

# DUALIZING COMPLEXES

08XG

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## 1. Introduction

08XH In this chapter we discuss dualizing complexes in commutative algebra. A reference is the book [Har66]. See Duality for Schemes, Section 1 for the global theory.

The goals of this chapter are the following:

- (1) Define what it means to have a dualizing complex  $\omega_A^\bullet$  over a Noetherian ring  $A$ , namely
  - (a) we have  $\omega_A^\bullet \in D^+(A)$ ,
  - (b) the cohomology modules  $H^i(\omega_A^\bullet)$  are all finite  $A$ -modules,
  - (c)  $\omega_A^\bullet$  has finite injective dimension, and

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- (d) we have  $A \rightarrow R\mathrm{Hom}_A(\omega_A^\bullet, \omega_A^\bullet)$  is a quasi-isomorphism.
- (2) List elementary properties of dualizing complexes.
- (3) Show a dualizing complex gives rise to a dimension function.
- (4) Show a dualizing complex gives rise to a good notion of a reflexive hull.
- (5) Prove Grothendieck's local duality theorem.
- (6) Discuss Cohen-Macaulay and Gorenstein rings.

We prove the finiteness theorem when a dualizing complex exists in the chapter on local cohomology, see Local Cohomology, Theorem 7.4.

## 2. Essential surjections and injections

08XI We will mostly work in categories of modules, but we may as well make the definition in general.

08XJ **Definition 2.1.** Let  $\mathcal{A}$  be an abelian category.

- (1) An injection  $A \subset B$  of  $\mathcal{A}$  is *essential*, or we say that  $B$  is an *essential extension of  $A$* , if every nonzero subobject  $B' \subset B$  has nonzero intersection with  $A$ .
- (2) A surjection  $f : A \rightarrow B$  of  $\mathcal{A}$  is *essential* if for every proper subobject  $A' \subset A$  we have  $f(A') \neq B$ .

Some lemmas about this notion.

08XK **Lemma 2.2.** Let  $\mathcal{A}$  be an abelian category.

- (1) If  $A \subset B$  and  $B \subset C$  are essential extensions, then  $A \subset C$  is an essential extension.
- (2) If  $A \subset B$  is an essential extension and  $C \subset B$  is a subobject, then  $A \cap C \subset C$  is an essential extension.
- (3) If  $A \rightarrow B$  and  $B \rightarrow C$  are essential surjections, then  $A \rightarrow C$  is an essential surjection.
- (4) Given an essential surjection  $f : A \rightarrow B$  and a surjection  $A \rightarrow C$  with kernel  $K$ , the morphism  $C \rightarrow B/f(K)$  is an essential surjection.

**Proof.** Omitted. □

08XL **Lemma 2.3.** Let  $R$  be a ring. Let  $M$  be an  $R$ -module. Let  $E = \mathrm{colim} E_i$  be a filtered colimit of  $R$ -modules. Suppose given a compatible system of essential injections  $M \rightarrow E_i$  of  $R$ -modules. Then  $M \rightarrow E$  is an essential injection.

**Proof.** Immediate from the definitions and the fact that filtered colimits are exact (Algebra, Lemma 8.8). □

08XM **Lemma 2.4.** Let  $R$  be a ring. Let  $M \subset N$  be  $R$ -modules. The following are equivalent

- (1)  $M \subset N$  is an essential extension,
- (2) for all  $x \in N$  nonzero there exists an  $f \in R$  such that  $fx \in M$  and  $fx \neq 0$ .

**Proof.** Assume (1) and let  $x \in N$  be a nonzero element. By (1) we have  $Rx \cap M \neq 0$ . This implies (2).

Assume (2). Let  $N' \subset N$  be a nonzero submodule. Pick  $x \in N'$  nonzero. By (2) we can find  $f \in R$  with  $fx \in M$  and  $fx \neq 0$ . Thus  $N' \cap M \neq 0$ . □

### 3. Injective modules

08XN Some results about injective modules over rings.

08XP **Lemma 3.1.** *Let  $R$  be a ring. Any product of injective  $R$ -modules is injective.*

**Proof.** Special case of Homology, Lemma 23.3.  $\square$

08XQ **Lemma 3.2.** *Let  $R \rightarrow S$  be a flat ring map. If  $E$  is an injective  $S$ -module, then  $E$  is injective as an  $R$ -module.*

**Proof.** This is true because  $\text{Hom}_R(M, E) = \text{Hom}_S(M \otimes_R S, E)$  by Algebra, Lemma 13.3 and the fact that tensoring with  $S$  is exact.  $\square$

08YV **Lemma 3.3.** *Let  $R \rightarrow S$  be an epimorphism of rings. Let  $E$  be an  $S$ -module. If  $E$  is injective as an  $R$ -module, then  $E$  is an injective  $S$ -module.*

**Proof.** This is true because  $\text{Hom}_R(N, E) = \text{Hom}_S(N, E)$  for any  $S$ -module  $N$ , see Algebra, Lemma 106.14.  $\square$

08XR **Lemma 3.4.** *Let  $R \rightarrow S$  be a ring map. If  $E$  is an injective  $R$ -module, then  $\text{Hom}_R(S, E)$  is an injective  $S$ -module.*

**Proof.** This is true because  $\text{Hom}_S(N, \text{Hom}_R(S, E)) = \text{Hom}_R(N, E)$  by Algebra, Lemma 13.4.  $\square$

08XS **Lemma 3.5.** *Let  $R$  be a ring. Let  $I$  be an injective  $R$ -module. Let  $E \subset I$  be a submodule. The following are equivalent*

- (1)  $E$  is injective, and
- (2) for all  $E \subset E' \subset I$  with  $E \subset E'$  essential we have  $E = E'$ .

*In particular, an  $R$ -module is injective if and only if every essential extension is trivial.*

**Proof.** The final assertion follows from the first and the fact that the category of  $R$ -modules has enough injectives (More on Algebra, Section 52).

Assume (1). Let  $E \subset E' \subset I$  as in (2). Then the map  $\text{id}_E : E \rightarrow E$  can be extended to a map  $\alpha : E' \rightarrow E$ . The kernel of  $\alpha$  has to be zero because it intersects  $E$  trivially and  $E'$  is an essential extension. Hence  $E = E'$ .

Assume (2). Let  $M \subset N$  be  $R$ -modules and let  $\varphi : M \rightarrow E$  be an  $R$ -module map. In order to prove (1) we have to show that  $\varphi$  extends to a morphism  $N \rightarrow E$ . Consider the set  $\mathcal{S}$  of pairs  $(M', \varphi')$  where  $M \subset M' \subset N$  and  $\varphi' : M' \rightarrow E$  is an  $R$ -module map agreeing with  $\varphi$  on  $M$ . We define an ordering on  $\mathcal{S}$  by the rule  $(M', \varphi') \leq (M'', \varphi'')$  if and only if  $M' \subset M''$  and  $\varphi''|_{M'} = \varphi'$ . It is clear that we can take the maximum of a totally ordered subset of  $\mathcal{S}$ . Hence by Zorn's lemma we may assume  $(M, \varphi)$  is a maximal element.

Choose an extension  $\psi : N \rightarrow I$  of  $\varphi$  composed with the inclusion  $E \rightarrow I$ . This is possible as  $I$  is injective. If  $\psi(N) \subset E$ , then  $\psi$  is the desired extension. If  $\psi(N)$  is not contained in  $E$ , then by (2) the inclusion  $E \subset E + \psi(N)$  is not essential, hence we can find a nonzero submodule  $K \subset E + \psi(N)$  meeting  $E$  in 0. This means that  $M' = \psi^{-1}(E + K)$  strictly contains  $M$ . Thus we can extend  $\varphi$  to  $M'$  using

$$M' \xrightarrow{\psi|_{M'}} E + K \rightarrow (E + K)/K = E$$

This contradicts the maximality of  $(M, \varphi)$ .  $\square$

08XT **Example 3.6.** Let  $R$  be a reduced ring. Let  $\mathfrak{p} \subset R$  be a minimal prime so that  $K = R_{\mathfrak{p}}$  is a field (Algebra, Lemma 24.1). Then  $K$  is an injective  $R$ -module. Namely, we have  $\text{Hom}_R(M, K) = \text{Hom}_K(M_{\mathfrak{p}}, K)$  for any  $R$ -module  $M$ . Since localization is an exact functor and taking duals is an exact functor on  $K$ -vector spaces we conclude  $\text{Hom}_R(-, K)$  is an exact functor, i.e.,  $K$  is an injective  $R$ -module.

