14] and [Ye15], the survey article [Ye6], and the lecture notes [Ye12].

A general treatment of derived categories of bimodules, based on K-flat DG ring resolutions, is in the paper [Ye16].

15.2. Adjunctions. Before we can tackle the functorial behavior of the squaring operation, we need some more basic facts relating the derived categories $\mathbf{D}(A)$ and $\mathbf{D}(B)$ in the presence of a ring homomorphism $A \rightarrow B$. In this subsection all rings are commutative.

cmnt: maybe this should be moved to an earlier location in the book?

Suppose $u : A \rightarrow B$ is a ring homomorphism. The restriction (or forgetful) functor

$$\text{Rest}_u : \mathbf{M}(B) \rightarrow \mathbf{M}(A)$$

sends a B -module N to the same abelian group, made into an A -module via u . This functor extends to a DG functor on complexes:

$$(15.2.1) \quad \text{Rest}_u : \mathbf{C}(B) \rightarrow \mathbf{C}(A).$$

Because it is an exact functor, it extends to derived categories:

$$\text{Rest}_u : \mathbf{D}(B) \rightarrow \mathbf{D}(A).$$

We shall usually suppress this functor when the meaning is clear, in order to reduce clutter.

For any A -module M there are functorial isomorphisms

$$A \otimes_A M \xrightarrow{\cong} M$$

and

$$\text{Hom}_A(A, M) \xrightarrow{\cong} M$$

in $\mathbf{M}(A)$. These isomorphisms extend to the derived category: for any complex of A -modules M there are functorial isomorphisms

$$(15.2.2) \quad A \otimes_A^{\mathbf{L}} M \xrightarrow{\cong} M$$

and

$$(15.2.3) \quad \text{RHom}_A(A, M) \xrightarrow{\cong} M$$

in $\mathbf{D}(A)$. Again, to reduce clutter, we will use these canonical isomorphisms implicitly.

Definition 15.2.4. A ring homomorphism $u : A \rightarrow B$ is called a *localization homomorphism* if there is an isomorphism of A -rings $B \cong A[S^{-1}] = A_S$ some multiplicatively closed set $S \subseteq A$.

Note that a localization ring homomorphism is flat.

Definition 15.2.5. Let $u : A \rightarrow B$ be a ring homomorphism, and let $M \in \mathbf{D}(A)$ and $N \in \mathbf{D}(B)$ be complexes.

- (1) A morphism

$$\theta : N \rightarrow M$$

in $\mathbf{D}(A)$ is called a *backward* (or *trace*) *morphism over u* .

(2) A morphism

$$\lambda : M \rightarrow N$$

in $\mathbf{D}(A)$ is called a *forward morphism over u* . In case the ring homomorphism u is a localization homomorphism, we also call λ a *localization morphism over u* .

The concepts of forward and backward morphisms make sense also in the categories $\mathbf{M}(-)$, $\mathbf{C}(-)$, $\mathbf{C}_{\text{str}}(-)$ and $\mathbf{K}(-)$.

There is an additive functor

$$(15.2.6) \quad \mathbf{CInd}_u : \mathbf{M}(A) \rightarrow \mathbf{M}(B), \quad \mathbf{CInd}_u(M) := \text{Hom}_A(B, M)$$

called *coinduction*. It has a right derived functor

$$(15.2.7) \quad \mathbf{RCInd}_u : \mathbf{D}(A) \rightarrow \mathbf{D}(B), \quad \mathbf{RCInd}_u(M) := \mathbf{RHom}_A(B, M).$$

cmnt: below change $\text{Hom}_A(B, M)$ to $\mathbf{CInd}_u(M)$?

The standard adjunction formula give rise to a bifunctorial bijection (an isomorphism of A -modules in fact)

$$(15.2.8) \quad \text{badj}_{u,M,N} : \text{Hom}_{\mathbf{M}(A)}(N, M) \xrightarrow{\cong} \text{Hom}_{\mathbf{M}(B)}(N, \text{Hom}_A(B, M))$$

for $M \in \mathbf{M}(A)$ and $N \in \mathbf{M}(B)$. We refer to this isomorphism as *backward adjunction*, since it takes a backward morphism $\theta : N \rightarrow M$ in $\mathbf{M}(A)$ to the morphism

$$\text{badj}_{u,M,N}(\theta) : N \rightarrow \text{Hom}_A(B, M)$$

in $\mathbf{M}(B)$.

We have already encountered the induction functor

$$(15.2.9) \quad \text{Ind}_u : \mathbf{M}(A) \rightarrow \mathbf{M}(B), \quad \text{Ind}_u(M) := B \otimes_A M,$$

and its left derived functor

$$(15.2.10) \quad \mathbf{LInd}_u : \mathbf{D}(A) \rightarrow \mathbf{D}(B), \quad \mathbf{LInd}_u(M) = B \otimes_A^L M.$$

cmnt: below change $B \otimes_A M$ to $\text{Ind}_u(M)$?

Likewise, there is a bifunctorial bijection

$$(15.2.11) \quad \text{fadj}_{u,M,N} : \text{Hom}_{\mathbf{M}(A)}(M, N) \xrightarrow{\cong} \text{Hom}_{\mathbf{M}(B)}(B \otimes_A M, N)$$

for $M \in \mathbf{M}(A)$ and $N \in \mathbf{M}(B)$. We refer to this isomorphism as *forward adjunction*, since it takes a forward morphism $\lambda : M \rightarrow N$ in $\mathbf{M}(A)$ to the morphism

$$(15.2.12) \quad \text{fadj}_{u,M,N}(\lambda) : B \otimes_A M \rightarrow N$$

in $\mathbf{M}(B)$.

The backward and forward adjunctions extend to derived categories:

Proposition 15.2.13. *Let $u : A \rightarrow B$ be a ring homomorphism.*

(1) *There is a unique isomorphism*

$$\text{dbadj}_{u,M,N} : \text{Hom}_{\mathbf{D}(A)}(N, M) \xrightarrow{\cong} \text{Hom}_{\mathbf{D}(B)}(N, \mathbf{RHom}_A(B, M))$$

called derived backward adjunction, which is functorial in $M \in \mathbf{D}(A)$ and $N \in \mathbf{D}(B)$, and such that the diagram

$$\begin{array}{ccc} \mathrm{Hom}_{\mathbf{C}_{\mathrm{str}}(A)}(N, M) & \xrightarrow{\mathrm{dbadj}} & \mathrm{Hom}_{\mathbf{C}_{\mathrm{str}}(B)}(N, \mathrm{Hom}_B(C, M)) \\ \downarrow \mathrm{Q} & & \downarrow \Theta_b \circ \mathrm{Q} \\ \mathrm{Hom}_{\mathbf{D}(A)}(N, M) & \xrightarrow{\mathrm{badj}} & \mathrm{Hom}_{\mathbf{D}(B)}(N, \mathrm{RHom}_B(C, M)) \end{array}$$

is commutative.

- (2) There is a unique isomorphism

$$\mathrm{dfadj}_{u, M, N} : \mathrm{Hom}_{\mathbf{D}(A)}(M, N) \xrightarrow{\cong} \mathrm{Hom}_{\mathbf{D}(B)}(B \otimes_A^L M, N)$$

called derived forward adjunction, which is functorial in $M \in \mathbf{D}(A)$ and $N \in \mathbf{D}(B)$, and such that the diagram

$$\begin{array}{ccc} \mathrm{Hom}_{\mathbf{C}_{\mathrm{str}}(A)}(M, N) & \xrightarrow{\mathrm{dfadj}} & \mathrm{Hom}_{\mathbf{C}_{\mathrm{str}}(B)}(B \otimes_A M, N) \\ \downarrow \mathrm{Q} & & \downarrow \Theta_f \circ \mathrm{Q} \\ \mathrm{Hom}_{\mathbf{D}(A)}(M, N) & \xrightarrow{\mathrm{fadj}} & \mathrm{Hom}_{\mathbf{D}(B)}(B \otimes_A^L M, N) \end{array}$$

is commutative.

Exercise 15.2.14. Prove Proposition 15.2.13. Give precise formulas for the morphisms Θ_b and Θ_f . (Hint: in item (1) (resp. (2)), look what happens when M is K -injective (resp. K -projective).)

Definition 15.2.15. Let $u : A \rightarrow B$ be a ring homomorphism, and let $M \in \mathbf{D}(B)$ and $N \in \mathbf{D}(C)$ be complexes.

- (1) A backward morphism $\theta : N \rightarrow M$ in $\mathbf{D}(A)$ over u is called a *nondegenerate backward morphism* if the corresponding morphism

$$\mathrm{dbadj}_{u, M, N}(\theta) : N \rightarrow \mathrm{RHom}_A(B, M)$$

in $\mathbf{D}(B)$ is an isomorphism.

- (2) A forward morphism $\lambda : M \rightarrow N$ in $\mathbf{D}(A)$ over u is called *nondegenerate forward morphism* if the corresponding morphism

$$\mathrm{dfadj}_{u, M, N}(\lambda) : B \otimes_A^L M \rightarrow N$$

in $\mathbf{D}(C)$ is an isomorphism.

Example 15.2.16. Given $u : A \rightarrow B$ and $M \in \mathbf{D}(B)$, let $N := \mathrm{RHom}_A(B, M) \in \mathbf{D}(B)$. The identity morphism $\mathrm{id}_N : N \rightarrow N$ in $\mathbf{D}(B)$ corresponds by adjunction to a trace morphism

$$\mathrm{Tr}_{u, M} : N \rightarrow M$$

in $\mathbf{D}(B)$. Since

$$\mathrm{dbadj}_{u, M, N}(\mathrm{Tr}_{u, M}) = \mathrm{id}_N,$$

we see that $\mathrm{Tr}_{u, M}$ is a nondegenerate trace morphism.

Example 15.2.17. Given $u : A \rightarrow B$ and $M \in \mathbf{D}(A)$, let $N := B \otimes_A^L M \in \mathbf{D}(B)$. The identity morphism $\mathrm{id}_N : N \rightarrow N$ in $\mathbf{D}(B)$ corresponds by adjunction to a forward morphism

$$(15.2.18) \quad q_{u,M} : M \rightarrow N$$

in $\mathbf{D}(A)$. Since

$$\mathrm{dfadj}_{u,M,N}(q_{u,M}) = \mathrm{id}_N,$$

we see that $q_{u,M}$ is a nondegenerate forward morphism.

Example 15.2.19. If $A = B$ and $u = \mathrm{id}_A$, then backward and forward morphisms over u are just morphisms in $\mathbf{D}(A)$. Nondegenerate (backward or forward) morphisms are just isomorphisms in $\mathbf{D}(A)$.

We end this subsection with a useful proposition, borrowed from [YeZh3]. It will be needed later on.

cmnt: is this the optimal place for this proposition?

Proposition 15.2.20. *Let $A \rightarrow B \rightarrow C$ be ring homomorphisms, and let $L \in \mathbf{D}(C)$, $M \in \mathbf{D}(B)$ and $N \in \mathbf{D}(A)$ be complexes. There is a morphism*

$$\Psi_{L,M,N} : \mathrm{RHom}_B(L, M) \otimes_A^L N \rightarrow \mathrm{RHom}_B(L, M \otimes_A^L N)$$

in $\mathbf{D}(C)$, called tensor-evaluation, which is functorial in these complexes.

Moreover, if conditions (a) and (b) below hold, then $\Psi_{L,M,N}$ is an isomorphism.

- (a) The ring B is noetherian.
- (b) The restriction of L to B is in $\mathbf{D}_f^-(B)$, the complex M is in $\mathbf{D}^+(B)$, and the complex N has finite flat dimension over A .

Proof. Let $\rho : M \rightarrow I$ be a K -injective resolution in $\mathbf{C}(B)$, let $\sigma : P \rightarrow N$ be a K -flat resolution in $\mathbf{C}(A)$, and let $\tau : I \otimes_A P \rightarrow J$ be a K -injective resolution in $\mathbf{C}(B)$. There is an obvious homomorphism

$$(15.2.21) \quad \tilde{\Psi}_{L,I,P} : \mathrm{Hom}_B(L, I) \otimes_A P \rightarrow \mathrm{Hom}_B(L, I \otimes_A P)$$

in $\mathbf{C}_{\mathrm{str}}(C)$. Its formula is

$$\tilde{\Psi}(\psi \otimes p)(l) := \pm \tau(\psi(l) \otimes p)$$

for homogeneous elements $\psi \in \mathrm{Hom}_B(L, I)$, $p \in P$ and $l \in L$, and with the Koszul sign rule. There also the homomorphism

$$(15.2.22) \quad \mathrm{Hom}_B(L, \tau) : \mathrm{Hom}_B(L, I \otimes_A P) \rightarrow \mathrm{Hom}_B(L, J).$$

The composition

$$(15.2.23) \quad \mathrm{Hom}_B(L, \tau) \circ \tilde{\Psi}_{L,I,P} : \mathrm{Hom}_B(L, I) \otimes_A P \rightarrow \mathrm{Hom}_B(L, J)$$

represents a morphism $\Psi_{L,M,N}$ in $\mathbf{D}(C)$, and this is functorial in the complexes L, M, N .

Now suppose conditions (a) and (b) hold. It suffices to prove that for a good choice of resolutions, the homomorphism in (15.2.23) is a quasi-isomorphism. For this we might as well forget C , and work in $\mathbf{C}_{\mathrm{str}}(B)$.

By smart truncation we can assume that M is a bounded below complex of B -modules. Because B is noetherian and $L \in \mathbf{D}_f^-(B)$, according to Corollary 11.3.32 there is a quasi-isomorphism $\pi : Q \rightarrow L$, where Q is a bounded above complex of

finitely generated free B -modules. Since N has finite flat dimension, we can assume that P is a bounded complex of flat A -modules.

Consider the next commutative diagram in $\mathbf{C}_{\text{str}}(B)$.

$$\begin{array}{ccccc}
 \text{Hom}_B(L, I) \otimes_A P & \xrightarrow{\tilde{\Psi}_{L,I,P}} & \text{Hom}_B(L, I \otimes_A P) & \xrightarrow{\text{Hom}_B(\text{id}, \tau)} & \text{Hom}_B(L, J) \\
 \downarrow \text{qi} & \text{Hom}_B(\pi, \text{id}) \otimes_A \text{id} & \downarrow \text{Hom}_B(\pi, \text{id}) & & \downarrow \text{Hom}_B(\pi, \text{id}) \\
 \text{Hom}_B(Q, I) \otimes_A P & \xrightarrow{\tilde{\Psi}_{Q,I,P}} & \text{Hom}_B(Q, I \otimes_A P) & \xrightarrow[\text{qi}]{\text{Hom}_B(\text{id}, \tau)} & \text{Hom}_B(Q, J) \\
 \uparrow \text{qi} & \text{Hom}_B(\text{id}, \rho) \otimes_A \text{id} & \uparrow \text{qi} & \text{Hom}_B(\text{id}, \rho \otimes_A \text{id}) & \\
 \text{Hom}_B(Q, M) \otimes_A P & \xrightarrow{\tilde{\Psi}_{Q,M,P}} & \text{Hom}_B(Q, M \otimes_A P) & &
 \end{array}$$

The homomorphisms marked “qi” are quasi-isomorphisms. The various boundedness conditions on the complexes Q, M, P imply that in each degree i we have a finite sums (as opposed to infinite products)

$$(\text{Hom}_B(Q, M) \otimes_A P)^i = \bigoplus_{j,k} \text{Hom}_B(Q^j, M^k) \otimes_A P^{i-k+j}$$

and

$$(\text{Hom}_B(Q, M \otimes_A P))^i = \bigoplus_{j,k} \text{Hom}_B(Q^j, M^k \otimes_A P^{i-k+j}).$$

Because each Q^j is a finitely generated free module, there is an isomorphism

$$\text{Hom}_B(Q^j, M^k) \otimes_A P^{i-k+j} \xrightarrow{\simeq} \text{Hom}_B(Q^j, M^k \otimes_A P^{i-k+j}).$$

Therefore $\tilde{\Psi}_{Q,M,P}$ is an isomorphism in $\mathbf{C}_{\text{str}}(B)$. \square

Exercise 15.2.24. Show that the tensor-evaluation morphism $\Psi_{L,M,N}$ in Proposition 15.2.20 exists when A, B, C are arbitrary DG rings and $A \rightarrow B \rightarrow C$ are DG ring homomorphisms. Try to find sufficient conditions on the DG rings and the DG modules for $\Psi_{L,M,N}$ to be an isomorphism. (See [YeZh3, Proposition 1.12], [Ye10, Theorem 5.20] and [Sha3, Proposition 1.5] for a few variations.)

15.3. Functoriality of the Squaring Operation. We now return to the flatness setup. In this subsection we assume:

Setup 15.3.1. A is a commutative ring, and the rings B, C, D, B', C', B'' are flat commutative A -rings.

To simplify notation we are going to borrow the “enveloping” notation from noncommutative ring theory. This is the content of the next definition.

Definition 15.3.2. Suppose $u : B \rightarrow C$ is an A -ring homomorphism.

- (1) We write $B^{\text{en}} := B \otimes_A B$, $C^{\text{en}} := C \otimes_A C$ and $u^{\text{en}} := u \otimes_A u$. Thus $u^{\text{en}} : B^{\text{en}} \rightarrow C^{\text{en}}$ is a homomorphism between flat A -rings.
- (2) Suppose $\theta : N \rightarrow M$ is a trace homomorphism in $\mathbf{C}_{\text{str}}(B)$ over u (see Definition 15.2.5(1)). We write $M^{\text{en}} := M \otimes_A M$, $N^{\text{en}} := N \otimes_A N$ and $\theta^{\text{en}} := \theta \otimes_A \theta$. Thus $\theta^{\text{en}} : N^{\text{en}} \rightarrow M^{\text{en}}$ is a trace homomorphism in $\mathbf{C}_{\text{str}}(B^{\text{en}})$ over u^{en} .

- (3) Suppose $\theta : N \rightarrow M$ is a forward homomorphism in $\mathbf{C}_{\text{str}}(B)$ over u (see Definition 15.2.5(2)). We write $M^{\text{en}} := M \otimes_A M$, $N^{\text{en}} := N \otimes_A N$ and $\lambda^{\text{en}} := \lambda \otimes_A \lambda$. Thus $\lambda^{\text{en}} : M^{\text{en}} \rightarrow N^{\text{en}}$ is a forward homomorphism in $\mathbf{C}_{\text{str}}(B^{\text{en}})$ over u^{en} .

Let $u : B \rightarrow C$ be an A -ring homomorphism, and let $\theta : N \rightarrow M$ be a trace morphism in $\mathbf{D}(B)$ over u . We choose a K-projective resolution $P \rightarrow M$ in $\mathbf{C}(B)$, and then a K-injective resolution $P^{\text{en}} \rightarrow I$ in $\mathbf{C}(B^{\text{en}})$. These give us a presentation $\text{pres}_{P,I}$ of $\text{Sq}_{B/A}(M)$; see formula (15.1.14). Similarly we choose a K-projective resolution $Q \rightarrow N$ in $\mathbf{C}(C)$, and then a K-injective resolution $Q^{\text{en}} \rightarrow J$ in $\mathbf{C}(C^{\text{en}})$. These give us a presentation $\text{pres}_{Q,J}$ of $\text{Sq}_{C/A}(N)$.

Next let us choose a K-projective resolution $\tilde{Q} \rightarrow Q$ of Q in $\mathbf{C}(B)$. The trace morphism $\theta : N \rightarrow M$ in $\mathbf{D}(B)$ is represented by a homomorphism $\theta : \tilde{Q} \rightarrow P$ in $\mathbf{C}_{\text{str}}(B)$. Namely the diagram

$$(15.3.3) \quad \begin{array}{ccccc} \tilde{Q} & \xrightarrow{\cong} & Q & \xrightarrow{\cong} & N \\ & \searrow & & & \downarrow \theta \\ & & P & \xrightarrow{\cong} & M \\ & \swarrow \text{Q}(\theta) & & & \end{array}$$

in $\mathbf{D}(B)$ is commutative.

Since B and C are flat over A , the complexes P, Q, \tilde{Q} are all K-flat over A . We obtain the solid diagram

$$(15.3.4) \quad \begin{array}{ccccc} \tilde{Q}^{\text{en}} & \xrightarrow{\text{qis}} & Q^{\text{en}} & \xrightarrow{\text{qis}} & J \\ & \searrow \tilde{\theta}^{\text{en}} & & & \downarrow \chi \\ & & P^{\text{en}} & \xrightarrow{\text{qis}} & I \end{array}$$

in $\mathbf{C}_{\text{str}}(B^{\text{en}})$, in which the arrows marked “qis” are quasi-isomorphism. Since I is K-injective, there is a homomorphism $\chi : J \rightarrow I$ that makes this diagram commutative up to homotopy. This induces a homomorphism

$$(15.3.5) \quad \text{Hom}_{u^{\text{en}}}(u, \chi) : \text{Hom}_{C^{\text{en}}}(C, J) \rightarrow \text{Hom}_{B^{\text{en}}}(B, I)$$

in $\mathbf{C}_{\text{str}}(B)$.

Proposition 15.3.6 (Trace Functoriality). *Let $u : B \rightarrow C$ be homomorphism between flat A -rings, and let $\theta : N \rightarrow M$ be a trace morphism in $\mathbf{D}(B)$ over u . There is a unique trace morphism*

$$\text{Sq}_{u/A}(\theta) : \text{Sq}_{C/A}(N) \rightarrow \text{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$ over u , called the square of θ , that has the following property:

- (\diamond) For any choices $P, Q, \tilde{Q}, \tilde{\theta}, I, J, \chi$ as above, the diagram

$$\begin{array}{ccc} \text{Hom}_{C^{\text{en}}}(C, J) & \xrightarrow{\text{pres}_{Q,J}} & \text{Sq}_{C/A}(N) \\ \downarrow \text{Q}(\text{Hom}_{u^{\text{en}}}(u, \chi)) & & \downarrow \text{Sq}_{u/A}(\theta) \\ \text{Hom}_{B^{\text{en}}}(B, I) & \xrightarrow{\text{pres}_{P,I}} & \text{Sq}_{B/A}(M) \end{array}$$

in $\mathbf{D}(B)$ is commutative.

Proof. This is because the complexes P, Q, \tilde{Q}, I, J are unique up to homotopy equivalence, and the homomorphisms $\tilde{\theta}, \chi$ are unique up to homotopy. \square

Proposition 15.3.7. *We are given this input:*

- Homomorphisms of flat A -rings $u : B \rightarrow C$ and $v : C \rightarrow D$.
- Complexes $M \in \mathbf{D}(B)$, $N \in \mathbf{D}(C)$ and $L \in \mathbf{D}(D)$.
- A trace morphism $\theta : N \rightarrow M$ in $\mathbf{D}(B)$ over u , and a trace morphism $\zeta : L \rightarrow N$ in $\mathbf{D}(C)$ over v .

Then the following hold:

- (1) There is equality

$$\mathrm{Sq}_{u/A}(\theta) \circ \mathrm{Sq}_{v/A}(\zeta) = \mathrm{Sq}_{v \circ u/A}(\theta \circ \zeta)$$

of trace morphisms $\mathrm{Sq}_{D/A}(L) \rightarrow \mathrm{Sq}_{B/A}(M)$ in $\mathbf{D}(B)$ over $v \circ u$.

- (2) If $C = B$ and $u = \mathrm{id}_B$, then

$$\mathrm{Sq}_{u/A}(\theta) = \mathrm{Sq}_{B/A}(\theta),$$

where the latter is the morphism from Definition 15.1.11(2).

Proof. (1) Say we choose a presentation $\mathrm{pres}_{R,K}$ of $\mathrm{Sq}_{D/A}(L)$. Then there is a homomorphism $\xi : J \rightarrow K$ such that $\mathrm{Hom}_{v \circ u}^{\mathrm{en}}(v, \xi)$ represents $\mathrm{Sq}_{v/A}(\zeta)$, as in Proposition 15.3.6. Due to the uniqueness up to homotopy of these choices, the homomorphism

$$\mathrm{Hom}_{(v \circ u)^{\mathrm{en}}}(v \circ u, \chi \circ \xi)$$

represents $\mathrm{Sq}_{v \circ u/A}(\theta \circ \zeta)$. But

$$\mathrm{Hom}_{(v \circ u)^{\mathrm{en}}}(v \circ u, \chi \circ \xi) = \mathrm{Hom}_{u^{\mathrm{en}}}(u, \chi) \circ \mathrm{Hom}_{v^{\mathrm{en}}}(v, \xi).$$

- (2) Clear. \square

Now consider a localization homomorphism $v : B \rightarrow B'$ of A -rings. Suppose we are given complexes $M \in \mathbf{D}(B)$ and $M' \in \mathbf{D}(B')$, and a localization morphism $\lambda : M \rightarrow M'$ in $\mathbf{D}(B)$ over v . Let's choose a K -projective resolution $P \rightarrow M$ in $\mathbf{C}(B)$, and then a K -injective resolution $\rho : P^{\mathrm{en}} \rightarrow I$ in $\mathbf{C}(B^{\mathrm{en}})$. Likewise let's choose a K -projective resolution $P' \rightarrow M'$ in $\mathbf{C}(B')$, and then a K -injective resolution $\rho' : P'^{\mathrm{en}} \rightarrow I'$ in $\mathbf{C}(B'^{\mathrm{en}})$. These choices give us presentations $\mathrm{pres}_{P,I}$ and $\mathrm{pres}_{P',I'}$ of $\mathrm{Sq}_{B/A}(M)$ and $\mathrm{Sq}_{B'/A}(M')$ respectively.

Because P is K -projective, there is a homomorphism $\tilde{\lambda} : P \rightarrow P'$ in $\mathbf{C}_{\mathrm{str}}(B)$ that makes the diagram

$$\begin{array}{ccc} P & \xrightarrow{\cong} & M \\ \mathrm{Q}(\tilde{\lambda}) \downarrow & & \downarrow \lambda \\ P' & \xrightarrow{\cong} & M' \end{array}$$

in $\mathbf{D}(B)$ commutative. On bimodules we get a homomorphism

$$\tilde{\lambda}^{\mathrm{en}} : P^{\mathrm{en}} \rightarrow P'^{\mathrm{en}}$$

in $\mathbf{C}_{\mathrm{str}}(B^{\mathrm{en}})$.

We have the following solid diagram in $\mathbf{C}_{\text{str}}(B'^{\text{en}})$:

$$(15.3.8) \quad \begin{array}{ccc} B'^{\text{en}} \otimes_{B^{\text{en}}} P^{\text{en}} & \xrightarrow{\text{id} \otimes \rho} & B'^{\text{en}} \otimes_{B^{\text{en}}} I \\ \text{fadj}_{v^{\text{en}}}(\tilde{\lambda}^{\text{en}}) \downarrow & & \downarrow \tilde{\xi} \\ P'^{\text{en}} & \xrightarrow{\rho'} & I' \end{array}$$

where $\text{fadj}(\tilde{\lambda}^{\text{en}})$ is the forward adjunction from (15.2.12). Since $v^{\text{en}} : B^{\text{en}} \rightarrow B'^{\text{en}}$ is flat, the homomorphism $\text{id} \otimes \rho$ above is a quasi-isomorphism. On the other hand the complex I' is K-injective. Therefore there is a homomorphism

$$\tilde{\xi} : B'^{\text{en}} \otimes_{B^{\text{en}}} I \rightarrow I'$$

in $\mathbf{C}_{\text{str}}(B'^{\text{en}})$ that makes the diagram (15.3.8) commutative up to homotopy. By forward adjunction, $\tilde{\xi} = \text{fadj}_{v^{\text{en}}}(\xi)$ for a unique homomorphism

$$(15.3.9) \quad \xi : I \rightarrow I'$$

in $\mathbf{C}_{\text{str}}(B^{\text{en}})$. We obtain a diagram

$$(15.3.10) \quad \begin{array}{ccc} P^{\text{en}} & \xrightarrow{\rho} & I \\ \tilde{\lambda}^{\text{en}} \downarrow & & \downarrow \xi \\ P'^{\text{en}} & \xrightarrow{\rho'} & I' \end{array}$$

in $\mathbf{C}_{\text{str}}(B^{\text{en}})$. Since (15.3.8) is commutative up to homotopy, the same is true for (15.3.10).

The homomorphism ξ induces a homomorphism

$$(15.3.11) \quad \text{Hom}_{B^{\text{en}}}(B, \xi) : \text{Hom}_{B^{\text{en}}}(B, I) \rightarrow \text{Hom}_{B^{\text{en}}}(B, I')$$

in $\mathbf{C}_{\text{str}}(B)$. By the forward adjunction formula (15.2.11) there is an isomorphism

$$\text{fadj}_{v^{\text{en}}, B, I'} : \text{Hom}_{B^{\text{en}}}(B, I') \xrightarrow{\cong} \text{Hom}_{B'^{\text{en}}}(B'^{\text{en}} \otimes_{B^{\text{en}}} B, I').$$

But $B \rightarrow B'$ is a localization, so there are unique B -ring isomorphisms

$$B'^{\text{en}} \otimes_{B^{\text{en}}} B = (B' \otimes_A B') \otimes_{B \otimes_A B} B \cong B' \otimes_B B' \cong B'.$$

Therefore in this particular situation we get an isomorphism

$$(15.3.12) \quad \text{fadj}_{v^{\text{en}}, B, I'} : \text{Hom}_{B^{\text{en}}}(B, I') \xrightarrow{\cong} \text{Hom}_{B'^{\text{en}}}(B', I')$$

in $\mathbf{C}_{\text{str}}(B)$.

Proposition 15.3.13 (Localization Functoriality). *Let $v : B \rightarrow B'$ be a localization homomorphism between flat A -rings, and let $\lambda : M \rightarrow M'$ be a localization morphism in $\mathbf{D}(B)$ over v . There is a unique localization morphism*

$$\text{Sq}_{v/A}(\lambda) : \text{Sq}_{B/A}(M) \rightarrow \text{Sq}_{B'/A}(M')$$

in $\mathbf{D}(B)$ over v , called the square of λ , that has the following property:

(†) For any choices of resolutions and homomorphisms as above, the diagram

$$\begin{array}{ccc}
 \mathrm{Hom}_{B^{\mathrm{en}}}(B, I) & \xrightarrow{\mathrm{pres}_{P, I}} & \mathrm{Sq}_{B/A}(M) \\
 \mathrm{Hom}_{B^{\mathrm{en}}}(B, \xi) \downarrow & & \downarrow \mathrm{Sq}_{v/A}(\lambda) \\
 \mathrm{Hom}_{B^{\mathrm{en}}}(B, I') & & \\
 \mathrm{fadj}_{v^{\mathrm{en}}, B, I'} \downarrow & & \\
 \mathrm{Hom}_{B'^{\mathrm{en}}}(B', I') & \xrightarrow{\mathrm{pres}_{P', I'}} & \mathrm{Sq}_{B'/A}(M')
 \end{array}$$

in $\mathbf{D}(B)$ is commutative.

Proof. The reason is that the choices made are unique up to homotopy. \square

In case $B' = C = B$, $v = u = \mathrm{id}_B$ and $\lambda = \theta$, there is an apparent conflict between the morphisms $\mathrm{Sq}_{v/A}(\lambda)$ from Proposition 15.3.13 and $\mathrm{Sq}_{u/A}(\theta)$ from Proposition 15.3.6. This apparent conflict is removed by part (2) of Proposition 15.3.14 below, in conjunction with part (2) of Proposition 15.3.7.

Proposition 15.3.14. *We are given this input:*

- Localization homomorphisms $v : B \rightarrow B'$ and $v' : B' \rightarrow B''$ between flat A -rings.
- Complexes $M \in \mathbf{D}(B)$, $M' \in \mathbf{D}(B')$ and $M'' \in \mathbf{D}(B'')$.
- A localization morphism $\lambda : M \rightarrow M'$ in $\mathbf{D}(B)$ over v , and a localization morphism $\lambda' : M' \rightarrow M''$ in $\mathbf{D}(B')$ over v' .

Then the following hold:

- (1) There is equality

$$\mathrm{Sq}_{v'/A}(\lambda') \circ \mathrm{Sq}_{v/A}(\lambda) = \mathrm{Sq}_{v' \circ v/A}(\lambda' \circ \lambda)$$

of localization morphisms $\mathrm{Sq}_{B/A}(M) \rightarrow \mathrm{Sq}_{B''/A}(M'')$ in $\mathbf{D}(B)$ over $v' \circ v$.

- (2) If $B' = B$ and $v = \mathrm{id}_B$, then

$$\mathrm{Sq}_{v/A}(\lambda) = \mathrm{Sq}_{B/A}(\lambda),$$

where the latter is the morphism from Definition 15.1.11(2).

Proof. This is similar to the proof of Proposition 15.3.7. We leave the details to the reader. \square

Exercise 15.3.15. Give a detailed proof of Proposition 15.3.14.

The next result relates the two type of functorialities of the squaring operation.

Theorem 15.3.16 (Compatibility of Traces and Localizations). *We are given a commutative diagram of homomorphisms between flat A -rings*

$$\begin{array}{ccc}
 B & \xrightarrow{u} & C \\
 v \downarrow & & \downarrow w \\
 B' & \xrightarrow{u'} & C'
 \end{array}$$

in which v is a localization, and

$$u' \otimes_B w : B' \otimes_B C \rightarrow C'$$

is an isomorphism (i.e. the diagram is cocartesian). We are also given this information:

- Complexes $M \in \mathbf{D}(B)$, $N \in \mathbf{D}(C)$, $M' \in \mathbf{D}(B')$ and $N' \in \mathbf{D}(C')$.
- A trace morphism $\theta : N \rightarrow M$ in $\mathbf{D}(B)$ over u .
- A localization morphism $\lambda : M \rightarrow M'$ in $\mathbf{D}(B)$ over v .
- A trace morphism $\theta' : N' \rightarrow M'$ in $\mathbf{D}(B')$ over u' .
- A localization morphism $\mu : N \rightarrow N'$ in $\mathbf{D}(C)$ over w .

These morphisms are required to render the diagram

$$\begin{array}{ccc} M & \xleftarrow{\theta} & N \\ \lambda \downarrow & & \downarrow \mu \\ M' & \xleftarrow{\theta'} & N' \end{array}$$

in $\mathbf{D}(B)$ commutative.

Then the diagram

$$\begin{array}{ccc} \mathrm{Sq}_{B/A}(M) & \xleftarrow{\mathrm{Sq}_{u/A}(\theta)} & \mathrm{Sq}_{C/A}(N) \\ \mathrm{Sq}_{v/A}(\lambda) \downarrow & & \downarrow \mathrm{Sq}_{w/A}(\mu) \\ \mathrm{Sq}_{B'/A}(M') & \xleftarrow{\mathrm{Sq}_{u'/A}(\theta')} & \mathrm{Sq}_{C'/A}(N') \end{array}$$

in $\mathbf{D}(B)$ is commutative.