08XU **Lemma 3.7.** *Let  $R$  be a ring. Let  $E$  be an  $R$ -module. The following are equivalent*

- (1)  *$E$  is an injective  $R$ -module, and*
- (2) *given an ideal  $I \subset R$  and a module map  $\varphi : I \rightarrow E$  there exists an extension of  $\varphi$  to an  $R$ -module map  $R \rightarrow E$ .*

**Proof.** The implication (1)  $\Rightarrow$  (2) follows from the definitions. Thus we assume (2) holds and we prove (1). First proof: The lemma follows from More on Algebra, Lemma 52.4. Second proof: Since  $R$  is a generator for the category of  $R$ -modules, the lemma follows from Injectives, Lemma 11.5.

Third proof: We have to show that every essential extension  $E \subset E'$  is trivial, see Lemma 3.5. Pick  $x \in E'$  and set  $I = \{f \in R \mid fx \in E\}$ . The map  $I \rightarrow E$ ,  $f \mapsto fx$  extends to  $\psi : R \rightarrow E$  by (2). Then  $x' = x - \psi(1)$  is an element of  $E'$  whose annihilator in  $E'/E$  is  $I$  and which is annihilated by  $I$  as an element of  $E'$ . Thus  $Rx' = (R/I)x'$  does not intersect  $E$ . Since  $E \subset E'$  is an essential extension it follows that  $x' \in E$  as desired.  $\square$

08XV **Lemma 3.8.** *Let  $R$  be a Noetherian ring. A direct sum of injective modules is injective.*

**Proof.** Let  $E_i$  be a family of injective modules parametrized by a set  $I$ . Set  $E = \bigcup E_i$ . To show that  $E$  is injective we use Lemma 3.7. Thus let  $\varphi : I \rightarrow E$  be a module map from an ideal of  $R$  into  $E$ . As  $I$  is a finite  $R$ -module (because  $R$  is Noetherian) we can find finitely many elements  $i_1, \dots, i_r \in I$  such that  $\varphi$  maps into  $\bigcup_{j=1, \dots, r} E_{i_j}$ . Then we can extend  $\varphi$  into  $\bigcup_{j=1, \dots, r} E_{i_j}$  using the injectivity of the modules  $E_{i_j}$ .  $\square$

0A6I **Lemma 3.9.** *Let  $R$  be a Noetherian ring. Let  $S \subset R$  be a multiplicative subset. If  $E$  is an injective  $R$ -module, then  $S^{-1}E$  is an injective  $S^{-1}R$ -module.*

**Proof.** Since  $R \rightarrow S^{-1}R$  is an epimorphism of rings, it suffices to show that  $S^{-1}E$  is injective as an  $R$ -module, see Lemma 3.3. To show this we use Lemma 3.7. Thus let  $I \subset R$  be an ideal and let  $\varphi : I \rightarrow S^{-1}E$  be an  $R$ -module map. As  $I$  is a finitely presented  $R$ -module (because  $R$  is Noetherian) we can find an  $f \in S$  and an  $R$ -module map  $I \rightarrow E$  such that  $f\varphi$  is the composition  $I \rightarrow E \rightarrow S^{-1}E$  (Algebra, Lemma 10.2). Then we can extend  $I \rightarrow E$  to a homomorphism  $R \rightarrow E$ . Then the composition

$$R \rightarrow E \rightarrow S^{-1}E \xrightarrow{f^{-1}} S^{-1}E$$

is the desired extension of  $\varphi$  to  $R$ .  $\square$

08XW **Lemma 3.10.** *Let  $R$  be a Noetherian ring. Let  $I$  be an injective  $R$ -module.*

- (1) *Let  $f \in R$ . Then  $E = \bigcup I[f^n] = I[f^\infty]$  is an injective submodule of  $I$ .*
- (2) *Let  $J \subset R$  be an ideal. Then the  $J$ -power torsion submodule  $I[J^\infty]$  is an injective submodule of  $I$ .*

**Proof.** We will use Lemma 3.5 to prove (1). Suppose that  $E \subset E' \subset I$  and that  $E'$  is an essential extension of  $E$ . We will show that  $E' = E$ . If not, then we can find  $x \in E'$  and  $x \notin E$ . Let  $J = \{a \in R \mid ax \in E'\}$ . Since  $R$  is Noetherian we can choose  $x$  with  $J$  maximal. Since  $R$  is Noetherian we can write  $J = (g_1, \dots, g_t)$  for some  $g_i \in R$ . Say  $f^{n_i}$  annihilates  $g_i x$ . Set  $n = \max\{n_i\}$ . Then  $x' = f^n x$  is an element of  $E'$  not in  $E$  and is annihilated by  $J$ . By maximality of  $J$  we see that  $Rx' = (R/J)x' \cap E = (0)$ . Hence  $E'$  is not an essential extension of  $E$  a contradiction.

To prove (2) write  $J = (f_1, \dots, f_t)$ . Then  $I[J^\infty]$  is equal to

$$(\dots((I[f_1^\infty])[f_2^\infty])\dots)[f_t^\infty]$$

and the result follows from (1) and induction.  $\square$

0A6J **Lemma 3.11.** *Let  $A$  be a Noetherian ring. Let  $E$  be an injective  $A$ -module. Then  $E \otimes_A A[x]$  has injective-amplitude  $[0, 1]$  as an object of  $D(A[x])$ . In particular,  $E \otimes_A A[x]$  has finite injective dimension as an  $A[x]$ -module.*

**Proof.** Let us write  $E[x] = E \otimes_A A[x]$ . Consider the short exact sequence of  $A[x]$ -modules

$$0 \rightarrow E[x] \rightarrow \text{Hom}_A(A[x], E[x]) \rightarrow \text{Hom}_A(A[x], E[x]) \rightarrow 0$$

where the first map sends  $p \in E[x]$  to  $f \mapsto fp$  and the second map sends  $\varphi$  to  $f \mapsto \varphi(xf) - x\varphi(f)$ . The second map is surjective because  $\text{Hom}_A(A[x], E[x]) = \prod_{n \geq 0} E[x]$  as an abelian group and the map sends  $(e_n)$  to  $(e_{n+1} - xe_n)$  which is surjective. As an  $A$ -module we have  $E[x] \cong \bigoplus_{n \geq 0} E$  which is injective by Lemma 3.8. Hence the  $A[x]$ -module  $\text{Hom}_A(A[x], E[x])$  is injective by Lemma 3.4 and the proof is complete.  $\square$

#### 4. Projective covers

08XX In this section we briefly discuss projective covers.

08XY **Definition 4.1.** Let  $R$  be a ring. A surjection  $P \rightarrow M$  of  $R$ -modules is said to be a *projective cover*, or sometimes a *projective envelope*, if  $P$  is a projective  $R$ -module and  $P \rightarrow M$  is an essential surjection.

Projective covers do not always exist. For example, if  $k$  is a field and  $R = k[x]$  is the polynomial ring over  $k$ , then the module  $M = R/(x)$  does not have a projective cover. Namely, for any surjection  $f : P \rightarrow M$  with  $P$  projective over  $R$ , the proper submodule  $(x-1)P$  surjects onto  $M$ . Hence  $f$  is not essential.

08XZ **Lemma 4.2.** *Let  $R$  be a ring and let  $M$  be an  $R$ -module. If a projective cover of  $M$  exists, then it is unique up to isomorphism.*

**Proof.** Let  $P \rightarrow M$  and  $P' \rightarrow M$  be projective covers. Because  $P$  is a projective  $R$ -module and  $P' \rightarrow M$  is surjective, we can find an  $R$ -module map  $\alpha : P \rightarrow P'$  compatible with the maps to  $M$ . Since  $P' \rightarrow M$  is essential, we see that  $\alpha$  is surjective. As  $P'$  is a projective  $R$ -module we can choose a direct sum decomposition  $P = \text{Ker}(\alpha) \oplus P'$ . Since  $P' \rightarrow M$  is surjective and since  $P \rightarrow M$  is essential we conclude that  $\text{Ker}(\alpha)$  is zero as desired.  $\square$

Here is an example where projective covers exist.

08Y0 **Lemma 4.3.** *Let  $(R, \mathfrak{m}, \kappa)$  be a local ring. Any finite  $R$ -module has a projective cover.*

**Proof.** Let  $M$  be a finite  $R$ -module. Let  $r = \dim_{\kappa}(M/\mathfrak{m}M)$ . Choose  $x_1, \dots, x_r \in M$  mapping to a basis of  $M/\mathfrak{m}M$ . Consider the map  $f : R^{\oplus r} \rightarrow M$ . By Nakayama's lemma this is a surjection (Algebra, Lemma 19.1). If  $N \subset R^{\oplus r}$  is a proper submodule, then  $N/\mathfrak{m}N \rightarrow \kappa^{\oplus r}$  is not surjective (by Nakayama's lemma again) hence  $N/\mathfrak{m}N \rightarrow M/\mathfrak{m}M$  is not surjective. Thus  $f$  is an essential surjection.  $\square$

### 5. Injective hulls

08Y1 In this section we briefly discuss injective hulls.