Proof. By the forward adjunction formula (15.2.11), the given morphisms in $\mathbf{D}(B)$ fit into a larger commutative diagram

(15.3.17)

$$\begin{array}{ccc} M & \xleftarrow{\theta} & N \\ \mathfrak{q}_{v,M} \downarrow & & \downarrow \mathfrak{q}_{w,N} \\ B' \otimes_B M & \xleftarrow{\mathrm{id} \otimes \theta} & B' \otimes_B N \\ \mathrm{dfadj}_v(\lambda) \downarrow & & \downarrow \mathrm{dfadj}_w(\mu) \\ M' & \xleftarrow{\theta'} & N' \end{array}$$

in which the bottom square is in the category $\mathbf{D}(B')$. Applying the squaring to (15.3.17) we obtain a diagram

$$(15.3.18) \quad \begin{array}{ccc} \mathrm{Sq}_{B/A}(M) & \xleftarrow{\mathrm{Sq}_{u/A}(\theta)} & \mathrm{Sq}_{C/A}(N) \\ \mathrm{Sq}_{v/A}(q_{v,M}) \downarrow & & \downarrow \mathrm{Sq}_{w/A}(q_{w,N}) \\ \mathrm{Sq}_{B'/A}(B' \otimes_B M) & \xleftarrow{\mathrm{Sq}_{u'/A}(\mathrm{id} \otimes \theta)} & \mathrm{Sq}_{C'/A}(B' \otimes_B N) \\ \mathrm{Sq}_{B'/A}(\mathrm{dfadj}_v(\lambda)) \downarrow & & \downarrow \mathrm{Sq}_{C'/A}(\mathrm{dfadj}_w(\mu)) \\ \mathrm{Sq}_{B'/A}(M') & \xleftarrow{\mathrm{Sq}_{u'/A}(\theta')} & \mathrm{Sq}_{C'/A}(N') \end{array}$$

The bottom square is commutative by Proposition 15.3.7. It remains to prove that the top square is commutative.

Thus we can assume that $M' = B' \otimes_B M$, $N' = C' \otimes_C N \cong B' \otimes_B N$, $\lambda = q_{v,M}$, $\mu = q_{w,N}$ and $\theta' = \mathrm{id} \otimes \theta$. Let us choose resolutions $P \rightarrow M$, $Q \rightarrow N$ and $\tilde{Q} \rightarrow Q$ as we did before Proposition 15.3.6. Letting $P' := B' \otimes_B P$, $Q' := B' \otimes_B Q$ and $\tilde{Q}' := B' \otimes_B \tilde{Q}$, these are resolutions of M' and N' respectively. Choose a homomorphism $\tilde{\theta} : \tilde{Q} \rightarrow P$ that represents θ , as in diagram (15.3.3). Then

$$\tilde{\theta}' := \mathrm{id}_{B'} \otimes \tilde{\theta} : \tilde{Q}' \rightarrow P'$$

represents θ' . There is a diagram

$$(15.3.19) \quad \begin{array}{ccccc} P & \xleftarrow{\tilde{\theta}} & \tilde{Q} & \xleftarrow{\quad} & Q \\ q_{v,P} \downarrow & & q_{v,\tilde{Q}} \downarrow & & q_{w,Q} \downarrow \\ P' & \xleftarrow{\tilde{\theta}'} & \tilde{Q}' & \xleftarrow{\quad} & Q' \end{array}$$

in $\mathbf{C}_{\mathrm{str}}(B)$ that's commutative up to homotopy. The unmarked arrows are quasi-isomorphisms.

Now we pass to bimodules. As before we choose \mathbf{K} -injective resolutions $P^{\mathrm{en}} \rightarrow I$ in $\mathbf{C}(B^{\mathrm{en}})$, $Q^{\mathrm{en}} \rightarrow J$ in $\mathbf{C}(C^{\mathrm{en}})$, $P'^{\mathrm{en}} \rightarrow I'$ in $\mathbf{C}(B'^{\mathrm{en}})$ and $Q'^{\mathrm{en}} \rightarrow J'$ in $\mathbf{C}(C'^{\mathrm{en}})$. Consider the following complicated diagram in $\mathbf{C}_{\mathrm{str}}(B^{\mathrm{en}})$:

$$(15.3.20) \quad \begin{array}{ccccccc} & & & \chi & & & \\ & & & \curvearrowright & & & \\ I & \xleftarrow{\quad} & P^{\mathrm{en}} & \xleftarrow{\tilde{\theta}^{\mathrm{en}}} & \tilde{Q}^{\mathrm{en}} & \xleftarrow{\quad} & Q^{\mathrm{en}} \xrightarrow{\quad} J \\ \xi_I \downarrow & & q_{v^{\mathrm{en}},P^{\mathrm{en}}} \downarrow & & q_{v^{\mathrm{en}},\tilde{Q}^{\mathrm{en}}} \downarrow & & q_{w^{\mathrm{en}},Q^{\mathrm{en}}} \downarrow & \downarrow \xi_J \\ I' & \xleftarrow{\quad} & P'^{\mathrm{en}} & \xleftarrow{\tilde{\theta}'^{\mathrm{en}}} & \tilde{Q}'^{\mathrm{en}} & \xleftarrow{\quad} & Q'^{\mathrm{en}} \xrightarrow{\quad} J' \\ & & & \curvearrowleft & & & & \\ & & & \chi' & & & & \end{array}$$

The unmarked arrows are quasi-isomorphisms. The top and bottom half-moons are two versions of diagram (15.3.4), and they are commutative up to homotopies. The two squares in the middle are the bimodule version of of diagram (15.3.19), and

too they are commutative up to homotopies. The two squares on the extreme left and right are two versions of (15.3.10), so they are commutative up to homotopies. Therefore the diagram

$$(15.3.21) \quad \begin{array}{ccc} I & \xleftarrow{\chi} & J \\ \xi_I \downarrow & & \downarrow \xi_J \\ I' & \xleftarrow{\chi'} & J' \end{array}$$

in $\mathbf{C}_{\text{str}}(B^{\text{en}})$, that is the outer boundary of (15.3.20), is commutative up to homotopy.

Finally, applying $\text{Hom}_{-^{\text{en}}}(-, -)$ to the diagram (15.3.21) we obtain the diagram

$$\begin{array}{ccc} \text{Hom}_{B^{\text{en}}}(B, I) & \xleftarrow{\text{Hom}_{u^{\text{en}}}(u, \chi)} & \text{Hom}_{C^{\text{en}}}(C, J) \\ \text{Hom}_{B^{\text{en}}}(B, \xi_I) \downarrow & & \downarrow \text{Hom}_{C^{\text{en}}}(C, \xi_J) \\ \text{Hom}_{B^{\text{en}}}(B, I') & \xleftarrow{\text{Hom}_{u^{\text{en}}}(u, \chi')} & \text{Hom}_{C^{\text{en}}}(C, J') \\ \text{fadj}_{v^{\text{en}}, B, I'} \downarrow & & \downarrow \text{fadj}_{w^{\text{en}}, C, J'} \\ \text{Hom}_{B'^{\text{en}}}(B', I') & \xleftarrow{\text{Hom}_{u'^{\text{en}}}(u', \chi')} & \text{Hom}_{C'^{\text{en}}}(C', J') \end{array}$$

in $\mathbf{C}_{\text{str}}(B)$. It is commutative up to homotopy. By Proposition 15.3.13, the outer boundary of this diagram represents the diagram

$$\begin{array}{ccc} \text{Sq}_{B/A}(M) & \xleftarrow{\text{Sq}_{u/A}(\theta)} & \text{Sq}_{C/A}(N) \\ \text{Sq}_{v/A}(q_{v, M}) \downarrow & & \downarrow \text{Sq}_{w/A}(q_{w, N}) \\ \text{Sq}_{B'/A}(B' \otimes_B M) & \xleftarrow{\text{Sq}_{u'/A}(\text{id} \otimes \theta)} & \text{Sq}_{C'/A}(B' \otimes_B N) \end{array}$$

in $\mathbf{D}(B)$, and therefore this last diagram is commutative. \square

cmnt:

leave the cup product until later - need it only for residue thm

15.4. Functoriality of Rigid Complexes. In this subsection we continue with Setup 15.3.1: A is a commutative ring, and the rings B, C, D, B', C', B'' are flat commutative A -rings.

The next definition is a generalization of Definition 15.1.19.

Definition 15.4.1. Let $u : B \rightarrow C$ be a homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\text{rig}/A}$, and let $(N, \sigma) \in \mathbf{D}(C)_{\text{rig}/A}$. A *rigid trace morphism* over u relative to A , denoted by

$$\theta : (N, \sigma) \rightarrow (M, \rho),$$

is a trace morphism $\theta : N \rightarrow M$ in $\mathbf{D}(B)$ over u (in the sense of Definition 15.2.5(1)), such that the diagram

$$\begin{array}{ccc} N & \xrightarrow{\sigma} & \mathrm{Sq}_{C/A}(N) \\ \theta \downarrow & & \downarrow \mathrm{Sq}_{u/A}(\theta) \\ M & \xrightarrow{\rho} & \mathrm{Sq}_{B/A}(M) \end{array}$$

in $\mathbf{D}(B)$ is commutative.

It is clear that if $w : C \rightarrow D$ is another homomorphism of A -rings, if $(L, \tau) \in \mathbf{D}(D)_{\mathrm{rig}/A}$, and if $\zeta : (L, \tau) \rightarrow (N, \sigma)$ is a rigid trace morphism over v relative to A , then

$$\theta \circ \zeta : (L, \tau) \rightarrow (M, \rho)$$

is a rigid trace morphism over $w \circ v$ relative to A .

Here is a generalization of Theorem 15.1.16.

Lemma 15.4.2. *Let $u : B \rightarrow C$ be a homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}$, let $(N, \sigma) \in \mathbf{D}(C)_{\mathrm{rig}/A}$, and let $\theta : (N, \sigma) \rightarrow (M, \rho)$ be a rigid trace morphism over u relative to A . For any element $c \in C$ there is equality*

$$\mathrm{Sq}_{u/A}(c \cdot \theta) = c^2 \cdot \mathrm{Sq}_{u/A}(\theta),$$

as trace morphisms $\mathrm{Sq}_{C/A}(N) \rightarrow \mathrm{Sq}_{B/A}(M)$ in $\mathbf{D}(B)$ over u .

Proof. It is very similar to the proof of Theorem 15.1.16, using any presentation of $\mathrm{Sq}_{u/A}(\theta)$ as in property (\diamond) in Proposition 15.3.6. \square

Theorem 15.4.3 (Uniqueness of the Nondegenerate Rigid Trace). *Let $u : B \rightarrow C$ be a homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}$ and let $(N, \sigma) \in \mathbf{D}(C)_{\mathrm{rig}/A}$. Assume that $N \in \mathbf{D}(C)$ has the derived Morita property. There is at most one nondegenerate rigid trace morphism*

$$\theta : (N, \sigma) \rightarrow (M, \rho)$$

in $\mathbf{D}(B)$ over u .

Proof. Suppose that

$$\theta_0, \theta_1 : (N, \sigma) \rightarrow (M, \rho)$$

are both nondegenerate rigid trace morphisms over u relative to A . For $i = 0, 1$ let

$$\phi_i : N \rightarrow \mathrm{RHom}_B(C, M)$$

be the morphism in $\mathbf{D}(C)$ that corresponds to θ_i by backward adjunction. Since the θ_i are nondegenerate, it follows that the ϕ_i are isomorphisms. Thus $\phi_1^{-1} \circ \phi_0$ is an automorphism of N in $\mathbf{D}(C)$. The derived Morita property of C says that

$$\phi_1^{-1} \circ \phi_0 = c \cdot \mathrm{id}_C$$

for some invertible element $c \in C$. Thus $\phi_0 = c \cdot \phi_1$, and therefore $\theta_0 = c \cdot \theta_1$.

By Lemma 15.4.2 we know that

$$\mathrm{Sq}_{u/A}(\theta_1) = \mathrm{Sq}_{u/A}(c \cdot \theta_0) = c^2 \cdot \mathrm{Sq}_{u/A}(\theta_0) =$$

Because θ_i is rigid, there is equality

$$\rho \circ \theta_i = \mathrm{Sq}_{u/A}(\theta_i) \circ \sigma.$$

Hence

$$(15.4.4) \quad c \cdot \rho \circ \theta_0 = \rho \circ \theta_1 = \mathrm{Sq}_{u/A}(\theta_1) \circ \sigma = c^2 \cdot \mathrm{Sq}_{u/A}(\theta_0) \circ \sigma = c^2 \cdot \rho \circ \theta_0.$$

Now because θ_0 is nondegenerate, there is a bijection

$$\mathrm{Hom}_{\mathbf{D}(B)}(N, \mathrm{Sq}_{B/A}(M)) \xrightarrow{\cong} \mathrm{Hom}_{\mathbf{D}(C)}(N, N)$$

that sends $\rho \circ \theta_0 \mapsto \mathrm{id}_N$. This bijection is C -linear. Equation (15.4.4) tells us that $c \cdot \mathrm{id}_N = c^2 \cdot \mathrm{id}_N$. By the derived Morita property, it follows that $c = c^2$. Hence $c = 1$, and therefore $\theta_0 = \theta_1$. \square

The next definition is another generalization of Definition 15.1.19.

Definition 15.4.5. Let $v : B \rightarrow B'$ be a localization homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}$, and let $(M', \rho') \in \mathbf{D}(B')_{\mathrm{rig}/A}$. A *rigid localization morphism* over v relative to A , denoted by

$$\lambda : (M, \rho) \rightarrow (M', \rho'),$$

is a localization morphism $\lambda : M \rightarrow M'$ in $\mathbf{D}(B)$ over v (in the sense of Definition 15.2.5(2)), such that the diagram

$$\begin{array}{ccc} M & \xrightarrow{\rho} & \mathrm{Sq}_{B/A}(M) \\ \lambda \downarrow & & \downarrow \mathrm{Sq}_{v/A}(\lambda) \\ M' & \xrightarrow{\rho'} & \mathrm{Sq}_{B'/A}(M') \end{array}$$

in $\mathbf{D}(B)$ is commutative.

It is clear that if $v' : B' \rightarrow B''$ is another localization homomorphism of A -rings, if $(M'', \rho'') \in \mathbf{D}(B'')_{\mathrm{rig}/A}$, and if $\lambda' : (M', \rho') \rightarrow (M'', \rho'')$ is a rigid localization morphism over v' relative to A , then

$$\lambda' \circ \lambda : (M, \rho) \rightarrow (M'', \rho'')$$

is a rigid localization morphism over $v \circ v'$ relative to A .

Since $\mathbf{D}(B')$ is a B' -linear category, for any forward morphism $\lambda : M \rightarrow M'$ in $\mathbf{D}(B')$ over v , and any element $b \in B'$, it makes sense to talk about the forward morphism $b \cdot \lambda : M \rightarrow M'$; this is the composition of λ with $b \cdot \mathrm{id}_{M'}$.

Lemma 15.4.6. *Let $v : B \rightarrow B'$ be a homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}$, let $(M', \rho') \in \mathbf{D}(B')_{\mathrm{rig}/A}$, and let $\lambda : (M, \rho) \rightarrow (M', \rho')$ be a rigid localization morphism over v relative to A . For any element $b \in B'$ there is equality*

$$\mathrm{Sq}_{v/A}(b \cdot \lambda) = b^2 \cdot \mathrm{Sq}_{v/A}(\lambda),$$

as localization morphisms $\mathrm{Sq}_{B/A}(B) \rightarrow \mathrm{Sq}_{B'/A}(M')$ in $\mathbf{D}(B)$ over v .

Proof. Again, this is very similar to the proof of Theorem 15.1.16, using any presentation of $\mathrm{Sq}_{v/A}(\lambda)$ as in property (†) in Proposition 15.3.13. \square

Theorem 15.4.7 (Uniqueness of the Nondegenerate Rigid Localization). *Let $v : B \rightarrow B'$ be a localization homomorphism of A -rings, let $(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}$ and let $(M', \rho') \in \mathbf{D}(B')_{\mathrm{rig}/A}$. Assume that $M' \in \mathbf{D}(M')$ has the derived Morita property. There is at most one nondegenerate rigid localization morphism*

$$\lambda : (M, \rho) \rightarrow (M', \rho')$$

in $\mathbf{D}(B)$ over v .

Exercise 15.4.8. Prove Theorem 15.4.7. (Hint: modify the proof of Theorem 15.4.3.)

15.5. Interlude: DG Ring Resolutions.

cmnt: this material belongs way back in the book... Maybe in Subsec 10.3, as an application of the existence of K-proj res in $\mathbf{C}(A)$.

For establishing the existence of coinduced rigidifying isomorphisms (in Subsection 15.6) we need to use DG rings a bit. (Not nearly as deeply as what is outlined in Remark 15.1.26.

Suppose A and B are central DG \mathbb{K} -rings. A homomorphism of DG \mathbb{K} -rings $u : A \rightarrow B$ induces a homomorphism of graded \mathbb{K} -rings $H(u) : H(A) \rightarrow H(B)$; cf. Example 3.3.19. The DG ring homomorphism u is called a *quasi-isomorphism of DG rings* if $H(u)$ is an isomorphism.

A DG ring homomorphism $u : A \rightarrow B$ induces a \mathbb{K} -linear DG functor

$$\text{Rest}_u : \mathbf{C}(B) \rightarrow \mathbf{C}(A)$$

called restriction, that was already encountered in Subsection 15.2. Since Rest_u is exact, it passes to a triangulated functor

$$\text{Rest}_u : \mathbf{D}(B) \rightarrow \mathbf{D}(A).$$

There is also the *induction* functor

$$\text{Ind}_u : \mathbf{C}(A) \rightarrow \mathbf{C}(B), \quad \text{Ind}_u(M) := B \otimes_A M.$$

It has a left derived functor

$$\text{LInd}_u : \mathbf{D}(A) \rightarrow \mathbf{D}(B), \quad \text{LInd}_u(M) := B \otimes_A^L M,$$

which is a \mathbb{K} -linear triangulated functor.

Proposition 15.5.1. *Let $u : A \rightarrow B$ be a homomorphism of central DG \mathbb{K} -rings. The functor LInd_u is a left adjoint to Rest_u . That is to say, for any $M \in \mathbf{D}(A)$ and $N \in \mathbf{D}(B)$ there is a \mathbb{K} -linear bijection*

$$\text{dfadj}_u : \text{Hom}_{\mathbf{D}(A)}(M, \text{Rest}_u(N)) \xrightarrow{\cong} \text{Hom}_{\mathbf{D}(B)}(\text{LInd}_u(M), N),$$

and it is functorial in M and N .

Proof. Choose a \mathbb{K} -projective resolution $\rho : P \rightarrow M$ in $\mathbf{C}(A)$. This gives us a presentation

$$\text{LInd}_u(M) \cong B \otimes_A P$$

in $\mathbf{D}(B)$. Now $B \otimes_A P$ is \mathbb{K} -projective in $\mathbf{C}(B)$. Thus we get isomorphisms

$$\begin{aligned} \text{Hom}_{\mathbf{D}(A)}(M, N) &\cong H^0(\text{Hom}_A(P, N)) \\ &\cong H^0(\text{Hom}_B(B \otimes_A P, N)) \cong \text{Hom}_{\mathbf{D}(B)}(\text{LInd}_u(M), N). \end{aligned}$$

The composed isomorphism is easily seen to be dfadj_u . □

Here is a fundamental result. It is the justification behind the use of DG ring resolutions. We do not know who discovered it.

Theorem 15.5.2. *Let $u : A \rightarrow B$ be a quasi-isomorphism of central DG \mathbb{K} -rings. Then*

$$\text{Rest}_u : \mathbf{D}(B) \rightarrow \mathbf{D}(A)$$

is an equivalence of \mathbb{K} -linear triangulated categories, with quasi-inverse LInd_u .

Proof. Take any $N \in \mathbf{D}(B)$. Let $M := \text{Rest}_u(N) \in \mathbf{D}(A)$. Choose a K-projective resolution $\rho : P \rightarrow M$ in $\mathbf{C}(A)$, so that $\text{LInd}_u(M) \cong B \otimes_A P$. There is an obvious homomorphism

$$(15.5.3) \quad \psi : B \otimes_A P \rightarrow N = M$$

in $\mathbf{C}_{\text{str}}(B)$, namely $\psi(b \otimes p) := b \cdot \rho(p)$. We claim that ψ is a quasi-isomorphism. To see that, we look at the commutative diagram

$$\begin{array}{ccc} B \otimes_A P & \xrightarrow{\psi} & N \\ u \otimes \text{id}_P \uparrow & & \uparrow \cong \\ A \otimes_A P & \xrightarrow{\text{id}_A \otimes \rho} & A \otimes_A N \end{array}$$

in $\mathbf{C}_{\text{str}}(A)$. The homomorphism $u \otimes \text{id}_P$ is a quasi-isomorphism because u is a quasi-isomorphism and P is K-flat. The homomorphism $\text{id}_A \otimes \rho$ is a quasi-isomorphism because ρ is a quasi-isomorphism and A is K-flat. Therefore ψ is a quasi-isomorphism.

This means that we have an isomorphism

$$\mathbf{Q}(\psi) : (\text{LInd}_u \circ \text{Rest}_u)(N) \xrightarrow{\cong} N$$

in $\mathbf{D}(B)$, and it is functorial in N .

On the other hand, starting from a complex $M \in \mathbf{D}(A)$, and choosing a K-projective resolution $\rho : P \rightarrow M$ as above, we can view the quasi-isomorphism ψ from (15.5.3) as a quasi-isomorphism in $\mathbf{C}_{\text{str}}(A)$. Thus we get an isomorphism

$$\mathbf{Q}(\psi) : (\text{Rest}_u \circ \text{LInd}_u)(M) \xrightarrow{\cong} M$$

in $\mathbf{D}(A)$, and this is functorial in M . □

Here is a useful strengthening of the theorem.

Proposition 15.5.4. *Let $u : A \rightarrow B$ be a quasi-isomorphism between central DG \mathbb{K} -rings. For any $L \in \mathbf{D}(B)$, $M \in \mathbf{D}(B^{\text{op}})$ and $N \in \mathbf{D}(B)$, there are isomorphisms*

$$M \otimes_A^L N \xrightarrow{\cong} M \otimes_B^L N$$

and

$$\text{RHom}_A(L, N) \xrightarrow{\cong} \text{RHom}_B(L, N)$$

in $\mathbf{D}(\mathbb{K})$. *These isomorphisms are functorial in M and N .*

Notice that the restriction functor Rest_u is suppressed in the proposition.

Proof. Choose a K-projective resolution $\rho : P \rightarrow M$ in $\mathbf{C}(A^{\text{op}})$. This produces an isomorphism

$$\psi_1 : P \otimes_A N \xrightarrow{\cong} M \otimes_A^L N.$$

in $\mathbf{D}(\mathbb{K})$. Next let us look at the DG module $P \otimes_A B \in \mathbf{C}(B^{\text{op}})$. This is K-projective over B^{op} ; and as shown in the proof of Theorem 15.5.2(2), the canonical

homomorphism $P \otimes_A B \rightarrow M$ in $\mathbf{C}_{\text{str}}(B^{\text{op}})$ is a quasi-isomorphism. In this way we have an isomorphism

$$\psi_2 : P \otimes_A N \xrightarrow{\cong} (P \otimes_A B) \otimes_B N \xrightarrow{\cong} M \otimes_B^L N$$

in $\mathbf{D}(\mathbb{K})$. The functorial isomorphism we want is $\psi_2 \circ \psi_1^{-1}$.

Now to the RHom . Let us choose a \mathbb{K} -projective resolution $\sigma : Q \rightarrow L$ in $\mathbf{C}(A)$. This produces an isomorphism

$$\phi_1 : \text{Hom}_A(Q, N) \xrightarrow{\cong} \text{RHom}_A(L, N)$$

in $\mathbf{D}(\mathbb{K})$. Again, the DG module $B \otimes_A Q \in \mathbf{C}(B)$ is \mathbb{K} -projective, and the canonical homomorphism $B \otimes_A Q \rightarrow L$ in $\mathbf{C}_{\text{str}}(B)$ is a quasi-isomorphism. In this way we have an isomorphism

$$\phi_2 : \text{Hom}_A(Q, N) \xrightarrow{\cong} \text{Hom}_B(B \otimes_A Q, N) \xrightarrow{\cong} \text{RHom}_B(L, N)$$

in $\mathbf{D}(\mathbb{K})$. The functorial isomorphism we want is $\phi_2 \circ \phi_1^{-1}$. \square

Definition 15.5.5. Let $A = \bigoplus_{i \in \mathbb{Z}} A^i$ be a central DG \mathbb{K} -ring.

- (1) A is called *weakly commutative* if

$$b \cdot a = (-1)^{i \cdot j} \cdot a \cdot b$$

for all $a \in A^i$ and $b \in A^j$.

- (2) A is called *strongly commutative* if it is weakly commutative, and also $a^2 = 0$ for all $a \in A^i$ such that i is odd.

- (3) A is called *nonpositive* if $A^i = 0$ for all $i > 0$.

- (4) A is called a *commutative DG ring* if it is nonpositive and strongly commutative.

This definition is taken from [Ye11]. In [YeZh3] the term “super-commutative” was used instead of “strongly commutative”. We already encountered weak and strong commutativity in Example 3.1.8.

Remark 15.5.6. Weak commutativity is the obvious commutativity condition in the graded setting, and is the prototype for the Koszul sign rule.

Strong commutativity has another reason. It’s role is to guarantee that a graded commutative polynomial ring $\mathbb{Z}[X]$ (see equation (15.5.10)) is flat over \mathbb{Z} . Without this condition, the square of an odd variable x would be a nonzero 2-torsion element.

Of course, if 2 is invertible in \mathbb{K} (e.g. if \mathbb{K} contains \mathbb{Q}), then weak and strong commutativity of a central DG \mathbb{K} -ring coincide. Since most texts dealing with DG rings assume that $\mathbb{Q} \subseteq \mathbb{K}$, the subtle distinction we make is absent from them.

A weakly commutative DG ring A is isomorphic to its opposite A^{op} ; the isomorphism $u : A \xrightarrow{\cong} A^{\text{op}}$ is

$$u(a) := (-1)^i \cdot a$$

for $a \in A^i$. This implies that any left DG A -module can be made into a right DG A -module, and vice-versa. The formula relating the left and right actions is

$$m \cdot a = (-1)^{i \cdot j} \cdot a \cdot m$$

for $a \in A^i$ and $m \in M^j$. On the level of categories we obtain an isomorphism of DG categories $\mathbf{C}(A) \cong \mathbf{C}(A^{\text{op}})$.

When A is weakly commutative, the tensor and Hom functors are A -bilinear (in the graded sense), and therefore their derived functors have more structure: they are $H^0(A)$ -bilinear triangulated bifunctors

$$(15.5.7) \quad (- \otimes_A^L -) : \mathbf{D}(A) \times \mathbf{D}(A) \rightarrow \mathbf{D}(A)$$

and

$$(15.5.8) \quad \mathrm{RHom}_A(-, -) : \mathbf{D}(A)^{\mathrm{op}} \times \mathbf{D}(A) \rightarrow \mathbf{D}(A).$$

When the DG rings in Proposition 15.5.4 are weakly commutative, this result can be amplified:

Corollary 15.5.9. *In the situation of Proposition 15.5.4, assume that A and B are weakly commutative. Then the isomorphisms*

$$M \otimes_A^L N \xrightarrow{\cong} M \otimes_B^L N$$

and

$$\mathrm{RHom}_A(L, N) \xrightarrow{\cong} \mathrm{RHom}_B(L, N)$$

are in $\mathbf{D}(B)$, when we consider these objects as DG B -modules via the actions on M and L respectively.

Proof. Going over the steps in the proof of the proposition, we see that all the moves are B -linear (in the graded sense). \square

By *nonpositive graded set* we mean a set X that is partitioned into subsets $X = \coprod_{i \leq 0} X^i$. The elements of X^i are said to have degree i .

Given a nonpositive graded set X , we can form the noncommutative polynomial ring $\mathbb{Z}\langle X \rangle$ in X over \mathbb{Z} . As a graded \mathbb{Z} -module, $\mathbb{Z}\langle X \rangle$ is free with basis the collection of monomials

$$\{x_1 \cdots x_l\}_{x_1, \dots, x_l \in X}.$$

The degree of a monomial $x_1 \cdots x_l$, with $x_p \in X^{i_p}$, is $i_1 + \cdots + i_l$. The multiplication in $\mathbb{Z}\langle X \rangle$ is defined by

$$(x_1 \cdots x_l) \cdot (x_{l+1} \cdots x_m) := x_1 \cdots x_m.$$

The *commutative polynomial ring* in X over \mathbb{Z} is the quotient ring

$$(15.5.10) \quad \mathbb{Z}[X] := \mathbb{Z}\langle X \rangle / I,$$

where I is the two-sided ideal of $\mathbb{Z}\langle X \rangle$ generated by the elements

$$y \cdot x - (-1)^{i \cdot j} \cdot x \cdot y$$

for all $x \in X^i$ and $y \in X^j$, and $x \cdot x$ if i is odd.

Recall that for a DG object M , the graded object gotten by forgetting the differential is denoted by M^{\natural} .

Definition 15.5.11. Let $A \rightarrow \tilde{B}$ be a homomorphism between commutative DG rings. We say that \tilde{B} is a *semi-free commutative DG ring over A* if there is an isomorphism of graded A^{\natural} -rings

$$\tilde{B}^{\natural} \cong A^{\natural} \otimes_{\mathbb{Z}} \mathbb{Z}[X]$$

for some nonpositive graded set X .

Definition 15.5.12. Let $f : A \rightarrow B$ be a homomorphism of commutative DG rings. A *semi-free commutative DG ring resolution* of B over A is a semi-free commutative DG ring \tilde{B} over A , together with a surjective quasi-isomorphism of DG A -rings $\tilde{B} \rightarrow B$.

Theorem 15.5.13. *Let $f : A \rightarrow B$ be a homomorphism of commutative DG rings. There exists a semi-free commutative DG ring resolution $\tilde{B} \rightarrow B$ of B over A .*

Proofs of Theorem 15.5.13 can be found in [YeZh3, Proposition 1.7(1)] and [Ye11, Theorem 3.21(1)]. We will not use this general theorem, but rather the slightly different Theorem 15.5.16 below, for which we provide a proof.

Example 15.5.14. Take $A := \mathbb{Z}$ and $B := Z/(6)$. The Koszul complex $\tilde{B} := K(\mathbb{Z}, 6)$ from Example 3.3.8 is a semi-free commutative DG ring resolution of B over A .

Definition 15.5.15. Let $f : A \rightarrow B$ be a homomorphism of commutative DG rings. A *K-projective commutative DG ring resolution* of B over A is a commutative DG ring \tilde{B} over A , which is K-projective as a DG A -module, together with a surjective quasi-isomorphism of DG A -rings $\tilde{B} \rightarrow B$.

Of course a semi-free commutative DG ring resolution is K-projective too. But often (and unlike Example 15.5.14) we can't produce semi-free commutative DG ring resolutions with suitable finiteness properties.

Theorem 15.5.16. *Let $A \rightarrow B$ be a homomorphism of commutative rings. Assume A is noetherian and B is finite over A . Then there exists a K-projective commutative DG ring resolution $v : \tilde{B} \rightarrow B$ of B over A , such that each \tilde{B}^i is a finitely generated free A -module.*

Proof. This is [YeZh3, Proposition 1.7(3)], but we will give the whole proof here.

The strategy is this: we will construct an ascending sequence of commutative DG A -rings $\{F_j(\tilde{B})\}_{j \geq 0}$, together with DG A -ring homomorphisms $F_j(v) : F_j(\tilde{B}) \rightarrow B$. For every j the DG ring $F_j(\tilde{B})$ will have the property that each $F_j(\tilde{B})^i$ is a finitely generated free A -module. For $i \geq -j$ the inclusion $F_{j+1}(\tilde{B})^i \rightarrow F_j(\tilde{B})^i$ will be bijective. In cohomology, the homomorphism

$$H^i(F_j(v)) : H^i(F_j(\tilde{B})) \rightarrow H^i(B)$$

will be surjective for all $i \geq -j$ and bijective for all $i \geq -j + 1$. Then

$$\tilde{B} := \lim_{j \rightarrow} F_j(\tilde{B})$$

and

$$v := \lim_{j \rightarrow} F_j(v)$$

will have the desired properties.

We start by choosing a finite collection $\{b_x\}_{x \in X^0}$ of elements of B that generate it as an A -ring. We consider the finite set X^0 to be of degree 0. Because the ring homomorphism $A \rightarrow B$ is finite, each $b_x \in B$ satisfies some monic polynomial $f_x(t) \in A[t]$. Define the ring $F_0(\tilde{B})$ to be

$$F_0(\tilde{B}) := A[X^0]/(\{f_x(b_x)\}_{x \in X^0}).$$

This ring is a finitely generated free A -module, and there is a surjection of A -rings

$$F_0(v) : F_0(\tilde{B}) \rightarrow B.$$

Now take any $j \geq 0$, and assume that $F_j(\tilde{B}) \rightarrow B$ has been constructed, and it satisfies the conditions stated above. In degree $i := -j$ we consider the finitely generated A -module

$$N_j := \text{Ker}(\text{H}^{-j}(F_j(v))).$$

It sits in an exact sequence

$$0 \rightarrow N_j \rightarrow \text{H}^{-j}(F_j(\tilde{B})) \xrightarrow{\text{H}^{-j}(F_j(v))} \text{H}^{-j}(B) \rightarrow 0.$$

Let us choose a finite collection of A -module generators on N_j , indexed by a finite set X^{-j-1} . We can left these generators to a collection $\{b_x\}_{x \in X^{-j-1}}$ of cocycles in $F_j(\tilde{B})^{-j}$.

Now we define the DG ring $F_{j+1}(\tilde{B})$. As a graded ring it is:

$$F_{j+1}(\tilde{B})^\natural := F_j(\tilde{B})^\natural \otimes_{\mathbb{Z}} \mathbb{Z}[X^{-j-1}]$$

where $\mathbb{Z}[X^{-j-1}]$ is the commutative polynomial ring in the finite graded set of degree $-j-1$ elements X^{-j-1} . The differential of $F_{j+1}(\tilde{B})$ extends that of $F_j(\tilde{B})$, and satisfies $d(x) := b_x$ for any variable $x \in X^{-j-1}$. Such a differential exists (and is unique) because there are no relations on the elements $x \in X^{-j-1}$ except for the strong commutativity relations, the ring $F_j(\tilde{B})$ is commutative, and $d(b_x) = 0$. The homomorphism $F_{j+1}(v)$ must vanish on X^{-j-1} by degree considerations. We leave it to the reader to verify that the conditions stated above hold for $F_{j+1}(\tilde{B})$ and $F_{j+1}(v)$. \square

Remark 15.5.17. If $A \rightarrow B$ is surjective, then we can choose $X^0 = \emptyset$. With this choice the DG ring \tilde{B} is semi-free over A . Moreover, the DG ring $F_1(\tilde{B})$ is just the Koszul complex over A of the collection $\{b_x\}_{x \in X^{-1}}$ of elements of $A = F_0(\tilde{B})$. Compare to Examples 15.5.14 and 3.3.8.

15.6. Induced and Coinduced Rigid Complexes. In this subsection we continue with Setup 15.3.1: A is a commutative ring, and the rings B, C, D, B', C', B'' are flat commutative A -rings. The purpose of this portion of the section is to show how rigidity is propagated along certain ring homomorphisms.