08Y2 **Definition 5.1.** Let  $R$  be a ring. A injection  $M \rightarrow I$  of  $R$ -modules is said to be an *injective hull* if  $I$  is an injective  $R$ -module and  $M \rightarrow I$  is an essential injection.

Injective hulls always exist.

08Y3 **Lemma 5.2.** *Let  $R$  be a ring. Any  $R$ -module has an injective hull.*

**Proof.** Let  $M$  be an  $R$ -module. By More on Algebra, Section 52 the category of  $R$ -modules has enough injectives. Choose an injection  $M \rightarrow I$  with  $I$  an injective  $R$ -module. Consider the set  $\mathcal{S}$  of submodules  $M \subset E \subset I$  such that  $E$  is an essential extension of  $M$ . We order  $\mathcal{S}$  by inclusion. If  $\{E_{\alpha}\}$  is a totally ordered subset of  $\mathcal{S}$ , then  $\bigcup E_{\alpha}$  is an essential extension of  $M$  too (Lemma 2.3). Thus we can apply Zorn's lemma and find a maximal element  $E \in \mathcal{S}$ . We claim  $M \subset E$  is an injective hull, i.e.,  $E$  is an injective  $R$ -module. This follows from Lemma 3.5.  $\square$

08Y4 **Lemma 5.3.** *Let  $R$  be a ring. Let  $M, N$  be  $R$ -modules and let  $M \rightarrow E$  and  $N \rightarrow E'$  be injective hulls. Then*

- (1) *for any  $R$ -module map  $\varphi : M \rightarrow N$  there exists an  $R$ -module map  $\psi : E \rightarrow E'$  such that*

$$\begin{array}{ccc} M & \longrightarrow & E \\ \varphi \downarrow & & \downarrow \psi \\ N & \longrightarrow & E' \end{array}$$

*commutes,*

- (2) *if  $\varphi$  is injective, then  $\psi$  is injective,*
- (3) *if  $\varphi$  is an essential injection, then  $\psi$  is an isomorphism,*
- (4) *if  $\varphi$  is an isomorphism, then  $\psi$  is an isomorphism,*
- (5) *if  $M \rightarrow I$  is an embedding of  $M$  into an injective  $R$ -module, then there is an isomorphism  $I \cong E \oplus I'$  compatible with the embeddings of  $M$ ,*

*In particular, the injective hull  $E$  of  $M$  is unique up to isomorphism.*

**Proof.** Part (1) follows from the fact that  $E'$  is an injective  $R$ -module. Part (2) follows as  $\text{Ker}(\psi) \cap M = 0$  and  $E$  is an essential extension of  $M$ . Assume  $\varphi$  is an essential injection. Then  $E \cong \psi(E) \subset E'$  by (2) which implies  $E' = \psi(E) \oplus E''$  because  $E$  is injective. Since  $E'$  is an essential extension of  $M$  (Lemma 2.2) we get  $E'' = 0$ . Part (4) is a special case of (3). Assume  $M \rightarrow I$  as in (5). Choose a map  $\alpha : E \rightarrow I$  extending the map  $M \rightarrow I$ . Arguing as before we see that  $\alpha$  is injective. Thus as before  $\alpha(E)$  splits off from  $I$ . This proves (5).  $\square$

08Y5 **Example 5.4.** Let  $R$  be a domain with fraction field  $K$ . Then  $R \subset K$  is an injective hull of  $R$ . Namely, by Example 3.6 we see that  $K$  is an injective  $R$ -module and by Lemma 2.4 we see that  $R \subset K$  is an essential extension.

08Y6 **Definition 5.5.** An object  $X$  of an additive category is called *indecomposable* if it is nonzero and if  $X = Y \oplus Z$ , then either  $Y = 0$  or  $Z = 0$ .

08Y7 **Lemma 5.6.** *Let  $R$  be a ring. Let  $E$  be an indecomposable injective  $R$ -module. Then*

- (1)  $E$  is the injective hull of any nonzero submodule of  $E$ ,
- (2) the intersection of any two nonzero submodules of  $E$  is nonzero,
- (3)  $\text{End}_R(E, E)$  is a noncommutative local ring with maximal ideal those  $\varphi : E \rightarrow E$  whose kernel is nonzero, and
- (4) the set of zerodivisors on  $E$  is a prime ideal  $\mathfrak{p}$  of  $R$  and  $E$  is an injective  $R_{\mathfrak{p}}$ -module.

**Proof.** Part (1) follows from Lemma 5.3. Part (2) follows from part (1) and the definition of injective hulls.

Proof of (3). Set  $A = \text{End}_R(E, E)$  and  $I = \{\varphi \in A \mid \text{Ker}(\varphi) \neq 0\}$ . The statement means that  $I$  is a two sided ideal and that any  $\varphi \in A$ ,  $\varphi \notin I$  is invertible. Suppose  $\varphi$  and  $\psi$  are not injective. Then  $\text{Ker}(\varphi) \cap \text{Ker}(\psi)$  is nonzero by (2). Hence  $\varphi + \psi \in I$ . It follows that  $I$  is a two sided ideal. If  $\varphi \in A$ ,  $\varphi \notin I$ , then  $E \cong \varphi(E) \subset E$  is an injective submodule, hence  $E = \varphi(E)$  because  $E$  is indecomposable.

Proof of (4). Consider the ring map  $R \rightarrow A$  and let  $\mathfrak{p} \subset R$  be the inverse image of the maximal ideal  $I$ . Then it is clear that  $\mathfrak{p}$  is a prime ideal and that  $R \rightarrow A$  extends to  $R_{\mathfrak{p}} \rightarrow A$ . Thus  $E$  is an  $R_{\mathfrak{p}}$ -module. It follows from Lemma 3.3 that  $E$  is injective as an  $R_{\mathfrak{p}}$ -module.  $\square$

08Y8 **Lemma 5.7.** *Let  $\mathfrak{p} \subset R$  be a prime of a ring  $R$ . Let  $E$  be the injective hull of  $R/\mathfrak{p}$ . Then*

- (1)  $E$  is indecomposable,
- (2)  $E$  is the injective hull of  $\kappa(\mathfrak{p})$ ,
- (3)  $E$  is the injective hull of  $\kappa(\mathfrak{p})$  over the ring  $R_{\mathfrak{p}}$ .

**Proof.** As  $R/\mathfrak{p} \subset \kappa(\mathfrak{p})$  we can extend the embedding to a map  $\kappa(\mathfrak{p}) \rightarrow E$ . Hence (2) holds. For  $f \in R$ ,  $f \notin \mathfrak{p}$  the map  $f : \kappa(\mathfrak{p}) \rightarrow \kappa(\mathfrak{p})$  is an isomorphism hence the map  $f : E \rightarrow E$  is an isomorphism, see Lemma 5.3. Thus  $E$  is an  $R_{\mathfrak{p}}$ -module. It is injective as an  $R_{\mathfrak{p}}$ -module by Lemma 3.3. Finally, let  $E' \subset E$  be a nonzero injective  $R$ -submodule. Then  $J = (R/\mathfrak{p}) \cap E'$  is nonzero. After shrinking  $E'$  we may assume that  $E'$  is the injective hull of  $J$  (see Lemma 5.3 for example). Observe that  $R/\mathfrak{p}$  is an essential extension of  $J$  for example by Lemma 2.4. Hence  $E' \rightarrow E$  is an isomorphism by Lemma 5.3 part (3). Hence  $E$  is indecomposable.  $\square$

08Y9 **Lemma 5.8.** *Let  $R$  be a Noetherian ring. Let  $E$  be an indecomposable injective  $R$ -module. Then there exists a prime ideal  $\mathfrak{p}$  of  $R$  such that  $E$  is the injective hull of  $\kappa(\mathfrak{p})$ .*

**Proof.** Let  $\mathfrak{p}$  be the prime ideal found in Lemma 5.6. Say  $\mathfrak{p} = (f_1, \dots, f_r)$ . Pick a nonzero element  $x \in \bigcap \text{Ker}(f_i : E \rightarrow E)$ , see Lemma 5.6. Then  $(R_{\mathfrak{p}})x$  is a module isomorphic to  $\kappa(\mathfrak{p})$  inside  $E$ . We conclude by Lemma 5.6.  $\square$

08YA **Proposition 5.9** (Structure of injective modules over Noetherian rings). *Let  $R$  be a Noetherian ring. Every injective module is a direct sum of indecomposable injective modules. Every indecomposable injective module is the injective hull of the residue field at a prime.*