Surprisingly we shall have to resort to DG ring resolutions to prove the next theorem. See Question 15.6.7 about this issue.

Theorem 15.6.1. *Let $u : B \rightarrow C$ be a homomorphism of A -rings, let $M \in \mathbf{D}(B)$, let $N \in \mathbf{D}(C)$, and let $\theta : N \rightarrow M$ be a nondegenerate trace morphism in $\mathbf{D}(B)$ over u . Assume these conditions hold:*

- *The complexes M and N have finite flat dimensions over A .*
- *The ring B is noetherian, and the ring homomorphism $B \rightarrow C$ is finite.*

Then the trace morphism

$$\text{Sq}_{u/A}(\theta) : \text{Sq}_{C/A}(N) \rightarrow \text{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$ over u is nondegenerate.

Before proving this theorem we need several lemmas. The catch in the next lemma is that the complex P of flat A -module is bounded *below*, not above.

Lemma 15.6.2. *Let P and N be bounded below complexes of A -modules. Assume that each P^i is a flat A -module, and that N has finite flat dimension over A . Then the canonical morphism $P \otimes_A^{\mathbb{L}} N \rightarrow P \otimes_A N$ in $\mathbf{D}(A)$ is an isomorphism.*

Proof. Choose a bounded flat resolution $Q \rightarrow N$ over A . We have to show that $P \otimes_A Q \rightarrow P \otimes_A N$ is a quasi-isomorphism. Let L be the cone on the quasi-isomorphism $Q \rightarrow N$. It is enough to show that the complex $P \otimes_A L$ is acyclic. We note that L is a bounded below acyclic complex and P is a bounded below complex of flat modules. To prove that $H^i(P \otimes_A L) = 0$ for any given i we might as well replace P with its stupid truncation

$$P' := \text{stt}^{\leq j_1}(P) = (\dots \rightarrow P^{j_1-1} \rightarrow P^{j_1} \rightarrow 0 \rightarrow \dots)$$

for $j_1 \gg i$. Now P' is K-flat, so $P' \otimes_A L$ is acyclic. \square

Lemma 15.6.3. *There is an isomorphism*

$$\Phi : \text{RHom}_B(C, M) \otimes_A^L \text{RHom}_B(C, M) \xrightarrow{\cong} \text{RHom}_{B^{\text{en}}}(C^{\text{en}}, M \otimes_A^L M)$$

in $\mathbf{D}(C^{\text{en}})$ such that the diagram

$$\begin{array}{ccc} \text{RHom}_B(C, M) \otimes_A^L \text{RHom}_B(C, M) & & \\ \downarrow \Phi & \searrow \Phi' & \\ \text{RHom}_{B^{\text{en}}}(C^{\text{en}}, M \otimes_A^L M) & \xrightarrow{\Phi''} & M \otimes_A^L M \end{array}$$

in $\mathbf{D}(B^{\text{en}})$, with

$$\Phi' := \text{RHom}_u(u, \text{id}) \otimes_A^L \text{RHom}_u(u, \text{id})$$

and

$$\Phi'' := \text{RHom}_{u^{\text{en}}}(u^{\text{en}}, \text{id}),$$

is commutative.

Proof. Let us choose a K-projective commutative DG ring resolution $v : \tilde{C} \rightarrow C$ over B , such that each \tilde{C}^i is a finitely generated free B -module. This can be done by Theorem 15.5.16. Because of flatness, the DG ring homomorphism $v^{\text{en}} : \tilde{C}^{\text{en}} \rightarrow C^{\text{en}}$ is a quasi-isomorphism. According to Theorem 15.5.2 the restriction functor

$$\text{Rest}_{v^{\text{en}}} : \mathbf{D}(C^{\text{en}}) \rightarrow \mathbf{D}(\tilde{C}^{\text{en}})$$

is an equivalence. And by Corollary 15.5.9 the operations RHom and \otimes^L respect this restriction functor.

Let $P \rightarrow M$ be a resolution by a bounded complex P of B -modules that are flat over A . This can be done using truncation, and the fact that M has finite flat dimension over A . Because \tilde{C} is K-projective over C , there is an isomorphism

$$\text{RHom}_B(C, M) \cong \text{Hom}_B(\tilde{C}, P)$$

in $\mathbf{D}(\tilde{C})$. The complex $\text{Hom}_B(\tilde{C}, P)$ is bounded below, and consists of flat A -modules. Also, since $\text{Hom}_B(\tilde{C}, P) \cong N$, this has finite flat dimension over A . By Lemma 15.6.2 there is an isomorphism

$$(15.6.4) \quad \text{RHom}_B(C, M) \otimes_A^L \text{RHom}_B(C, M) \cong \text{Hom}_B(\tilde{C}, P) \otimes_A \text{Hom}_B(\tilde{C}, P)$$

in $\mathbf{D}(\tilde{C}^{\text{en}})$.

Similarly, because \tilde{C}^{en} is K-projective over C^{en} , there is an isomorphism

$$(15.6.5) \quad \text{RHom}_{B^{\text{en}}}(C^{\text{en}}, M \otimes_A^L M) \cong \text{Hom}_{B^{\text{en}}}(\tilde{C}^{\text{en}}, P \otimes_A P)$$

in $\mathbf{D}(\tilde{C}^{\text{en}})$.

The finiteness of \tilde{C} over B implies – as in the proof of Proposition 15.2.20 – that the canonical homomorphism

$$(15.6.6) \quad \mathrm{Hom}_B(\tilde{C}, P) \otimes_A \mathrm{Hom}_B(\tilde{C}, P) \rightarrow \mathrm{Hom}_{B^{\mathrm{en}}}(\tilde{C}^{\mathrm{en}}, P \otimes_A P)$$

is an isomorphism in $\mathbf{C}_{\mathrm{str}}(\tilde{C}^{\mathrm{en}})$.

The combination of (15.6.4), (15.6.5) and (15.6.6) gives us the isomorphism Φ . Since these isomorphisms commute with the homomorphisms to $P \otimes_A P$ it follows the diagram above is commutative, i.e. $\Phi'' \circ \Phi = \Phi'$. \square

Question 15.6.7. Is it really necessary to employ DG ring resolutions in the proof of this lemma?

Lemma 15.6.8. *Suppose*

$$\phi : \mathrm{Sq}_{C/A}(\mathrm{RCInd}_u(M)) \rightarrow \mathrm{RCInd}_u(\mathrm{Sq}_{B/A}(M))$$

is a morphism in $\mathbf{D}(C)$ such that the diagram

$$\begin{array}{ccc} \mathrm{Sq}_{C/A}(\mathrm{RCInd}_u(M)) & & \\ \downarrow \phi & \searrow \mathrm{Sq}_{u/A}(\mathrm{Tr}_{u,M}) & \\ \mathrm{RCInd}_u(\mathrm{Sq}_{B/A}(M)) & \xrightarrow{\mathrm{Tr}_{u, \mathrm{Sq}_{B/A}(M)}} & \mathrm{Sq}_{B/A}(M) \end{array}$$

in $\mathbf{D}(B)$ is commutative. Then

$$\phi = \mathrm{dbadj}_u(\mathrm{Sq}_{u/A}(\mathrm{Tr}_{u,M})).$$

Exercise 15.6.9. Prove Lemma 15.6.8. (Hint: it is easy, just a bit confusing.)

Proof of Theorem 15.6.1. Because the trace morphism $\theta : N \rightarrow M$ is nondegenerate, we can assume that

$$N = \mathrm{RCInd}_u(M) = \mathrm{RHom}_B(C, M)$$

and $\theta = \mathrm{Tr}_{u,M}$. The trace morphism

$$\mathrm{Sq}_{u/A}(\theta) : \mathrm{Sq}_{C/A}(N) \rightarrow \mathrm{Sq}_{B/A}(M)$$

in $\mathbf{D}(B)$ is nondegenerate iff the morphism

$$\mathrm{dbadj}_u(\mathrm{Sq}_{u/A}(\theta)) : \mathrm{Sq}_{C/A}(N) \rightarrow \mathrm{RCInd}_u(\mathrm{Sq}_{B/A}(M))$$

in $\mathbf{D}(C)$ is an isomorphism.

We have this sequence of isomorphisms in $\mathbf{D}(C)$:

$$\begin{aligned} (15.6.10) \quad \mathrm{Sq}_{C/A}(N) &= \mathrm{RHom}_{C^{\mathrm{en}}}(C, N \otimes_A^{\mathrm{L}} N) \\ &= \mathrm{RHom}_{C^{\mathrm{en}}}(C, \mathrm{RHom}_B(C, M) \otimes_A^{\mathrm{L}} \mathrm{RHom}_B(C, M)) \\ &\cong^{\diamond} \mathrm{RHom}_{C^{\mathrm{en}}}(C, \mathrm{RHom}_{B^{\mathrm{en}}}(C^{\mathrm{en}}, M \otimes_A^{\mathrm{L}} M)) \\ &\cong^{\dagger} \mathrm{RHom}_{B^{\mathrm{en}}}(C, M \otimes_A^{\mathrm{L}} M) \\ &\cong^{\ddagger} \mathrm{RHom}_B(C, \mathrm{RHom}_{B^{\mathrm{en}}}(B, M \otimes_A^{\mathrm{L}} M)) \\ &= \mathrm{RCInd}_u(\mathrm{Sq}_{B/A} M). \end{aligned}$$

The isomorphism marked \diamond is $\mathrm{RHom}_{C^{\mathrm{en}}}(C, \Phi)$, where Φ is the isomorphism from Lemma 15.6.3. The isomorphism \dagger comes from the Hom-tensor adjunction formula, applied to the ring homomorphisms $B^{\mathrm{en}} \rightarrow C^{\mathrm{en}} \rightarrow C$. And the isomorphism

‡ comes from the Hom-tensor adjunction formula, applied to the ring homomorphisms $B^{\text{en}} \rightarrow B \rightarrow C$. All objects appearing in (15.6.10) admit obvious morphisms to $\text{Sq}_{B/A}(M)$ in $\mathbf{D}(B)$, the all the isomorphisms in (15.6.10) respect them. Therefore, by Lemma 15.6.8, the composition of the isomorphisms in (15.6.10) equals $\text{dbadj}_u(\text{Sq}_{u/A}(\text{Tr}_{u,M}))$. \square

Theorem 15.6.11 (Coinduced Rigidity for Finite Homomorphisms). *Let $u : B \rightarrow C$ be a homomorphism of A -rings, and let $(M, \rho) \in \mathbf{D}(B)_{\text{rig}/A}$. Define*

$$N := \text{RHom}_B(C, M) \in \mathbf{D}(C).$$

Assume these conditions hold:

- *The complexes M and N have finite flat dimensions over A .*
- *The ring B is noetherian, and the ring homomorphism $B \rightarrow C$ is finite.*

Then the complex N has a unique rigidifying isomorphism

$$\sigma : N \xrightarrow{\cong} \text{Sq}_{C/A}(N)$$

in $\mathbf{D}(C)$, such that the nondegenerate trace morphism

$$\text{Tr}_{u,M} : N \rightarrow M$$

in $\mathbf{D}(B)$ over u becomes a rigid trace morphism

$$\text{Tr}_{u,M} : (N, \sigma) \rightarrow (M, \rho)$$

over u relative to A .

Proof. Consider the solid diagram below:

$$(15.6.12) \quad \begin{array}{ccc} N & \xrightarrow{\sigma} & \text{Sq}_{C/A}(N) \\ \theta \downarrow & & \downarrow \text{Sq}_{u/A}(\theta) \\ M & \xrightarrow{\rho} & \text{Sq}_{B/A}(M) \end{array}$$

in $\mathbf{D}(B)$, where $\theta := \text{Tr}_{u,M}$. We are looking for an isomorphism σ in $\mathbf{D}(C)$ that will make (15.6.12) into a commutative diagram.

Let us apply the functor RCInd_u to the bottom row of (15.6.12). There is a functorial morphism dbadj_u going down, so we get this solid diagram in $\mathbf{D}(C)$:

$$(15.6.13) \quad \begin{array}{ccc} N & \xrightarrow{\sigma} & \text{Sq}_{C/A}(N) \\ \text{id}_N \downarrow \cong & & \downarrow \text{dbadj}_u(\text{Sq}_{u/A}(\theta)) \\ \text{RCInd}_u(M) & \xrightarrow[\cong]{\text{RCInd}_u(\rho)} & \text{RCInd}_u(\text{Sq}_{B/A}(M)) \end{array}$$

Here we used the equality $\text{dbadj}_u(\theta) = \text{id}_N$. The morphism $\text{Sq}_{u/A}(\theta)$ is nondegenerate by Theorem 15.6.1, and thus $\text{dbadj}_u(\text{Sq}_{u/A}(\theta))$ is an isomorphism. It follows that there is a unique isomorphism σ in $\mathbf{D}(C)$ that makes diagram (15.6.13) commutative. By backward adjunction, the σ is the unique morphism $N \rightarrow \text{Sq}_{C/A}(N)$ in $\mathbf{D}(C)$ that makes diagram (15.6.12) in $\mathbf{D}(B)$ commutative. \square

We now move to localization homomorphisms.

Theorem 15.6.14. *Let $v : B \rightarrow B'$ be a localization homomorphism of A -rings, and let $\lambda : M \rightarrow M'$ be a nondegenerate localization morphism over v . Assume that the next conditions hold:*

- *The complex M has finite flat dimension over A .*
- *The ring $B^{\text{en}} = B \otimes_A B$ is noetherian.*

Then the localization morphism

$$\text{Sq}_{v/A}(\lambda) : \text{Sq}_{B/A}(M) \rightarrow \text{Sq}_{B'/A}(M')$$

in $\mathbf{D}(B)$ over v is nondegenerate .

Proof. We need to show that the morphism

$$(15.6.15) \quad \text{dfadj}_v(\text{Sq}_{v/A}(\lambda)) : B' \otimes_B \text{Sq}_{B/A}(M) \rightarrow \text{Sq}_{B'/A}(M')$$

in $\mathbf{D}(B')$ is an isomorphism. Recall that

$$\text{Sq}_{B/A}(M) = \text{RHom}_{B^{\text{en}}}(B, M \otimes_A^{\mathbf{L}} M)$$

and

$$\text{Sq}_{B'/A}(M') = \text{RHom}_{B'^{\text{en}}}(B', M' \otimes_A^{\mathbf{L}} M').$$

We begin by examining the following morphism:

$$(15.6.16) \quad \Psi : \text{RHom}_{B^{\text{en}}}(B, M \otimes_A^{\mathbf{L}} M) \otimes_{B^{\text{en}}} B'^{\text{en}} \rightarrow \text{RHom}_{B'^{\text{en}}}(B', M' \otimes_A^{\mathbf{L}} M')$$

in $\mathbf{D}(B)$. Recall that the B structure on the objects comes from the action on the first arguments (B and B' respectively) of RHom . It is a tensor-evaluation morphism, of the sort studied in Proposition 15.2.20. The assumption on M ensures that the complex $M \otimes_A^{\mathbf{L}} M$ has bounded cohomology. Clearly $B \in \mathbf{D}_f^-(B^{\text{en}})$, and B'^{en} has finite flat dimension over B^{en} . Hence, by Proposition 15.2.20, the morphism (15.6.16) is an isomorphism.

Because $B' \otimes_B B' = B'$, if we apply $B' \otimes_B (-) = \text{LInd}_v$ to (15.6.16) it remains an isomorphism, but now in $\mathbf{D}(B')$. We obtain a commutative diagram

$$(15.6.17) \quad \begin{array}{ccc} B' \otimes_B \text{Sq}_{B/A}(M) & & \\ \downarrow & \searrow \text{dfadj}_v(\text{Sq}_{v/A}(\lambda)) & \\ B' \otimes_B \text{Sq}_{B/A}(M) \otimes_{B^{\text{en}}} B'^{\text{en}} & \xrightarrow[\cong]{B' \otimes_B \Psi} & \text{Sq}_{B'/A}(M') \end{array}$$

It remains to prove that the vertical morphism in (15.6.17) is an isomorphism. For that we use Lemma 15.1.7 – it tells us that

$$B' \otimes_B \text{Sq}_{B/A}(M) \otimes_{B^{\text{en}}} B'^{\text{en}} \cong B' \otimes_B B' \otimes_B B' \otimes_B \text{Sq}_{B/A}(M)$$

in $\mathbf{D}(B')$. But $B' \otimes_B B' \otimes_B B' = B'$. □

Theorem 15.6.18 (Induced Rigidity for Localization Homomorphisms). *Let $v : B \rightarrow B'$ be a localization homomorphism of A -rings, and let $(M, \rho) \in \mathbf{D}(B)_{\text{rig}/A}$. Define*

$$M' := B' \otimes_B M \in \mathbf{D}(B').$$

Assume these conditions hold:

- *The complex M has finite flat dimension over A .*
- *The ring $B^{\text{en}} = B \otimes_A B$ is noetherian.*

Then the complex M' has a unique rigidifying isomorphism

$$\rho' : M' \xrightarrow{\cong} \mathrm{Sq}_{B'/A}(M')$$

in $\mathbf{D}(B')$, such that the nondegenerate localization morphism

$$q_{v,M} : M \rightarrow M'$$

in $\mathbf{D}(B)$ over v becomes a rigid localization morphism

$$q_{v,M} : (M, \rho) \rightarrow (M', \rho')$$

over v relative to A .

Exercise 15.6.19. Prove Theorem 15.6.18. (Hint: modify the proof of Theorem 15.6.11, using Theorem 15.6.14 instead of Theorem 15.6.1 of course.)