**Proof.** The second statement is Lemma 5.8. For the first statement, let  $I$  be an injective  $R$ -module. We will use transfinite induction to construct  $I_\alpha \subset I$  for ordinals  $\alpha$  which are direct sums of indecomposable injective  $R$ -modules  $E_{\beta+1}$  for  $\beta < \alpha$ . For  $\alpha = 0$  we let  $I_0 = 0$ . Suppose given an ordinal  $\alpha$  such that  $I_\alpha$  has been constructed. Then  $I_\alpha$  is an injective  $R$ -module by Lemma 3.8. Hence  $I \cong I_\alpha \oplus I'$ . If  $I' = 0$  we are done. If not, then  $I'$  has an associated prime by Algebra, Lemma 62.7. Thus  $I'$  contains a copy of  $R/\mathfrak{p}$  for some prime  $\mathfrak{p}$ . Hence  $I'$  contains an indecomposable submodule  $E$  by Lemmas 5.3 and 5.7. Set  $I_{\alpha+1} = I_\alpha \oplus E_\alpha$ . If  $\alpha$  is a limit ordinal and  $I_\beta$  has been constructed for  $\beta < \alpha$ , then we set  $I_\alpha = \bigcup_{\beta < \alpha} I_\beta$ . Observe that  $I_\alpha = \bigoplus_{\beta < \alpha} E_{\beta+1}$ . This concludes the proof.  $\square$

## 6. Duality over Artinian local rings

08YW Let  $(R, \mathfrak{m}, \kappa)$  be an artinian local ring. Recall that this implies  $R$  is Noetherian and that  $R$  has finite length as an  $R$ -module. Moreover an  $R$ -module is finite if and only if it has finite length. We will use these facts without further mention in this section. Please see Algebra, Sections 51 and 52 and Algebra, Proposition 59.6 for more details.

08YX **Lemma 6.1.** *Let  $(R, \mathfrak{m}, \kappa)$  be an artinian local ring. Let  $E$  be an injective hull of  $\kappa$ . For every finite  $R$ -module  $M$  we have*

$$\text{length}_R(M) = \text{length}_R(\text{Hom}_R(M, E))$$

*In particular, the injective hull  $E$  of  $\kappa$  is a finite  $R$ -module.*

**Proof.** Because  $E$  is an essential extension of  $\kappa$  we have  $\kappa = E[\mathfrak{m}]$  where  $E[\mathfrak{m}]$  is the  $\mathfrak{m}$ -torsion in  $E$  (notation as in More on Algebra, Section 78). Hence  $\text{Hom}_R(\kappa, E) \cong \kappa$  and the equality of lengths holds for  $M = \kappa$ . We prove the displayed equality of the lemma by induction on the length of  $M$ . If  $M$  is nonzero there exists a surjection  $M \rightarrow \kappa$  with kernel  $M'$ . Since the functor  $M \mapsto \text{Hom}_R(M, E)$  is exact we obtain a short exact sequence

$$0 \rightarrow \text{Hom}_R(\kappa, E) \rightarrow \text{Hom}_R(M, E) \rightarrow \text{Hom}_R(M', E) \rightarrow 0.$$

Additivity of length for this sequence and the sequence  $0 \rightarrow M' \rightarrow M \rightarrow \kappa \rightarrow 0$  and the equality for  $M'$  (induction hypothesis) and  $\kappa$  implies the equality for  $M$ . The final statement of the lemma follows as  $E = \text{Hom}_R(R, E)$ .  $\square$

08YY **Lemma 6.2.** *Let  $(R, \mathfrak{m}, \kappa)$  be an artinian local ring. Let  $E$  be an injective hull of  $\kappa$ . For any finite  $R$ -module  $M$  the evaluation map*

$$M \longrightarrow \text{Hom}_R(\text{Hom}_R(M, E), E)$$

*is an isomorphism. In particular  $R = \text{Hom}_R(E, E)$ .*

**Proof.** Observe that the displayed arrow is injective. Namely, if  $x \in M$  is a nonzero element, then there is a nonzero map  $Rx \rightarrow \kappa$  which we can extend to a map  $\varphi : M \rightarrow E$  that doesn't vanish on  $x$ . Since the source and target of the arrow have the same length by Lemma 6.1 we conclude it is an isomorphism. The final statement follows on taking  $M = R$ .  $\square$



To state the next lemma, denote  $\text{Mod}_R^{fg}$  the category of finite  $R$ -modules over a ring  $R$ .

08YZ **Lemma 6.3.** *Let  $(R, \mathfrak{m}, \kappa)$  be an artinian local ring. Let  $E$  be an injective hull of  $\kappa$ . The functor  $D(-) = \text{Hom}_R(-, E)$  induces an exact anti-equivalence  $\text{Mod}_R^{fg} \rightarrow \text{Mod}_R^{fg}$  and  $D \circ D \cong \text{id}$ .*

**Proof.** We have seen that  $D \circ D = \text{id}$  on  $\text{Mod}_R^{fg}$  in Lemma 6.2. It follows immediately that  $D$  is an anti-equivalence.  $\square$

08Z0 **Lemma 6.4.** *Assumptions and notation as in Lemma 6.3. Let  $I \subset R$  be an ideal and  $M$  a finite  $R$ -module. Then*

$$D(M[I]) = D(M)/ID(M) \quad \text{and} \quad D(M/IM) = D(M)[I]$$

**Proof.** Say  $I = (f_1, \dots, f_t)$ . Consider the map

$$M^{\oplus t} \xrightarrow{f_1, \dots, f_t} M$$

with cokernel  $M/IM$ . Applying the exact functor  $D$  we conclude that  $D(M/IM)$  is  $D(M)[I]$ . The other case is proved in the same way.  $\square$

## 7. Injective hull of the residue field

08Z1 Most of our results will be for Noetherian local rings in this section.

08Z2 **Lemma 7.1.** *Let  $R \rightarrow S$  be a surjective map of local rings with kernel  $I$ . Let  $E$  be the injective hull of the residue field of  $R$  over  $R$ . Then  $E[I]$  is the injective hull of the residue field of  $S$  over  $S$ .*

**Proof.** Observe that  $E[I] = \text{Hom}_R(S, E)$  as  $S = R/I$ . Hence  $E[I]$  is an injective  $S$ -module by Lemma 3.4. Since  $E$  is an essential extension of  $\kappa = R/\mathfrak{m}_R$  it follows that  $E[I]$  is an essential extension of  $\kappa$  as well. The result follows.  $\square$

08Z3 **Lemma 7.2.** *Let  $(R, \mathfrak{m}, \kappa)$  be a local ring. Let  $E$  be the injective hull of  $\kappa$ . Let  $M$  be a  $\mathfrak{m}$ -power torsion  $R$ -module with  $n = \dim_{\kappa}(M[\mathfrak{m}]) < \infty$ . Then  $M$  is isomorphic to a submodule of  $E^{\oplus n}$ .*

**Proof.** Observe that  $E^{\oplus n}$  is the injective hull of  $\kappa^{\oplus n} = M[\mathfrak{m}]$ . Thus there is an  $R$ -module map  $M \rightarrow E^{\oplus n}$  which is injective on  $M[\mathfrak{m}]$ . Since  $M$  is  $\mathfrak{m}$ -power torsion the inclusion  $M[\mathfrak{m}] \subset M$  is an essential extension (for example by Lemma 2.4) we conclude that the kernel of  $M \rightarrow E^{\oplus n}$  is zero.  $\square$

08Z4 **Lemma 7.3.** *Let  $(R, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $E$  be an injective hull of  $\kappa$  over  $R$ . Let  $E_n$  be an injective hull of  $\kappa$  over  $R/\mathfrak{m}^n$ . Then  $E = \bigcup E_n$  and  $E_n = E[\mathfrak{m}^n]$ .*

**Proof.** We have  $E_n = E[\mathfrak{m}^n]$  by Lemma 7.1. We have  $E = \bigcup E_n$  because  $\bigcup E_n = E[\mathfrak{m}^{\infty}]$  is an injective  $R$ -submodule which contains  $\kappa$ , see Lemma 3.10.  $\square$

The following lemma tells us the injective hull of the residue field of a Noetherian local ring only depends on the completion.