The last theorem in this subsection says that coinduced rigidity respects “localization base change”. Here is the setup:

Setup 15.6.20. We are given a commutative diagram of homomorphisms of A -rings

$$\begin{array}{ccc} B & \xrightarrow{u} & C \\ v \downarrow & & \downarrow w \\ B' & \xrightarrow{u'} & C' \end{array}$$

such that

$$u' \otimes_B w : B' \otimes_B C \rightarrow C'$$

is an isomorphism (i.e. the diagram is cocartesian). We are also given a rigid complex

$$(M, \rho) \in \mathbf{D}(B)_{\mathrm{rig}/A}.$$

Based on this input we define these complexes:

- ▷ $N := \mathrm{RHom}_B(C, M) \in \mathbf{D}(C)$.
- ▷ $M' := B' \otimes_B M \in \mathbf{D}(B')$.
- ▷ $N' := C' \otimes_C N \in \mathbf{D}(C')$.

We are given this further information:

- The ring homomorphism u is finite.
- The ring homomorphism v is a localization.
- The rings B and B^{en} are noetherian.
- The complexes M and N have finite flat dimensions over A .

It is easy to see that the homomorphism u' is finite, and the homomorphism w is a localization.

Lemma 15.6.21. *There is a unique isomorphism*

$$N' \cong \mathrm{RHom}_{B'}(C', M')$$

in $\mathbf{D}(C')$, that makes the diagram

$$\begin{array}{ccc} M & \xleftarrow{\mathrm{Tr}_{u,M}} & N \\ q_{v,M} \downarrow & & \downarrow q_{w,N} \\ M' & \xleftarrow{\mathrm{Tr}_{u',M'}} & N' \end{array}$$

in $\mathbf{D}(B)$ commutative.

Exercise 15.6.22. Prove Lemma 15.6.21.

Theorem 15.6.23 (Compatibility of Coinduced and Induced Rigidity). *Consider Setup 15.6.20. Let*

$$\sigma : N \xrightarrow{\cong} \mathrm{Sq}_{C/A}(N)$$

and

$$\rho' : M' \xrightarrow{\cong} \mathrm{Sq}_{B'/A}(M')$$

be the coinduced and induced rigidifying isomorphisms from Theorems 15.6.11 and 15.6.18 respectively. There is a unique rigidifying isomorphism

$$\sigma' : N' \xrightarrow{\cong} \mathrm{Sq}_{C'/A}(N')$$

in $\mathbf{D}(C')$, such that in the diagram

$$\begin{array}{ccc} (M, \rho) & \xleftarrow{\mathrm{Tr}_{u,M}} & (N, \sigma) \\ \mathrm{q}_{v,M} \downarrow & & \downarrow \mathrm{q}_{w,N} \\ (M', \rho') & \xleftarrow{\mathrm{Tr}_{u',M'}} & (N', \sigma') \end{array}$$

the morphism $\mathrm{Tr}_{u',M'}$ is a nondegenerate rigid trace morphism relative to A , and the morphism $\mathrm{q}_{w,N}$ is a nondegenerate rigid localization morphism relative to A .

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Proof. Let's write $\theta := \mathrm{Tr}_{u,M}$, $\theta' := \mathrm{Tr}_{u',M'}$, $\lambda := \mathrm{q}_{v,M}$ and $\mu := \mathrm{q}_{w,n}$. Define

$$\sigma' : N' \xrightarrow{\cong} \mathrm{Sq}_{C'/A}(N')$$

to be the rigidifying isomorphism induced from

$$\sigma : N \xrightarrow{\cong} \mathrm{Sq}_{C/A}(N),$$

as in Theorem 15.6.18. Consider the following cube diagram in $\mathbf{D}(B)$, where we omit subscripts from the $\mathrm{Sq}_{-/-}(-)$ to reduce clutter.

$$\begin{array}{ccccc} M & \xleftarrow{\theta} & N & & \\ \lambda \downarrow & \searrow \rho & \downarrow \mu & \searrow \sigma & \\ M' & \xleftarrow{\theta'} & N' & \xrightarrow{\mathrm{Sq}(\theta)} & \mathrm{Sq}(N) \\ & \searrow \rho' & \downarrow \sigma' & \searrow \mathrm{Sq}(\lambda) & \downarrow \mathrm{Sq}(\mu) \\ & & \mathrm{Sq}(M') & \xrightarrow{\mathrm{Sq}(\theta')} & \mathrm{Sq}(N') \end{array}$$

The top face is commutative because θ is a rigid trace morphism. The rear vertical face is commutative by Lemma 15.6.21. The left and right vertical faces are commutative because λ and μ are rigid localization morphisms. The front vertical face is commutative due to Theorem 15.3.16. All four vertical morphisms are nondegenerate localization morphisms: λ and μ are so by definition; and $\text{Sq}(\lambda)$ and $\text{Sq}(\mu)$ are so by Theorem 15.6.14. Therefore, by forward adjunction, the bottom face is isomorphic to the square diagram gotten by applying LInd_v to the top face. We conclude that the bottom face is also a commutative diagram. This says that

$$\theta' : (N', \sigma') \rightarrow (M', \rho')$$

is a rigid trace morphism. We already know that θ' is a nondegenerate trace morphism. \square

Remark 15.6.24. The results in Subsections 15.3, 15.4 and 15.6 on localization homomorphisms are actually true (with some subtle changes) for *essentially étale homomorphisms*. The proofs are much harder. They will be included in the paper [Ye13]. See an outline in the lecture notes [Ye12].

16. RIGID DUALIZING COMPLEXES OVER COMMUTATIVE RINGS

In section we combine the material on dualizing complexes from Section 14 with the material on rigid complexes from Section 15.

16.1. Rigid Dualizing Complexes. Essentially finitely type (EFT) ring homomorphisms were introduced in Definition 14.2.17.

Definition 16.1.1. For a noetherian commutative ring \mathbb{K} we denote by $\text{Ring}/_{\text{feft}} \mathbb{K}$ the category whose objects are the flat essentially finite type (FEFT) commutative \mathbb{K} -rings. The morphisms in $\text{Ring}/_{\text{feft}} \mathbb{K}$ are the \mathbb{K} -ring homomorphisms $A \rightarrow B$ (these are not required to be flat).

Here there is a more restrictive setup than Setup 15.3.1:

Setup 16.1.2. We fix a regular noetherian commutative base ring \mathbb{K} . The rings A, B, C, A', B', A'' , and the homomorphisms between them, are in $\text{Ring}/_{\text{feft}} \mathbb{K}$.

Recall the special meaning of “regular ring” in this book – see Convention 14.2.10. It is easy to see that all rings in $\text{Ring}/_{\text{feft}} \mathbb{K}$ are noetherian and have finite Krull dimensions; and all homomorphisms $A \rightarrow B$ in $\text{Ring}/_{\text{feft}} \mathbb{K}$ are essentially finite type.

Because \mathbb{K} is regular, any complex $M \in \mathbf{D}^b(\mathbb{K})$ automatically has finite flat dimension over. In particular this is true for dualizing complexes over any ring $A \in \text{Ring}/_{\text{feft}} \mathbb{K}$.

In Subsection 16.3 we will require the base ring \mathbb{K} to be a field, for technical reasons.

Definition 16.1.3. A *rigid dualizing complex over A relative to \mathbb{K}* is a rigid complex (R, ρ) over A relative to \mathbb{K} , as in Definition 15.1.18, such that R is a dualizing complex over A , in the sense of Definition 14.2.9.

The category of rigid complexes over A relative to \mathbb{K} is denoted by $\mathbf{D}(A)_{\text{rig}/\mathbb{K}}$. See Definition 15.1.19.

Theorem 16.1.4. *Let A be a flat essentially finite type ring over the regular noetherian ring \mathbb{K} . Then A has a rigid dualizing complex (R_A, ρ_A) , and it is unique up to a unique isomorphism in $\mathbf{D}(A)_{\text{rig}/\mathbb{K}}$.*

Proof. We first prove existence. As in the proof of Theorem 14.2.33, we factor the ring homomorphism $\mathbb{K} \rightarrow A$ into $\mathbb{K} \rightarrow A_{\text{pl}} \rightarrow A_{\text{ft}} \rightarrow A$, where $A_{\text{pl}} = \mathbb{K}[t_1, \dots, t_n]$ is a polynomial ring, $A_{\text{pl}} \rightarrow A_{\text{ft}}$ is surjective, and $A_{\text{ft}} \rightarrow A$ is a localization.

According to Exercise 15.1.22, the ring A_{pl} has a rigid complex $(R_{\text{pl}}, \rho_{\text{pl}})$ relative to \mathbb{K} , where $R_{\text{pl}} = A_{\text{pl}}[n]$. Since A_{pl} is a regular ring, $(R_{\text{pl}}, \rho_{\text{pl}})$ is a rigid dualizing complex.

Let

$$R_{\text{ft}} := \text{RHom}_{A_{\text{pl}}}(A_{\text{ft}}, R_{\text{pl}}) \in \mathbf{D}(A_{\text{ft}}).$$

This is a dualizing complex over A_{ft} ; and by Theorem 15.6.11 it has a coinduced rigidifying isomorphism ρ_{ft} . Thus $(R_{\text{ft}}, \rho_{\text{ft}})$ is a rigid dualizing complex over A_{ft} relative to \mathbb{K} .

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Finally let

$$R_A := A \otimes_{A_{\text{ft}}} R_{\text{ft}} \in \mathbf{D}(A).$$

This is a dualizing complex over A . According to Theorem 15.6.18 it has an induced rigidifying isomorphism ρ_A . Thus (R_A, ρ_A) is a rigid dualizing complex over A relative to \mathbb{K} .

Now let us prove uniqueness. Suppose (R', ρ') is another rigid dualizing complex over A relative to \mathbb{K} . Let $A = \prod_{i=1}^r A_i$ be the connected component decomposition of A . Corollary 14.2.53 says that

$$R' \cong R \otimes_A^L P,$$

where $P \cong \bigoplus_{i=1}^r L_i[n_i]$ for integers n_i and rank 1 projective A_i -modules L_i . Let's write $A^{\text{en}} := A \otimes_{\mathbb{K}} A$. There is an isomorphism

$$(16.1.5) \quad R' \otimes_{\mathbb{K}}^L R' = (R \otimes_A^L P) \otimes_{\mathbb{K}}^L (R \otimes_A^L P) \cong (R \otimes_{\mathbb{K}}^L R) \otimes_{A^{\text{en}}}^L (P \otimes_{\mathbb{K}}^L P)$$

in $\mathbf{D}(A^{\text{en}})$, and $P \otimes_{\mathbb{K}}^L P$ has finite flat dimension over A^{en} . So we have this sequence of isomorphisms in $\mathbf{D}(A)$:

$$(16.1.6) \quad \begin{aligned} R \otimes_A^L P &\cong R' \cong \text{Sq}_{A/\mathbb{K}}(R') = \text{RHom}_{A^{\text{en}}}(A, R' \otimes_{\mathbb{K}}^L R') \\ &\cong^{\diamond} \text{RHom}_{A^{\text{en}}}(A, (R \otimes_{\mathbb{K}}^L R) \otimes_{A^{\text{en}}}^L (P \otimes_{\mathbb{K}}^L P)) \\ &\cong^{\dagger} \text{RHom}_{A^{\text{en}}}(A, R \otimes_{\mathbb{K}}^L R) \otimes_{A^{\text{en}}}^L (P \otimes_{\mathbb{K}}^L P) \\ &= \text{Sq}_{A/\mathbb{K}}(R) \otimes_{A^{\text{en}}}^L (P \otimes_{\mathbb{K}}^L P) \\ &\cong R \otimes_{A^{\text{en}}}^L (P \otimes_{\mathbb{K}}^L P) \cong R \otimes_A^L P \otimes_A^L P. \end{aligned}$$

The isomorphism \cong^{\diamond} is by (16.1.5), and the isomorphism \cong^{\dagger} is by Proposition 15.2.20. We also used the rigidifying isomorphisms of R and R' . Now

$$\text{RHom}_A(R, R \otimes_A^L P) \cong \text{RHom}_A(R, R) \otimes_A^L P \cong P,$$

again using Proposition 15.2.20, and by the derived Morita property of R . Likewise

$$\text{RHom}_A(R, R \otimes_A^L P \otimes_A^L P) \cong P \otimes_A^L P.$$

Thus, together with (16.1.6), we deduce that $P \otimes_A^L P \cong P$. But then on each connected component A_i we have

$$L_i[n_i] \cong L_i[n_i] \otimes_A L_i[n_i] = (L_i \otimes_A L_i)[2 \cdot n_i].$$

This implies that $L_i \cong A_i$ and $n_i = 0$. We see that actually $P \cong A$, so there is an isomorphism $\phi^{\diamond} : R \xrightarrow{\cong} R'$ in $\mathbf{D}(A)$.

The isomorphism ϕ^{\diamond} might not be rigid; but due to the derived Morita property, there is an invertible element $a \in A$ such that

$$\text{Sq}_{A/\mathbb{K}}(\phi^{\diamond}) \circ \rho_A = a \cdot \rho' \circ \phi^{\diamond}$$

as isomorphisms $R \xrightarrow{\cong} R'$. Define $\phi := a^{-1} \cdot \phi^{\diamond}$. Then, according to Theorem 15.1.16, we have

$$\text{Sq}_{A/\mathbb{K}}(\phi) \circ \rho_A = a^{-2} \cdot \text{Sq}_{A/\mathbb{K}}(\phi^{\diamond}) \circ \rho_A = a^{-2} \cdot a \cdot \rho' \circ \phi^{\diamond} = \rho' \circ \phi.$$

We see that

$$\phi : (R_A, \rho_A) \xrightarrow{\cong} (R', \rho')$$

is a rigid isomorphism. Its uniqueness is already known. \square

Theorem 16.1.7. *Let $u : A \rightarrow B$ be a finite homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. There is a unique nondegenerate rigid trace morphism*

$$\text{Tr}_{u/\mathbb{K}} = \text{Tr}_{B/A/\mathbb{K}} : (R_B, \rho_B) \rightarrow (R_A, \rho_A)$$

in $\mathbf{D}(A)$ over u relative to \mathbb{K} .

Proof. According to Theorem 15.4.3 there is at most one such morphism.

Let us prove existence. Consider the complex $N := \text{RHom}_A(B, R_A) \in \mathbf{D}(B)$. This is a dualizing complex by Proposition 14.2.31. On the other hand, by Theorem 15.6.11 the complex N has a rigidifying isomorphism σ , such that

$$\text{Tr}_{u, R_A} : (N, \sigma) \rightarrow (R_A, \rho_A)$$

is a nondegenerate rigid trace morphism. But by the uniqueness in Theorem 16.1.4, there is an isomorphism

$$(N, \sigma) \cong (R_B, \rho_B)$$

in $\mathbf{D}(B)_{\text{rig}/\mathbb{K}}$. □

Definition 16.1.8. Let $u : A \rightarrow B$ be a finite homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$, and let R_A and R_B be the respective rigid dualizing complexes. The morphism

$$\text{Tr}_{u/\mathbb{K}} = \text{Tr}_{B/A/\mathbb{K}} : R_B \rightarrow R_A$$

in $\mathbf{D}(A)$ from Theorem 16.1.7 is called the *rigid trace over u* .

In the definition above we are hiding the rigidifying isomorphisms ρ_A and ρ_B . But of course without them we can't make any sense of “the respective rigid dualizing complexes”.

Corollary 16.1.9. *Let $u : A \rightarrow B$ and $v : B \rightarrow C$ be finite homomorphisms in $\text{Ring}/_{\text{feft}} \mathbb{K}$. The rigid traces satisfy*

$$\text{Tr}_{u/\mathbb{K}} \circ \text{Tr}_{v/\mathbb{K}} = \text{Tr}_{v \circ u/\mathbb{K}}$$

as morphisms $R_C \rightarrow R_A$ in $\mathbf{D}(A)$.

Proof. Both are nondegenerate rigid trace morphisms

$$(R_C, \rho_C) \rightarrow (R_A, \rho_A).$$

□

Theorem 16.1.10. *Let $v : A \rightarrow A'$ be a localization homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. There is a unique nondegenerate rigid localization morphism*

$$\mathfrak{q}_{v/\mathbb{K}} = \mathfrak{q}_{A'/A/\mathbb{K}} : (R_A, \rho_A) \rightarrow (R_{A'}, \rho_{A'})$$

in $\mathbf{D}(A)$ over v relative to \mathbb{K} .

Proof. According to Theorem 15.4.7 there is at most one such morphism.

Let us prove existence. Consider the complex $M' := A' \otimes_A R_A \in \mathbf{D}(A')$. This is a dualizing complex by Proposition 14.2.32. On the other hand, by Theorem 15.6.18 the complex M' has a rigidifying isomorphism ρ' , such that

$$\mathfrak{q}_{v, R_A} : (R_A, \rho_A) \rightarrow (M', \rho')$$

is a nondegenerate rigid localization morphism. By the uniqueness in Theorem 16.1.4, there is an isomorphism

$$(M', \rho') \cong (R_{A'}, \rho_{A'})$$

in $\mathbf{D}(A')_{\text{rig}/\mathbb{K}}$. □

Definition 16.1.11. Let $v : A \rightarrow A'$ be a localization homomorphism in $\text{Ring}/_{\text{left}} \mathbb{K}$, and let R_A and $R_{A'}$ be the respective rigid dualizing complexes. The morphism

$$q_{v/\mathbb{K}} = q_{A'/A/\mathbb{K}} : R_A \rightarrow R_{A'}$$

in $\mathbf{D}(A)$ from Theorem 16.1.10 is called the *rigid localization over v* .

Again, in the definition above we are hiding the rigidifying isomorphisms ρ_A and $\rho_{A'}$.