08Z5 **Lemma 7.4.** *Let  $R \rightarrow S$  be a flat local homomorphism of local Noetherian rings such that  $R/\mathfrak{m}_R \cong S/\mathfrak{m}_R S$ . Then the injective hull of the residue field of  $R$  is the injective hull of the residue field of  $S$ .*

**Proof.** Set  $\kappa = R/\mathfrak{m}_R = S/\mathfrak{m}_S$ . Let  $E_R$  be the injective hull of  $\kappa$  over  $R$ . Let  $E_S$  be the injective hull of  $\kappa$  over  $S$ . Observe that  $E_S$  is an injective  $R$ -module by Lemma 3.2. Choose an extension  $E_R \rightarrow E_S$  of the identification of residue fields. This map is an isomorphism by Lemma 7.3 because  $R \rightarrow S$  induces an isomorphism  $R/\mathfrak{m}_R^n \rightarrow S/\mathfrak{m}_S^n$  for all  $n$ .  $\square$

08Z6 **Lemma 7.5.** *Let  $(R, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $E$  be an injective hull of  $\kappa$  over  $R$ . Then  $\text{Hom}_R(E, E)$  is canonically isomorphic to the completion of  $R$ .*

**Proof.** Write  $E = \bigcup E_n$  with  $E_n = E[\mathfrak{m}^n]$  as in Lemma 7.3. Any endomorphism of  $E$  preserves this filtration. Hence

$$\text{Hom}_R(E, E) = \lim \text{Hom}_R(E_n, E_n)$$

The lemma follows as  $\text{Hom}_R(E_n, E_n) = \text{Hom}_{R/\mathfrak{m}^n}(E_n, E_n) = R/\mathfrak{m}^n$  by Lemma 6.2.  $\square$

08Z7 **Lemma 7.6.** *Let  $(R, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $E$  be an injective hull of  $\kappa$  over  $R$ . Then  $E$  satisfies the descending chain condition.*

**Proof.** If  $E \subset M_1 \subset M_2 \dots$  is a sequence of submodules, then

$$\text{Hom}_R(E, E) \rightarrow \text{Hom}_R(M_1, E) \rightarrow \text{Hom}_R(M_2, E) \rightarrow \dots$$

is sequence of surjections. By Lemma 7.5 each of these is a module over the completion  $R^\wedge = \text{Hom}_R(E, E)$ . Since  $R^\wedge$  is Noetherian (Algebra, Lemma 96.6) the sequence stabilizes:  $\text{Hom}_R(M_n, E) = \text{Hom}_R(M_{n+1}, E) = \dots$ . Since  $E$  is injective, this can only happen if  $\text{Hom}_R(M_n/M_{n+1}, E)$  is zero. However, if  $M_n/M_{n+1}$  is nonzero, then it contains a nonzero element annihilated by  $\mathfrak{m}$ , because  $E$  is  $\mathfrak{m}$ -power torsion by Lemma 7.3. In this case  $M_n/M_{n+1}$  has a nonzero map into  $E$ , contradicting the assumed vanishing. This finishes the proof.  $\square$

08Z8 **Lemma 7.7.** *Let  $(R, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $E$  be an injective hull of  $\kappa$ .*

- (1) *For an  $R$ -module  $M$  the following are equivalent:*
  - (a)  *$M$  satisfies the ascending chain condition,*
  - (b)  *$M$  is a finite  $R$ -module, and*
  - (c) *there exist  $n, m$  and an exact sequence  $R^{\oplus m} \rightarrow R^{\oplus n} \rightarrow M \rightarrow 0$ .*
- (2) *For an  $R$ -module  $M$  the following are equivalent:*
  - (a)  *$M$  satisfies the descending chain condition,*
  - (b)  *$M$  is  $\mathfrak{m}$ -power torsion and  $\dim_\kappa(M[\mathfrak{m}]) < \infty$ , and*
  - (c) *there exist  $n, m$  and an exact sequence  $0 \rightarrow M \rightarrow E^{\oplus n} \rightarrow E^{\oplus m}$ .*

**Proof.** We omit the proof of (1).

Let  $M$  be an  $R$ -module with the descending chain condition. Let  $x \in M$ . Then  $\mathfrak{m}^n x$  is a descending chain of submodules, hence stabilizes. Thus  $\mathfrak{m}^n x = \mathfrak{m}^{n+1} x$  for some  $n$ . By Nakayama's lemma (Algebra, Lemma 19.1) this implies  $\mathfrak{m}^n x = 0$ , i.e.,  $x$  is  $\mathfrak{m}$ -power torsion. Since  $M[\mathfrak{m}]$  is a vector space over  $\kappa$  it has to be finite dimensional in order to have the descending chain condition.

Assume that  $M$  is  $\mathfrak{m}$ -power torsion and has a finite dimensional  $\mathfrak{m}$ -torsion submodule  $M[\mathfrak{m}]$ . By Lemma 7.2 we see that  $M$  is a submodule of  $E^{\oplus n}$  for some  $n$ . Consider the quotient  $N = E^{\oplus n}/M$ . By Lemma 7.6 the module  $E$  has the descending chain condition hence so do  $E^{\oplus n}$  and  $N$ . Therefore  $N$  satisfies (2)(a) which

implies  $N$  satisfies (2)(b) by the second paragraph of the proof. Thus by Lemma 7.2 again we see that  $N$  is a submodule of  $E^{\oplus m}$  for some  $m$ . Thus we have a short exact sequence  $0 \rightarrow M \rightarrow E^{\oplus n} \rightarrow E^{\oplus m}$ .

Assume we have a short exact sequence  $0 \rightarrow M \rightarrow E^{\oplus n} \rightarrow E^{\oplus m}$ . Since  $E$  satisfies the descending chain condition by Lemma 7.6 so does  $M$ .  $\square$

08Z9 **Proposition 7.8** (Matlis duality). *Let  $(R, \mathfrak{m}, \kappa)$  be a complete local Noetherian ring. Let  $E$  be an injective hull of  $\kappa$  over  $R$ . The functor  $D(-) = \text{Hom}_R(-, E)$  induces an anti-equivalence*

$$\left\{ \begin{array}{l} R\text{-modules with the} \\ \text{descending chain condition} \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{l} R\text{-modules with the} \\ \text{ascending chain condition} \end{array} \right\}$$

and we have  $D \circ D = \text{id}$  on either side of the equivalence.

**Proof.** By Lemma 7.5 we have  $R = \text{Hom}_R(E, E) = D(E)$ . Of course we have  $E = \text{Hom}_R(R, E) = D(R)$ . Since  $E$  is injective the functor  $D$  is exact. The result now follows immediately from the description of the categories in Lemma 7.7.  $\square$

## 8. Deriving torsion

0BJA Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal (if  $I$  is not finitely generated perhaps a different definition should be used). Let  $Z = V(I) \subset \text{Spec}(A)$ . Recall that the category  $I^\infty$ -torsion of  $I$ -power torsion modules only depends on the closed subset  $Z$  and not on the choice of the finitely generated ideal  $I$  such that  $Z = V(I)$ , see More on Algebra, Lemma 77.6. In this section we will consider the functor

$$H_I^0 : \text{Mod}_A \longrightarrow I^\infty\text{-torsion}, \quad M \longmapsto M[I^\infty] = \bigcup M[I^n]$$

which sends  $M$  to the submodule of  $I$ -power torsion.

Let  $A$  be a ring and let  $I$  be a finitely generated ideal. Note that  $I^\infty$ -torsion is a Grothendieck abelian category (direct sums exist, filtered colimits are exact, and  $\bigoplus A/I^n$  is a generator by More on Algebra, Lemma 77.2). Hence the derived category  $D(I^\infty\text{-torsion})$  exists, see Injectives, Remark 13.3. Our functor  $H_I^0$  is left exact and has a derived extension which we will denote

$$R\Gamma_I : D(A) \longrightarrow D(I^\infty\text{-torsion}).$$

**Warning:** this functor does not deserve the name local cohomology unless the ring  $A$  is Noetherian. The functors  $H_I^0$ ,  $R\Gamma_I$ , and the satellites  $H_I^p$  only depend on the closed subset  $Z \subset \text{Spec}(A)$  and not on the choice of the finitely generated ideal  $I$  such that  $V(I) = Z$ . However, we insist on using the subscript  $I$  for the functors above as the notation  $R\Gamma_Z$  is going to be used for a different functor, see (9.0.1), which agrees with the functor  $R\Gamma_I$  only (as far as we know) in case  $A$  is Noetherian (see Lemma 10.1).

0A6L **Lemma 8.1.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. The functor  $R\Gamma_I$  is right adjoint to the functor  $D(I^\infty\text{-torsion}) \rightarrow D(A)$ .*

**Proof.** This follows from the fact that taking  $I$ -power torsion submodules is the right adjoint to the inclusion functor  $I^\infty\text{-torsion} \rightarrow \text{Mod}_A$ . See Derived Categories, Lemma 28.5.  $\square$

0954 **Lemma 8.2.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. For any object  $K$  of  $D(A)$  we have*

$$R\Gamma_I(K) = \text{hocolim } R\text{Hom}_A(A/I^n, K)$$

in  $D(A)$  and

$$R^q\Gamma_I(K) = \text{colim}_n \text{Ext}_A^q(A/I^n, K)$$

as modules for all  $q \in \mathbf{Z}$ .

**Proof.** Let  $J^\bullet$  be a  $K$ -injective complex representing  $K$ . Then

$$R\Gamma_I(K) = J^\bullet[I^\infty] = \text{colim } J^\bullet[I^n] = \text{colim } \text{Hom}_A(A/I^n, J^\bullet)$$

The first equality is the definition. By Derived Categories, Lemma 31.7 we obtain the second equality. The third equality is clear because  $H^q(\text{Hom}_A(A/I^n, J^\bullet)) = \text{Ext}_A^q(A/I^n, K)$  and because filtered colimits are exact in the category of abelian groups.  $\square$

0A6M **Lemma 8.3.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. Let  $K^\bullet$  be a complex of  $A$ -modules such that  $f : K^\bullet \rightarrow K^\bullet$  is an isomorphism for some  $f \in I$ , i.e.,  $K^\bullet$  is a complex of  $A_f$ -modules. Then  $R\Gamma_I(K^\bullet) = 0$ .*

**Proof.** Namely, in this case the cohomology modules of  $R\Gamma_I(K^\bullet)$  are both  $f$ -power torsion and  $f$  acts by automorphisms. Hence the cohomology modules are zero and hence the object is zero.  $\square$

Let  $A$  be a ring and  $I \subset A$  a finitely generated ideal. By More on Algebra, Lemma 77.5 the category of  $I$ -power torsion modules is a Serre subcategory of the category of all  $A$ -modules, hence there is a functor

0A6N (8.3.1) 
$$D(I^\infty\text{-torsion}) \rightarrow D_{I^\infty\text{-torsion}}(A)$$

see Derived Categories, Section 13.

0A6P **Lemma 8.4.** *Let  $A$  be a ring and let  $I$  be a finitely generated ideal. Let  $M$  and  $N$  be  $I$ -power torsion modules.*

- (1)  $\text{Hom}_{D(A)}(M, N) = \text{Hom}_{D(I^\infty\text{-torsion})}(M, N)$ ,
- (2)  $\text{Ext}_{D(A)}^1(M, N) = \text{Ext}_{D(I^\infty\text{-torsion})}^1(M, N)$ ,
- (3)  $\text{Ext}_{D(I^\infty\text{-torsion})}^2(M, N) \rightarrow \text{Ext}_{D(A)}^2(M, N)$  is not surjective in general,
- (4) (8.3.1) is not an equivalence in general.

**Proof.** Parts (1) and (2) follow immediately from the fact that  $I$ -power torsion forms a Serre subcategory of  $\text{Mod}_A$ . Part (4) follows from part (3).

For part (3) let  $A$  be a ring with an element  $f \in A$  such that  $A[f]$  contains a nonzero element  $x$  annihilated by  $f$  and  $A$  contains elements  $x_n$  with  $f^n x_n = x$ . Such a ring  $A$  exists because we can take

$$A = \mathbf{Z}[f, x, x_n]/(fx, f^n x_n - x)$$

Given  $A$  set  $I = (f)$ . Then the exact sequence

$$0 \rightarrow A[f] \rightarrow A \xrightarrow{f} A \rightarrow A/fA \rightarrow 0$$

defines an element in  $\text{Ext}_A^2(A/fA, A[f])$ . We claim this element does not come from an element of  $\text{Ext}_{D(f^\infty\text{-torsion})}^2(A/fA, A[f])$ . Namely, if it did, then there would be an exact sequence

$$0 \rightarrow A[f] \rightarrow M \rightarrow N \rightarrow A/fA \rightarrow 0$$

where  $M$  and  $N$  are  $f$ -power torsion modules defining the same 2 extension class. Since  $A \rightarrow A$  is a complex of free modules and since the 2 extension classes are the same we would be able to find a map

$$\begin{array}{ccccccccc} 0 & \longrightarrow & A[f] & \longrightarrow & A & \longrightarrow & A & \longrightarrow & A/fA & \longrightarrow & 0 \\ & & \downarrow & & \downarrow \varphi & & \downarrow \psi & & \downarrow & & \\ 0 & \longrightarrow & A[f] & \longrightarrow & M & \longrightarrow & N & \longrightarrow & A/fA & \longrightarrow & 0 \end{array}$$

(some details omitted). Then we could replace  $M$  by the image of  $\varphi$  and  $N$  by the image of  $\psi$ . Then  $M$  would be a cyclic module, hence  $f^n M = 0$  for some  $n$ . Considering  $\varphi(x_{n+1})$  we get a contradiction with the fact that  $f^{n+1}x_n = x$  is nonzero in  $A[f]$ .  $\square$

### 9. Local cohomology

0952 Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. Set  $Z = V(I) \subset \text{Spec}(A)$ . We will construct a functor

0A6Q (9.0.1) 
$$R\Gamma_Z : D(A) \longrightarrow D_{I^\infty\text{-torsion}}(A).$$

which is right adjoint to the inclusion functor. For notation see Section 8. The cohomology modules of  $R\Gamma_Z(K)$  are the *local cohomology groups of  $K$  with respect to  $Z$* . In fact, we will show  $R\Gamma_Z$  computes cohomology with support in  $Z$  for the associated complex of quasi-coherent sheaves on  $\text{Spec}(A)$ . See Local Cohomology, Lemma 2.1. By Lemma 8.4 this functor will in general **not** be equal to  $R\Gamma_I(-)$  even viewed as functors into  $D(A)$ . In Section 10 we will show that if  $A$  is Noetherian, then the two agree.

0A6R **Lemma 9.1.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. There exists a right adjoint  $R\Gamma_Z$  (9.0.1) to the inclusion functor  $D_{I^\infty\text{-torsion}}(A) \rightarrow D(A)$ . In fact, if  $I$  is generated by  $f_1, \dots, f_r \in A$ , then we have*

$$R\Gamma_Z(K) = (A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0}f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \otimes_A^L K$$

functorially in  $K \in D(A)$ .

**Proof.** Say  $I = (f_1, \dots, f_r)$  is an ideal. Let  $K^\bullet$  be a complex of  $A$ -modules. There is a canonical map of complexes

$$(A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0}f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \longrightarrow A.$$

from the extended Čech complex to  $A$ . Tensoring with  $K^\bullet$ , taking associated total complex, we get a map

$$\text{Tot} \left( K^\bullet \otimes_A (A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0}f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \right) \longrightarrow K^\bullet$$

in  $D(A)$ . We claim the cohomology modules of the complex on the left are  $I$ -power torsion, i.e., the LHS is an object of  $D_{I^\infty\text{-torsion}}(A)$ . Namely, we have

$$(A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0}f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) = \text{colim } K(A, f_1^n, \dots, f_r^n)$$

by More on Algebra, Lemma 26.13. Moreover, multiplication by  $f_i^n$  on the complex  $K(A, f_1^n, \dots, f_r^n)$  is homotopic to zero by More on Algebra, Lemma 26.6. Since

$$H^q(\text{LHS}) = \text{colim } H^q(\text{Tot}(K^\bullet \otimes_A K(A, f_1^n, \dots, f_r^n)))$$

we obtain our claim. On the other hand, if  $K^\bullet$  is an object of  $D_{I^\infty\text{-torsion}}(A)$ , then the complexes  $K^\bullet \otimes_A A_{f_{i_0} \dots f_{i_p}}$  have vanishing cohomology. Hence in this case the map  $LHS \rightarrow K^\bullet$  is an isomorphism in  $D(A)$ . The construction

$$R\Gamma_Z(K^\bullet) = \text{Tot} \left( K^\bullet \otimes_A (A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0} f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \right)$$

is functorial in  $K^\bullet$  and defines an exact functor  $D(A) \rightarrow D_{I^\infty\text{-torsion}}(A)$  between triangulated categories. It follows formally from the existence of the natural transformation  $R\Gamma_Z \rightarrow \text{id}$  given above and the fact that this evaluates to an isomorphism on  $K^\bullet$  in the subcategory, that  $R\Gamma_Z$  is the desired right adjoint.  $\square$

0BJB **Lemma 9.2.** *Let  $A \rightarrow B$  be a ring homomorphism and let  $I \subset A$  be a finitely generated ideal. Set  $J = IB$ . Set  $Z = V(I)$  and  $Y = V(J)$ . Then*

$$R\Gamma_Z(M_A) = R\Gamma_Y(M)_A$$

*functorially in  $M \in D(B)$ . Here  $(-)_A$  denotes the restriction functors  $D(B) \rightarrow D(A)$  and  $A : D_{J^\infty\text{-torsion}}(B) \rightarrow D_{I^\infty\text{-torsion}}(A)$ .*