Corollary 16.1.12. Let $v : A \rightarrow A'$ and $v' : A' \rightarrow A''$ be localization homomorphisms in $\text{Ring}/_{\text{left}} \mathbb{K}$. The rigid localizations satisfy

$$q_{v'/\mathbb{K}} \circ q_{v/\mathbb{K}} = q_{v' \circ v/\mathbb{K}}$$

as morphisms $R_A \rightarrow R_{A''}$ in $\mathbf{D}(A)$.

Proof. Both are nondegenerate rigid localization morphisms

$$(R_A, \rho_A) \rightarrow (R_{A''}, \rho_{A''}).$$

□

Theorem 16.1.13 (Base Change for the Rigid Trace). *We are given a commutative diagram*

$$\begin{array}{ccc} A & \xrightarrow{u} & B \\ v \downarrow & & \downarrow w \\ A' & \xrightarrow{u'} & B' \end{array}$$

in $\text{Ring}/_{\text{left}} \mathbb{K}$, in which u is finite, v is a localization, and

$$u' \otimes_A w : A' \otimes_A B \rightarrow B'$$

is an isomorphism (i.e. the diagram is cocartesian). Then the diagram

$$\begin{array}{ccc} R_A & \xleftarrow{\text{Tr}_{u/\mathbb{K}}} & R_B \\ q_{v/\mathbb{K}} \downarrow & & \downarrow q_{w/\mathbb{K}} \\ R_{A'} & \xleftarrow{\text{Tr}_{u'/\mathbb{K}}} & R_{B'} \end{array}$$

in $\mathbf{D}(A)$, in which the horizontal arrows are the rigid traces, and the vertical arrows are the rigid localizations, is commutative.

Proof. Define $M' := A' \otimes_A R_A$, and give it the rigidifying isomorphism ρ' induced from ρ_A . Then define $N' := B' \otimes_B R_B$. By Lemma 15.6.21 there is an isomorphism $N' \cong \text{RHom}_{A'}(B', M')$. And by Theorem 15.6.23 the complex N' has a rigidifying isomorphism σ' such that the diagram

$$\begin{array}{ccc} (R_A, \rho_A) & \xleftarrow{\text{Tr}_{u/\mathbb{K}}} & (R_B, \rho_B) \\ q_{v, R_A} \downarrow & & \downarrow q_{w, R_B} \\ (M', \rho') & \xleftarrow{\text{Tr}_{u', M'}} & (N', \sigma') \end{array}$$

is commutative, the morphism $\text{Tr}_{u',M'}$ is a nondegenerate rigid trace morphism relative to \mathbb{K} , and the morphism q_{w,R_B} is a nondegenerate rigid localization morphism relative to \mathbb{K} .

Now N' is a dualizing complex over B' . This means that (N, σ') is a rigid dualizing complex over B' relative to \mathbb{K} . By Theorem 16.1.4 there is an isomorphism

$$\psi : (N', \sigma') \xrightarrow{\cong} (R_{B'}, \rho_{B'})$$

in $\mathbf{D}(B')_{\text{rig}/\mathbb{K}}$. Similarly there is an isomorphism

$$\phi : (M', \rho') \xrightarrow{\cong} (R_{A'}, \rho_{A'})$$

in $\mathbf{D}(A')_{\text{rig}/\mathbb{K}}$. Let's examine the next commutative diagram, in which the dashed arrows are the unique ones that fit.

$$\begin{array}{ccc}
 (R_A, \rho_A) & \xleftarrow{\text{Tr}_{u/\mathbb{K}}} & (R_B, \rho_B) \\
 \downarrow q_{v,R_A} & & \downarrow q_{w,R_B} \\
 (M', \rho') & \xleftarrow{\text{Tr}_{u',M'}} & (N', \sigma') \\
 \downarrow \phi \cong & & \downarrow \cong \psi \\
 (R_{A'}, \rho_{A'}) & \xleftarrow{\quad\quad\quad} & (R_{B'}, \rho_{B'})
 \end{array}$$

The dashed arrow leaving (R_B, ρ_B) is a nondegenerate rigid localization morphism, so by Theorem 16.1.10 it must be $q_{w/\mathbb{K}}$. Similarly, the dashed arrow leaving (R_A, ρ_A) must be $q_{v/\mathbb{K}}$. The dashed arrow leaving $(R_{B'}, \rho_{B'})$ is a nondegenerate rigid trace morphism, so by Theorem 16.1.7 it must be $\text{Tr}_{u/\mathbb{K}}$. \square

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16.2. Rigid Residue Complexes. We begin this subsection with the assumptions of Setup 16.1.2. This means that \mathbb{K} is a regular noetherian ring, and all other rings are in the category $\mathbf{Ring}/_{\text{left}} \mathbb{K}$.

Residue complexes were introduced in Subsection 14.4.

Definition 16.2.1. A *rigid residue complex* over A relative to \mathbb{K} is a rigid complex (\mathcal{K}_A, ρ_A) over A relative to \mathbb{K} , such that \mathcal{K}_A is a residue complex over A .

In Definition 15.1.19 we introduced the category $\mathbf{D}(A)_{\text{rig}/\mathbb{K}}$. Recall that the objects of $\mathbf{D}(A)_{\text{rig}/\mathbb{K}}$ are rigid complexes (M, ρ) over A relative to \mathbb{K} ; and the morphisms

$$\phi : (M, \rho) \rightarrow (N, \sigma)$$

are the morphisms $\phi : M \rightarrow N$ in $\mathbf{D}(A)$ for which there is equality

$$\sigma \circ \phi = \text{Sq}_{A/\mathbb{K}}(\phi) \circ \rho.$$

Rigid residue complexes live, or rather move, in another category.

Definition 16.2.2. The category $\mathbf{C}(A)_{\text{rig}/\mathbb{K}}$ is defined as follows. Its objects are the rigid complexes (M, ρ) over A relative to \mathbb{K} . Given two objects (M, ρ) and (N, σ) , a morphism

$$\phi : (M, \rho) \rightarrow (N, \sigma)$$

in $\mathbf{C}(A)_{\text{rig}/\mathbb{K}}$ is a morphism $\phi : M \rightarrow N$ in $\mathbf{C}_{\text{str}}(A)$, such that the diagram

$$\begin{array}{ccc} M & \xrightarrow[\cong]{\rho} & \text{Sq}_{A/\mathbb{K}}(M) \\ \text{Q}(\phi) \downarrow & & \downarrow \text{Sq}_{A/\mathbb{K}}(\text{Q}(\phi)) \\ N & \xrightarrow[\cong]{\sigma} & \text{Sq}_{A/\mathbb{K}}(N) \end{array}$$

in $\mathbf{D}(A)$ is commutative.

Let us emphasize the hybrid nature of the category $\mathbf{C}(A)_{\text{rig}/\mathbb{K}}$: the morphisms are homomorphisms of complexes (literally degree 0 homomorphisms graded A -modules $\phi : M \rightarrow N$ that commute with the differentials); but they must satisfy a compatibility condition (rigidity) in the derived category.

Theorem 16.2.3. *Let A be an FEFT ring over the regular noetherian ring \mathbb{K} . The ring A has a rigid residue complex (\mathcal{K}_A, ρ_A) relative to \mathbb{K} , and it is unique, up to a unique isomorphism in $\mathbf{C}(A)_{\text{rig}/\mathbb{K}}$.*

Proof. Existence: by Theorem 16.1.4 there is a rigid dualizing complex (R_A, ρ_A) over A/\mathbb{K} . Let \mathcal{K}_A be the minimal injective resolution of the complex R_A . According to Theorem 14.4.17, \mathcal{K}_A is a residue complex. It inherits the rigidifying isomorphism ρ_A from R_A . So the pair (\mathcal{K}_A, ρ_A) is a residue complex over A/\mathbb{K} .

Uniqueness: suppose (\mathcal{K}', ρ') is another residue complex over A/\mathbb{K} . Theorem 16.1.4 tells us that there is a unique isomorphism

$$\phi : (\mathcal{K}_A, \rho_A) \xrightarrow{\sim} (\mathcal{K}', \rho')$$

in $\mathbf{D}(A)_{\text{rig}/\mathbb{K}}$. But by Theorem 14.4.15 the function

$$\text{Q} : \text{Hom}_{\mathbf{C}(A)_{\text{rig}/\mathbb{K}}}((\mathcal{K}_A, \rho_A), (\mathcal{K}', \rho')) \rightarrow \text{Hom}_{\mathbf{D}(A)_{\text{rig}/\mathbb{K}}}((\mathcal{K}_A, \rho_A), (\mathcal{K}', \rho'))$$

is bijective. □

Lemma 16.2.4. *Let $u : A \rightarrow B$ be a finite homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. There is a unique homomorphism*

$$\text{Tr}_{u/\mathbb{K}} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

in $\mathbf{C}_{\text{str}}(A)$, such that

$$\mathbb{Q}(\text{Tr}_{u/\mathbb{K}}) : (\mathcal{K}_B, \rho_B) \rightarrow (\mathcal{K}_A, \rho_A)$$

is the nondegenerate rigid trace morphism in $\mathbf{D}(A)$ over u from Definition 16.1.8.

Proof. Since

$$\mathcal{K}_B \cong \text{Hom}_A(B, \mathcal{K}_B) = \text{CInd}_u(\mathcal{K}_A) \cong \text{RCInd}_u(\mathcal{K}_A)$$

in $\mathbf{C}_{\text{str}}(B)$, backward adjunction says that

$$\text{Hom}_{\mathbf{C}_{\text{str}}(A)}(\mathcal{K}_B, \mathcal{K}_A) \cong \text{Hom}_{\mathbf{C}_{\text{str}}(B)}(\mathcal{K}_B, \text{CInd}_u(\mathcal{K}_A)).$$

As in the proof of Theorem 16.2.3, there is an isomorphism

$$\mathbb{Q} : \text{Hom}_{\mathbf{C}_{\text{str}}(B)}(\mathcal{K}_B, \text{CInd}_u(\mathcal{K}_A)) \cong \text{Hom}_{\mathbf{D}(B)}(\mathcal{K}_B, \text{RCInd}_u(\mathcal{K}_A)).$$

Finally, by derived backward adjunction there is an isomorphism

$$\text{Hom}_{\mathbf{D}(A)}(\mathcal{K}_B, \mathcal{K}_A) \cong \text{Hom}_{\mathbf{D}(B)}(\mathcal{K}_B, \text{CInd}_u(\mathcal{K}_A)).$$

The homomorphism $\text{Tr}_{u/\mathbb{K}}$ that we are looking for is the one that is sent to nondegenerate rigid trace morphism in $\mathbf{D}(A)$ from Definition 16.1.8. \square

Definition 16.2.5. Let $u : A \rightarrow B$ be a finite homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. The homomorphism

$$\text{Tr}_{u/\mathbb{K}} = \text{Tr}_{B/A/\mathbb{K}} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

in $\mathbf{C}_{\text{str}}(A)$ from Lemma 16.2.4 is called the *rigid trace homomorphism in $\mathbf{C}_{\text{str}}(A)$ over u* .

Lemma 16.2.6. *Let $v : A \rightarrow A'$ be a localization homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. There is a unique homomorphism*

$$\mathbb{q}_{v/\mathbb{K}} : \mathcal{K}_A \rightarrow \mathcal{K}_{A'}$$

in $\mathbf{C}_{\text{str}}(A)$, such that

$$\mathbb{Q}(\mathbb{q}_{v/\mathbb{K}}) : (\mathcal{K}_A, \rho_A) \rightarrow (\mathcal{K}_{A'}, \rho_{A'})$$

is the nondegenerate rigid localization morphism in $\mathbf{D}(A)$ over v from Definition 16.1.11.

Exercise 16.2.7. Prove Lemma 16.2.6. (Hint: like the proof of Lemma 16.2.4, but using forward adjunction.)

Definition 16.2.8. Let $v : A \rightarrow A'$ be a localization homomorphism in $\text{Ring}/_{\text{feft}} \mathbb{K}$. The homomorphism

$$\mathbb{q}_{v/\mathbb{K}} = \mathbb{q}_{A'/A/\mathbb{K}} : \mathcal{K}_A \rightarrow \mathcal{K}_{A'}$$

in $\mathbf{C}_{\text{str}}(A)$ from Lemma 16.2.4 is called the *rigid localization homomorphism in $\mathbf{C}_{\text{str}}(A)$ over v* .

Theorem 16.2.9. *Let \mathbb{K} be a regular noetherian ring. All rings and homomorphisms below are in the category $\text{Ring}/_{\text{feft}} \mathbb{K}$.*

(1) Let $u : A \rightarrow B$ and $v : B \rightarrow C$ be finite homomorphisms. Then

$$\mathrm{Tr}_{u/\mathbb{K}} \circ \mathrm{Tr}_{v/\mathbb{K}} = \mathrm{Tr}_{v \circ u/\mathbb{K}},$$

as homomorphisms $\mathcal{K}_C \rightarrow \mathcal{K}_A$ in $\mathbf{C}_{\mathrm{str}}(A)$.

(2) Let $v : A \rightarrow A'$ and $v' : A' \rightarrow A''$ be localization homomorphisms. Then

$$\mathfrak{q}_{v'/\mathbb{K}} \circ \mathfrak{q}_{v/\mathbb{K}} = \mathfrak{q}_{v' \circ v/\mathbb{K}},$$

as homomorphisms $\mathcal{K}_A \rightarrow \mathcal{K}_{A''}$ in $\mathbf{C}_{\mathrm{str}}(A)$.

(3) In the situation of Theorem 16.1.13, the diagram

$$\begin{array}{ccc} \mathcal{K}_A & \xleftarrow{\mathrm{Tr}_{u/\mathbb{K}}} & \mathcal{K}_B \\ \mathfrak{q}_{v/\mathbb{K}} \downarrow & & \downarrow \mathfrak{q}_{w/\mathbb{K}} \\ \mathcal{K}_{A'} & \xleftarrow{\mathrm{Tr}_{u'/\mathbb{K}}} & \mathcal{K}_{B'} \end{array}$$

in $\mathbf{C}_{\mathrm{str}}(A)$ is commutative.

Proof. (1) Because the composition of two nondegenerate rigid trace homomorphisms is again a nondegenerate rigid trace homomorphism, this is a consequence of the uniqueness in Lemma 16.2.4.

(2) Because the composition of two nondegenerate rigid localization homomorphisms is again a nondegenerate rigid localization homomorphism, this is a consequence of the uniqueness in Lemma 16.2.6.

(3) Several steps involving backward and forward adjunctions, as done in the proofs of Theorem 16.2.3 and the lemmas following it, imply that there is a canonical bijection

$$Q : \mathrm{Hom}_{\mathbf{C}_{\mathrm{str}}(A)}(\mathcal{K}_B, \mathcal{K}_{A'}) \xrightarrow{\cong} \mathrm{Hom}_{\mathbf{D}(A)}(\mathcal{K}_B, \mathcal{K}_{A'}).$$

The commutativity of the diagram here is then a consequence of the commutativity of the diagram in Theorem 16.1.13. \square

16.3. The Ind-Rigid Trace homomorphism.

cmnt: proofs missing in this Subsec

In this subsection we must use infinitesimal methods. By necessity this introduces torsion (cf. Example 16.3.3 below). If we had DG ring resolutions at our disposal (see Remark 15.1.26) that would not pose a problem. But in this book we choose not to do that (because it is too complicated). Thus we are forced to make the next restrictive assumption in the current subsection.

Setup 16.3.1. The base ring \mathbb{K} is a field. The category of essentially finite type commutative \mathbb{K} -rings will be denoted by $\text{Ring}/_{\text{eft}} \mathbb{K}$. The rings A, B, C, A', B', A'' , and the homomorphisms between them, are in $\text{Ring}/_{\text{eft}} \mathbb{K}$.

Definition 16.3.2. For a prime ideal $\mathfrak{p} \subseteq A$ and a number $l \in \mathbb{N}$ we write

$$A_{\mathfrak{p},l} := A_{\mathfrak{p}}/\mathfrak{p}_{\mathfrak{p}}^{l+1}.$$

This is an artian local ring, with maximal ideal $\mathfrak{p}_{\mathfrak{p}}/\mathfrak{p}_{\mathfrak{p}}^{l+1}$, and we call it the l -th infinitesimal neighborhood of the residue field $\mathbf{k}(\mathfrak{p})$.

Observe that for $l = 0$ we do have $A_{\mathfrak{p},0} = \mathbf{k}(\mathfrak{p})$. This justifies the name given to $A_{\mathfrak{p},l}$.

Example 16.3.3. Assume (contrary to Setup 16.3.1) that $\mathbb{K} = \mathbb{Z}$. Let $A := \mathbb{Z}$, and let $\mathfrak{p} := (p)$ for some positive prime p . Then A is flat over \mathbb{K} , but $A_{\mathfrak{p},l} = \mathbb{Z}/(p^{l+1})$ is not a flat \mathbb{K} -ring for any $l \in \mathbb{N}$.

We begin with an analysis of the structure of the rigid residue complex \mathcal{K}_A . The dimension function \dim_R relative to a dualizing complex R was introduced in Definition 14.4.2.

Definition 16.3.4. Let $A \in \text{Ring}/_{\text{eft}} \mathbb{K}$. The rigid dimension function relative to \mathbb{K} is the dimension function

$$\text{rig.dim}_{\mathbb{K}} : \text{Spec } A \rightarrow \mathbb{Z}$$

given by the formula

$$\text{rig.dim}_{\mathbb{K}}(\mathfrak{p}) := \dim_R(\mathfrak{p}),$$

where R is any rigid dualizing complex over A relative to \mathbb{K} .

Definition 16.3.5. Let $A \in \text{Ring}/_{\text{feft}} \mathbb{K}$ be an artinian local ring, with maximal ideal \mathfrak{m} . We define

$$\text{rig.dim}_{\mathbb{K}}(A) := \text{rig.dim}_{\mathbb{K}}(\mathfrak{m}).$$

This definition makes sense, because the maximal ideal \mathfrak{m} is the only point in the set $\text{Spec } A$. Of course the Krull dimension of the ring A is zero.