**Proof.** This follows from uniqueness of adjoint functors as both  $R\Gamma_Z((-)_A)$  and  $R\Gamma_Y(-)_A$  are right adjoint to the functor  $D_{I^\infty\text{-torsion}}(A) \rightarrow D(B)$ ,  $K \mapsto K \otimes_A^L B$ . Alternatively, one can use the description of  $R\Gamma_Z$  and  $R\Gamma_Y$  in terms of alternating Čech complexes (Lemma 9.1). Namely, if  $I = (f_1, \dots, f_r)$  then  $J$  is generated by the images  $g_1, \dots, g_r \in B$  of  $f_1, \dots, f_r$ . Then the statement of the lemma follows from the existence of a canonical isomorphism

$$\begin{aligned} M_A \otimes_A (A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0} f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \\ = M \otimes_B (B \rightarrow \prod_{i_0} B_{g_{i_0}} \rightarrow \prod_{i_0 < i_1} B_{g_{i_0} g_{i_1}} \rightarrow \dots \rightarrow B_{g_1 \dots g_r}) \end{aligned}$$

for any  $B$ -module  $M$ .  $\square$

0ALZ **Lemma 9.3.** *Let  $A \rightarrow B$  be a ring homomorphism and let  $I \subset A$  be a finitely generated ideal. Set  $J = IB$ . Let  $Z = V(I)$  and  $Y = V(J)$ . Then*

$$R\Gamma_Z(K) \otimes_A^L B = R\Gamma_Y(K \otimes_A^L B)$$

*functorially in  $K \in D(A)$ .*

**Proof.** This follows from uniqueness of adjoint functors as both  $R\Gamma_Z(-) \otimes_A^L B$  and  $R\Gamma_Y(- \otimes_A^L B)$  are right adjoint to the functor  $D_{J^\infty\text{-torsion}}(B) \rightarrow D(A)$ . Alternatively, one can use the description of  $R\Gamma_Z$  and  $R\Gamma_Y$  in terms of alternating Čech complexes (Lemma 9.1) and use that formation of the extended Čech complex commutes with base change.  $\square$

0A6S **Lemma 9.4.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. Let  $K^\bullet$  be a complex of  $A$ -modules such that  $f : K^\bullet \rightarrow K^\bullet$  is an isomorphism for some  $f \in I$ , i.e.,  $K^\bullet$  is a complex of  $A_f$ -modules. Then  $R\Gamma_Z(K^\bullet) = 0$ .*

**Proof.** Namely, in this case the cohomology modules of  $R\Gamma_Z(K^\bullet)$  are both  $f$ -power torsion and  $f$  acts by automorphisms. Hence the cohomology modules are zero and hence the object is zero.  $\square$

0ALY **Lemma 9.5.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. For  $K, L \in D(A)$  we have*

$$R\Gamma_Z(K \otimes_A^L L) = K \otimes_A^L R\Gamma_Z(L) = R\Gamma_Z(K) \otimes_A^L L = R\Gamma_Z(K) \otimes_A^L R\Gamma_Z(L)$$

If  $K$  or  $L$  is in  $D_{I^\infty\text{-torsion}}(A)$  then so is  $K \otimes_A^{\mathbf{L}} L$ .

**Proof.** By Lemma 9.1 we know that  $R\Gamma_Z$  is given by  $C \otimes^{\mathbf{L}} -$  for some  $C \in D(A)$ . Hence, for  $K, L \in D(A)$  general we have

$$R\Gamma_Z(K \otimes_A^{\mathbf{L}} L) = K \otimes^{\mathbf{L}} L \otimes_A^{\mathbf{L}} C = K \otimes_A^{\mathbf{L}} R\Gamma_Z(L)$$

The other equalities follow formally from this one. This also implies the last statement of the lemma.  $\square$

0BJC **Lemma 9.6.** *Let  $A$  be a ring and let  $I, J \subset A$  be finitely generated ideals. Set  $Z = V(I)$  and  $Y = V(J)$ . Then  $Z \cap Y = V(I + J)$  and  $R\Gamma_Y \circ R\Gamma_Z = R\Gamma_{Y \cap Z}$  as functors  $D(A) \rightarrow D_{(I+J)^\infty\text{-torsion}}(A)$ . For  $K \in D^+(A)$  there is a spectral sequence*

$$E_2^{p,q} = H_Y^p(H_Z^q(K)) \Rightarrow H_{Y \cap Z}^{p+q}(K)$$

as in *Derived Categories, Lemma 22.2*.

**Proof.** There is a bit of abuse of notation in the lemma as strictly speaking we cannot compose  $R\Gamma_Y$  and  $R\Gamma_Z$ . The meaning of the statement is simply that we are composing  $R\Gamma_Z$  with the inclusion  $D_{I^\infty\text{-torsion}}(A) \rightarrow D(A)$  and then with  $R\Gamma_Y$ . Then the equality  $R\Gamma_Y \circ R\Gamma_Z = R\Gamma_{Y \cap Z}$  follows from the fact that

$$D_{I^\infty\text{-torsion}}(A) \rightarrow D(A) \xrightarrow{R\Gamma_Y} D_{(I+J)^\infty\text{-torsion}}(A)$$

is right adjoint to the inclusion  $D_{(I+J)^\infty\text{-torsion}}(A) \rightarrow D_{I^\infty\text{-torsion}}(A)$ . Alternatively one can prove the formula using Lemma 9.1 and the fact that the tensor product of extended Čech complexes on  $f_1, \dots, f_r$  and  $g_1, \dots, g_m$  is the extended Čech complex on  $f_1, \dots, f_r, g_1, \dots, g_m$ . The final assertion follows from this and the cited lemma.  $\square$

The following lemma is the analogue of More on Algebra, Lemma 80.21 for complexes with torsion cohomologies.

0AM0 **Lemma 9.7.** *Let  $A \rightarrow B$  be a flat ring map and let  $I \subset A$  be a finitely generated ideal such that  $A/I = B/IB$ . Then base change and restriction induce quasi-inverse equivalences  $D_{I^\infty\text{-torsion}}(A) = D_{(IB)^\infty\text{-torsion}}(B)$ .*

**Proof.** More precisely the functors are  $K \mapsto K \otimes_A^{\mathbf{L}} B$  for  $K$  in  $D_{I^\infty\text{-torsion}}(A)$  and  $M \mapsto M_A$  for  $M$  in  $D_{(IB)^\infty\text{-torsion}}(B)$ . The reason this works is that  $H^i(K \otimes_A^{\mathbf{L}} B) = H^i(K) \otimes_A B = H^i(K)$ . The first equality holds as  $A \rightarrow B$  is flat and the second by More on Algebra, Lemma 78.2.  $\square$

The following lemma was shown for  $\text{Hom}$  and  $\text{Ext}^1$  of modules in More on Algebra, Lemmas 78.3 and 78.8.

05EH **Lemma 9.8.** *Let  $A \rightarrow B$  be a flat ring map and let  $I \subset A$  be a finitely generated ideal such that  $A/I \rightarrow B/IB$  is an isomorphism. For  $K \in D_{I^\infty\text{-torsion}}(A)$  and  $L \in D(A)$  the map*

$$R\text{Hom}_A(K, L) \longrightarrow R\text{Hom}_B(K \otimes_A B, L \otimes_A B)$$

is a quasi-isomorphism. In particular, if  $M, N$  are  $A$ -modules and  $M$  is  $I$ -power torsion, then the canonical map

$$\text{Ext}_A^i(M, N) \longrightarrow \text{Ext}_B^i(M \otimes_A B, N \otimes_A B)$$

is an isomorphism for all  $i$ .

**Proof.** Let  $Z = V(I) \subset \text{Spec}(A)$  and  $Y = V(IB) \subset \text{Spec}(B)$ . Since the cohomology modules of  $K$  are  $I$  power torsion, the canonical map  $R\Gamma_Z(L) \rightarrow L$  induces an isomorphism

$$R\text{Hom}_A(K, R\Gamma_Z(L)) \rightarrow R\text{Hom}_A(K, L)$$

in  $D(A)$ . Similarly, the cohomology modules of  $K \otimes_A B$  are  $IB$  power torsion and we have an isomorphism

$$R\text{Hom}_B(K \otimes_A B, R\Gamma_Y(L \otimes_A B)) \rightarrow R\text{Hom}_B(K \otimes_A B, L \otimes_A B)$$

in  $D(B)$ . By Lemma 9.3 we have  $R\Gamma_Z(L) \otimes_A B = R\Gamma_Y(L \otimes_A B)$ . Hence it suffices to show that the map

$$R\text{Hom}_A(K, R\Gamma_Z(L)) \rightarrow R\text{Hom}_B(K \otimes_A B, R\Gamma_Z(L) \otimes_A B)$$

is a quasi-isomorphism. This follows from Lemma 9.7.  $\square$

### 10. Local cohomology for Noetherian rings

0BJD Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. Set  $Z = V(I) \subset \text{Spec}(A)$ . Recall that (8.3.1) is the functor

$$D(I^\infty\text{-torsion}) \rightarrow D_{I^\infty\text{-torsion}}(A)$$

In fact, there is a natural transformation of functors

0A6U (10.0.1)  $(8.3.1) \circ R\Gamma_I(-) \longrightarrow R\Gamma_Z(-)$

Namely, given a complex of  $A$ -modules  $K^\bullet$  the canonical map  $R\Gamma_I(K^\bullet) \rightarrow K^\bullet$  in  $D(A)$  factors (uniquely) through  $R\Gamma_Z(K^\bullet)$  as  $R\Gamma_I(K^\bullet)$  has  $I$ -power torsion cohomology modules (see Lemma 8.1). In general this map is not an isomorphism (we've seen this in Lemma 8.4).