Proposition 16.3.6. Let $L \in \text{Ring}/_{\text{eft}} \mathbb{K}$ be a field. There is equality

$$\text{rig.dim}_{\mathbb{K}}(L) = \text{tr.deg}_{\mathbb{K}}(L),$$

where the second number is the transcendence degree of the field extension $\mathbb{K} \rightarrow L$.

Exercise 16.3.7. Prove this proposition. (Hint: find a rational function field $\mathbb{K}(t_1, \dots, t_n)$ such that L is a finite extension of it. Then calculate.)

Definition 16.3.8. Let $A \in \text{Ring}/_{\text{eft}} \mathbb{K}$ be an artinian local ring, with rigid residue complex \mathcal{K}_A , and with $i := \text{rig.dim}_{\mathbb{K}}(A)$. We define the *rigid dual module* of A to be the A -module $\mathcal{K}(A) := \mathcal{K}_A^{-i}$.

The A -module $\mathcal{K}(A)$ is an indecomposable injective (an injective hull of the residue field $\mathbf{k}(\mathfrak{m}) = A/\mathfrak{m}$). And the rigid residue complex of A/\mathbb{K} is

$$(16.3.9) \quad (\mathcal{K}_A, \rho_A) = (\mathcal{K}(A)[i], \rho_A) \in \mathbf{C}(A)_{\text{rig}/\mathbb{K}}.$$

Remark 16.3.10. An explanatory remark is due here. Consider the situation of Definition 16.3.8. The rigid dual module $\mathcal{K}(A)$ has more structure than just an indecomposable injective. It, or rather the rigid residue complex $\mathcal{K}(A)[i]$, is equipped with a rigidifying isomorphism

$$\rho_A : \mathcal{K}(A)[i] \xrightarrow{\cong} \text{Sq}_{A/\mathbb{K}}(\mathcal{K}(A)[i])$$

in $\mathbf{D}(A)$. This is what makes the constructions below work.

Lemma 16.3.11. *Let $u : A \rightarrow B$ be a homomorphism between artinian local rings in $\text{Ring}/_{\text{eft}} \mathbb{K}$. Let $\mathfrak{m} \subseteq A$ and $\mathfrak{n} \subseteq B$ be the maximal ideals. The three conditions below are equivalent.*

- (i) *The ring homomorphism $u : A \rightarrow B$ is finite.*
- (ii) *The field extension $\mathbf{k}(\mathfrak{m}) \rightarrow \mathbf{k}(\mathfrak{n})$ is finite.*
- (iii) *The rigid dimensions $\text{rig.dim}_{\mathbb{K}}(A)$ and $\text{rig.dim}_{\mathbb{K}}(B)$ are equal.*

Proof. ??? □

Definition 16.3.12. Let $u : A \rightarrow B$ be finite homomorphism between artinian local rings in $\text{Ring}/_{\text{eft}} \mathbb{K}$. The *rigid trace homomorphism*

$$\text{Tr}_{B/A/\mathbb{K}} : \mathcal{K}(B) \rightarrow \mathcal{K}(A)$$

in $\mathbf{M}(A)$ over u is defined to be the degree $-i$ component of the rigid trace homomorphism

$$\text{Tr}_{B/A/\mathbb{K}} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

in $\mathbf{C}_{\text{str}}(A)$, where $i := \text{rig.dim}_{\mathbb{K}}(A) = \text{rig.dim}_{\mathbb{K}}(B)$.

Lemma 16.3.13. *Let $A \in \text{Ring}/_{\text{eft}} \mathbb{K}$. Consider a prime ideal \mathfrak{p} in A with $i := \text{rig.dim}_{\mathbb{K}}(\mathfrak{p})$. Then the $A_{\mathfrak{p}}$ -module $\mathcal{K}_{A_{\mathfrak{p}}}^{-i}$ is isomorphic to $J(\mathfrak{p})$.*

Proof. ??? □

Let \mathfrak{p} and i be as in the last lemma. We consider the infinitesimal neighborhoods $A_{\mathfrak{p},l}$, for $l \geq 0$, of the residue field $\mathbf{k}(\mathfrak{p}) = A_{\mathfrak{p},0}$. For every l the canonical surjection $A_{\mathfrak{p},l+1} \rightarrow A_{\mathfrak{p},l}$ is a finite homomorphism in $\text{Ring}/_{\text{eft}} \mathbb{K}$, and hence there is the rigid trace homomorphism

$$(16.3.14) \quad \text{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p},l+1}/\mathbb{K}} : \mathcal{K}(A_{\mathfrak{p},l}) \rightarrow \mathcal{K}(A_{\mathfrak{p},l+1})$$

in $\mathbf{M}(A_{\mathfrak{p}})$. Due to functoriality (Theorem 16.2.9(1)) these homomorphisms make the collection of $A_{\mathfrak{p}}$ -modules $\{\mathcal{K}(A_{\mathfrak{p},l})\}_{l \in \mathbb{N}}$ into a direct system. There are also the canonical surjective ring homomorphisms $A_{\mathfrak{p}} \rightarrow A_{\mathfrak{p},l}$, and the corresponding rigid trace homomorphisms

$$(16.3.15) \quad \text{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p}}/\mathbb{K}} : \mathcal{K}(A_{\mathfrak{p},l}) \rightarrow \mathcal{K}_{A_{\mathfrak{p}}}^{-i}$$

in $\mathbf{M}(A)$. The diagram below in $\mathbf{M}(A)$ is commutative.

$$(16.3.16) \quad \begin{array}{ccc} \mathcal{K}(A_{\mathfrak{p},l}) & \xrightarrow{\mathrm{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p},l+1}/\mathbb{K}}} & \mathcal{K}(A_{\mathfrak{p},l+1}) \\ & \searrow \mathrm{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p}}/\mathbb{K}} & \downarrow \mathrm{Tr}_{A_{\mathfrak{p},l+1}/A_{\mathfrak{p}}/\mathbb{K}} \\ & & \mathcal{K}_{A_{\mathfrak{p}}}^{-i} \end{array}$$

Lemma 16.3.17. *Let $A \in \mathrm{Ring}/_{\mathrm{eft}} \mathbb{K}$, and let $\mathfrak{p} \subseteq A$ with $\mathrm{rig.\dim}_{\mathbb{K}}(\mathfrak{p}) = i$. Then:*

- (1) *For any l the homomorphism of $A_{\mathfrak{p}}$ -modules*

$$\mathrm{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p},l+1}/\mathbb{K}} : \mathcal{K}(A_{\mathfrak{p},l}) \rightarrow \mathcal{K}(A_{\mathfrak{p},l+1})$$

is injective.

- (2) *The homomorphism of $A_{\mathfrak{p}}$ -modules*

$$\lim_{l \rightarrow} \mathrm{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p},l}/\mathbb{K}} : \lim_{l \rightarrow} \mathcal{K}(A_{\mathfrak{p},l}) \rightarrow \mathcal{K}_{A_{\mathfrak{p}}}^{-i}$$

is bijective.

Proof. ??? □

By Definition 14.4.14, the rigid residue complex \mathcal{K}_A has this decomposition:

$$\mathcal{K}_A^{-i} \cong \bigoplus_{\dim_{\mathbb{K}}(\mathfrak{p})=i} J(\mathfrak{p}),$$

where $J(\mathfrak{p})$ is the indecomposable injective module corresponding to the prime ideal \mathfrak{p} . Recall that for an A -module M we denote by $\Gamma_{\mathfrak{p}}(M)$ the \mathfrak{p} -torsion submodule. The next lemmas let us give a more effective decomposition of \mathcal{K}_A^{-i} .

Lemma 16.3.18. *Let $A \in \mathrm{Ring}/_{\mathrm{eft}} \mathbb{K}$. Fix a prime ideal \mathfrak{p} in A with $\mathrm{rig.\dim}_{\mathbb{K}}(\mathfrak{p}) = i$. The rigid localization homomorphism*

$$\mathfrak{q}_{A_{\mathfrak{p}}/A/\mathbb{K}} : \mathcal{K}_A \rightarrow \mathcal{K}_{A_{\mathfrak{p}}}$$

in $\mathbf{C}_{\mathrm{str}}(A)$ induces an isomorphism

$$\mathfrak{q}_{A_{\mathfrak{p}}/A/\mathbb{K}} : \Gamma_{\mathfrak{p}}(\mathcal{K}_A^{-i}) \xrightarrow{\cong} \mathcal{K}_{A_{\mathfrak{p}}}^{-i}$$

in $\mathbf{M}(A)$.

Proof. ??? □

Lemma 16.3.19. *Let $A \in \mathrm{Ring}/_{\mathrm{eft}} \mathbb{K}$. Fix an integer i . Then:*

- (1) *There is a canonical decomposition of A -modules*

$$\mathcal{K}_A^{-i} = \bigoplus_{\dim_{\mathbb{K}}(\mathfrak{p})=i} \Gamma_{\mathfrak{p}}(\mathcal{K}_A^{-i}).$$

- (2) *The homomorphism of A -modules*

$$\sum_{\dim_{\mathbb{K}}(\mathfrak{p})=i} \mathfrak{q}_{A_{\mathfrak{p}}/A/\mathbb{K}} : \mathcal{K}_A^{-i} \rightarrow \bigoplus_{\dim_{\mathbb{K}}(\mathfrak{p})=i} \mathcal{K}_{A_{\mathfrak{p}}}^{-i}$$

is bijective.

Proof. ??? □

Combining Lemmas 16.3.19 and 16.3.17 we get this useful fact: there is a canonical isomorphism of A -modules

$$(16.3.20) \quad \mathcal{K}_A^{-i} \cong \bigoplus_{\text{rig.dim}_{\mathbb{K}}(\mathfrak{p})=i} \lim_{l \rightarrow} \mathcal{K}(A_{\mathfrak{p},l}).$$

In words: the degree $-i$ term of the rigid residue complex \mathcal{K}_A is approximated, as a direct limit, by the rigid dual modules $\mathcal{K}(A_{\mathfrak{p},l})$ of the various infinitesimal neighborhoods of the residue fields $\mathbf{k}(\mathfrak{p})$, for the primes $\mathfrak{p} \subseteq A$ of rigid dimension i .

For a convenient reference, here is the same formula for a second ring B :

$$(16.3.21) \quad \mathcal{K}_B^{-i} \cong \bigoplus_{\text{rig.dim}_{\mathbb{K}}(\mathfrak{q})=i} \lim_{l \rightarrow} \mathcal{K}(B_{\mathfrak{q},l}).$$

Here we run over the prime ideals $\mathfrak{q} \subseteq B$. In view of the direct limit expression (16.3.20) and (16.3.21), giving a homomorphism

$$\phi_{B/A} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

in $\mathbf{G}^0(A)$ amounts to specifying, for any $i \in \mathbb{Z}$, any $\mathfrak{q} \in \text{Spec } B$ with $\text{rig.dim}_{\mathbb{K}}(\mathfrak{q}) = i$, and any $l \in \mathbb{N}$, a homomorphism

$$\phi_{B/A,\mathfrak{q},l} : \mathcal{K}(B_{\mathfrak{q},l}) \rightarrow \mathcal{K}_A^{-i},$$

such that

$$\phi_{B/A,\mathfrak{q},l} = \phi_{B/A,\mathfrak{q},l+1} \circ \text{Tr}_{A_{\mathfrak{p},l}/A_{\mathfrak{p},l+1}}.$$

Definition 16.3.22 (The Ind-Rigid Trace). Let \mathbb{K} be a field, and let $u : A \rightarrow B$ be a homomorphism in $\text{Ring}/_{\text{eft}} \mathbb{K}$. The *ind-rigid trace homomorphism*

$$\text{Tr}_{u/\mathbb{K}} = \text{Tr}_{B/A/\mathbb{K}} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

is the homomorphism in $\mathbf{G}^0(A)$ defined as follows. As explained above, it suffices to define the A -module homomorphism

$$\text{Tr}_{u/\mathbb{K}}|_{\mathcal{K}(B_{\mathfrak{q},l})} : \mathcal{K}(B_{\mathfrak{q},l}) \rightarrow \mathcal{K}_A^{-i}$$

for any $i \in \mathbb{Z}$, any $\mathfrak{q} \in \text{Spec } B$ with $\text{rig.dim}_{\mathbb{K}}(\mathfrak{q}) = i$, and any $l \in \mathbb{N}$. There are two cases, depending on the prime ideal $\mathfrak{p} := u^{-1}(\mathfrak{q}) \in \text{Spec } A$.

- (Finite case) If $\text{rig.dim}_{\mathbb{K}}(\mathfrak{p}) = i$, then the induced homomorphism

$$u_{\mathfrak{q},l} : A_{\mathfrak{p},l} \rightarrow B_{\mathfrak{q},l}$$

is finite. We define $\text{Tr}_u|_{\mathcal{K}(B_{\mathfrak{q},l})}$ to be the composition of

$$\text{Tr}_{B_{\mathfrak{q},l}/A_{\mathfrak{p},l}} : \mathcal{K}(B_{\mathfrak{q},l}) \rightarrow \mathcal{K}(A_{\mathfrak{p},l})$$

with the inclusion

$$\mathcal{K}(A_{\mathfrak{p},l}) \hookrightarrow \mathcal{K}_A^{-i}.$$

from (16.3.20).

- (Infinite case) If $\text{dim}_{\mathbb{K}}(\mathfrak{p}) < i$, then we define $\text{Tr}_u|_{\mathcal{K}(B_{\mathfrak{q},l})} := 0$.

Notice that in the finite case the homomorphisms agree for varying l , due to ???.

Theorem 16.3.23 (Properties of the Ind-Rigid Trace). *Let \mathbb{K} be a field. Then:*

- (1) *Let $u : A \rightarrow B$ and $v : B \rightarrow C$ be homomorphisms in $\text{Ring}/_{\text{eft}} \mathbb{K}$. Then*

$$\text{Tr}_{u/\mathbb{K}} \circ \text{Tr}_{v/\mathbb{K}} = \text{Tr}_{v \circ u/\mathbb{K}},$$

as homomorphisms $\mathcal{K}_C \rightarrow \mathcal{K}_A$ in $\mathbf{G}^0(A)$.

- (2) If $u : A \rightarrow B$ is a finite homomorphisms in $\text{Ring}/_{\text{eft}} \mathbb{K}$, then the ind-rigid trace

$$\text{Tr}_{u/\mathbb{K}} : \mathcal{K}_B \rightarrow \mathcal{K}_A$$

in $\mathbf{G}^0(A)$ over u equals the rigid trace in $\mathbf{C}_{\text{str}}(A)$ over u . In particular, this is a strict homomorphism of complexes.

- (3) Suppose we are given a commutative diagram

$$\begin{array}{ccc} A & \xrightarrow{u} & B \\ v \downarrow & & \downarrow w \\ A' & \xrightarrow{u'} & B' \end{array}$$

in $\text{Ring}/_{\text{eft}} \mathbb{K}$, in which v is a localization, and

$$u' \otimes_A w : A' \otimes_A B \rightarrow B'$$

is an isomorphism (i.e. the diagram is cocartesian). Then the diagram

$$\begin{array}{ccc} \mathcal{K}_A & \xleftarrow{\text{Tr}_{u/\mathbb{K}}} & \mathcal{K}_B \\ \mathfrak{q}_{v/\mathbb{K}} \downarrow & & \downarrow \mathfrak{q}_{w/\mathbb{K}} \\ \mathcal{K}_{A'} & \xleftarrow{\text{Tr}_{u'/\mathbb{K}}} & \mathcal{K}_{B'} \end{array}$$

in $\mathbf{G}^0(A)$, in which the horizontal arrows are the ind-rigid traces, and the vertical arrows are the rigid localizations, is commutative.

Proof. ???

□

Remark 16.3.24. Item (2) in the last theorem implies that for a finite homomorphism $u : A \rightarrow B$, the ind-rigid trace is a homomorphism of complexes. Later, once we have made everything geometric, this property – that the ind-rigid trace commutes with the differentials – will be the *Residue Theorem* for a proper map of schemes $f : X \rightarrow Y$.

cmnt: stuff on essentially smooth homomorphisms will be entered later.

cmnt: to here 26/04/17

Later Material

17. DERIVED CATEGORIES IN GEOMETRY [LATER]

- 17.1. **Recalling Facts on Ringed Spaces.**
- 17.2. **K-Flat Resolutions in $\mathbf{C}(\mathcal{A})$ [later].**
- 17.3. **K-Injective Resolutions in $\mathbf{C}(\mathcal{A})$ [later].**
- 17.4. **K-Flasque Resolutions in $\mathbf{C}(\mathcal{A})$ [later].**
- 17.5. **Standard Derived Functors in Geometry [later].**
- 17.6. **Survey: Poincaré-Verdier Duality [later, optional].**
- 17.7. **Survey: Applications to Birational Geometry [later, optional].**

18. RESIDUES AND DUALITY IN ALGEBRAIC GEOMETRY [LATER]

- 18.1. **Dualizing Complexes on Schemes [later].**
- 18.2. **Rigid Residue Complexes on Schemes [later].**
- 18.3. **The Residue Theorem [later].**
- 18.4. **Grothendieck Duality for Proper Maps [later].**
- 18.5. **Perverse Coherent Sheaves on Schemes [later, optional].**
- 18.6. **Survey of Related Material [later, optional].**

19. DERIVED CATEGORIES IN NONCOMMUTATIVE ALGEBRA [LATER]

- 19.1. **Noncommutative Dualizing Complexes [later].**
- 19.2. **Noncommutative Tilting Complexes [later].**
- 19.3. **The Noncommutative Derived Picard Group of a Ring [later].**
- 19.4. **Derived Morita Theory [later].**

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