0955 **Lemma 10.1.** *Let  $A$  be a Noetherian ring and let  $I \subset A$  be an ideal.*

- (1) *the adjunction  $R\Gamma_I(K) \rightarrow K$  is an isomorphism for  $K \in D_{I^\infty\text{-torsion}}(A)$ ,*
- (2) *the functor (8.3.1)  $D(I^\infty\text{-torsion}) \rightarrow D_{I^\infty\text{-torsion}}(A)$  is an equivalence,*
- (3) *the transformation of functors (10.0.1) is an isomorphism, in other words  $R\Gamma_I(K) = R\Gamma_Z(K)$  for  $K \in D(A)$ .*

**Proof.** A formal argument, which we omit, shows that it suffices to prove (1).

Let  $M$  be an  $I$ -power torsion  $A$ -module. Choose an embedding  $M \rightarrow J$  into an injective  $A$ -module. Then  $J[I^\infty]$  is an injective  $A$ -module, see Lemma 3.10, and we obtain an embedding  $M \rightarrow J[I^\infty]$ . Thus every  $I$ -power torsion module has an injective resolution  $M \rightarrow J^\bullet$  with  $J^n$  also  $I$ -power torsion. It follows that  $R\Gamma_I(M) = M$  (this is not a triviality and this is not true in general if  $A$  is not Noetherian). Next, suppose that  $K \in D_{I^\infty\text{-torsion}}^+(A)$ . Then the spectral sequence

$$R^q\Gamma_I(H^p(K)) \Rightarrow R^{p+q}\Gamma_I(K)$$

(Derived Categories, Lemma 21.3) converges and above we have seen that only the terms with  $q = 0$  are nonzero. Thus we see that  $R\Gamma_I(K) \rightarrow K$  is an isomorphism.

Suppose  $K$  is an arbitrary object of  $D_{I^\infty\text{-torsion}}(A)$ . We have

$$R^q\Gamma_I(K) = \text{colim Ext}_A^q(A/I^n, K)$$



by Lemma 8.2. Choose  $f_1, \dots, f_r \in A$  generating  $I$ . Let  $K_n^\bullet = K(A, f_1^n, \dots, f_r^n)$  be the Koszul complex with terms in degrees  $-r, \dots, 0$ . Since the pro-objects  $\{A/I^n\}$  and  $\{K_n^\bullet\}$  in  $D(A)$  are the same by More on Algebra, Lemma 82.1, we see that

$$R^q\Gamma_I(K) = \operatorname{colim} \operatorname{Ext}_A^q(K_n^\bullet, K)$$

Pick any complex  $K^\bullet$  of  $A$ -modules representing  $K$ . Since  $K_n^\bullet$  is a finite complex of finite free modules we see that

$$\operatorname{Ext}_A^q(K_n, K) = H^q(\operatorname{Tot}((K_n^\bullet)^\vee \otimes_A K^\bullet))$$

where  $(K_n^\bullet)^\vee$  is the dual of the complex  $K_n^\bullet$ . See More on Algebra, Lemma 66.2. As  $(K_n^\bullet)^\vee$  is a complex of finite free  $A$ -modules sitting in degrees  $0, \dots, r$  we see that the terms of the complex  $\operatorname{Tot}((K_n^\bullet)^\vee \otimes_A K^\bullet)$  are the same as the terms of the complex  $\operatorname{Tot}((K_n^\bullet)^\vee \otimes_A \tau_{\geq q-r-2} K^\bullet)$  in degrees  $q-1$  and higher. Hence we see that

$$\operatorname{Ext}_A^q(K_n, K) = \operatorname{Ext}_A^q(K_n, \tau_{\geq q-r-2} K)$$

for all  $n$ . It follows that

$$R^q\Gamma_I(K) = R^q\Gamma_I(\tau_{\geq q-r-2} K) = H^q(\tau_{\geq q-r-2} K) = H^q(K)$$

Thus we see that the map  $R\Gamma_I(K) \rightarrow K$  is an isomorphism.  $\square$

0956 **Lemma 10.2.** *If  $A$  is a Noetherian ring and  $I = (f_1, \dots, f_r)$  an ideal. There are canonical isomorphisms*

$$R\Gamma_I(A) \rightarrow (A \rightarrow \prod_{i_0} A_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} A_{f_{i_0} f_{i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}) \rightarrow R\Gamma_Z(A)$$

in  $D(A)$ .

**Proof.** This follows from Lemma 10.1 and the computation of the functor  $R\Gamma_Z$  in Lemma 9.1.  $\square$

0957 **Lemma 10.3.** *If  $A \rightarrow B$  is a homomorphism of Noetherian rings and  $I \subset A$  is an ideal, then in  $D(B)$  we have*

$$R\Gamma_I(A) \otimes_A^{\mathbf{L}} B = R\Gamma_Z(A) \otimes_A^{\mathbf{L}} B = R\Gamma_Y(B) = R\Gamma_{IB}(B)$$

where  $Y = V(IB) \subset \operatorname{Spec}(B)$ .

**Proof.** Combine Lemmas 10.2 and 9.3.  $\square$

## 11. Depth

0AVY In this section we revisit the notion of depth introduced in Algebra, Section 71.

0AVZ **Lemma 11.1.** *Let  $A$  be a Noetherian ring, let  $I \subset A$  be an ideal, and let  $M$  be a finite  $A$ -module such that  $IM \neq M$ . Then the following integers are equal:*

- (1)  $\operatorname{depth}_I(M)$ ,
- (2) the smallest integer  $i$  such that  $\operatorname{Ext}_A^i(A/I, M)$  is nonzero, and
- (3) the smallest integer  $i$  such that  $H_I^i(M)$  is nonzero.

Moreover, we have  $\operatorname{Ext}_A^i(N, M) = 0$  for  $i < \operatorname{depth}_I(M)$  for any finite  $A$ -module  $N$  annihilated by a power of  $I$ .

**Proof.** We prove the equality of (1) and (2) by induction on  $\text{depth}_I(M)$  which is allowed by Algebra, Lemma 71.4.

Base case. If  $\text{depth}_I(M) = 0$ , then  $I$  is contained in the union of the associated primes of  $M$  (Algebra, Lemma 62.9). By prime avoidance (Algebra, Lemma 14.2) we see that  $I \subset \mathfrak{p}$  for some associated prime  $\mathfrak{p}$ . Hence  $\text{Hom}_A(A/I, M)$  is nonzero. Thus equality holds in this case.

Assume that  $\text{depth}_I(M) > 0$ . Let  $f \in I$  be a nonzerodivisor on  $M$  such that  $\text{depth}_I(M/fM) = \text{depth}_I(M) - 1$ . Consider the short exact sequence

$$0 \rightarrow M \rightarrow M \rightarrow M/fM \rightarrow 0$$

and the associated long exact sequence for  $\text{Ext}_A^*(A/I, -)$ . Note that  $\text{Ext}_A^i(A/I, M)$  is a finite  $A/I$ -module (Algebra, Lemmas 70.9 and 70.8). Hence we obtain

$$\text{Hom}_A(A/I, M/fM) = \text{Ext}_A^1(A/I, M)$$

and short exact sequences

$$0 \rightarrow \text{Ext}_A^i(A/I, M) \rightarrow \text{Ext}_A^i(A/I, M/fM) \rightarrow \text{Ext}_A^{i+1}(A/I, M) \rightarrow 0$$

Thus the equality of (1) and (2) by induction.

Observe that  $\text{depth}_I(M) = \text{depth}_{I^n}(M)$  for all  $n \geq 1$  for example by Algebra, Lemma 67.8. Hence by the equality of (1) and (2) we see that  $\text{Ext}_A^i(A/I^n, M) = 0$  for all  $n$  and  $i < \text{depth}_I(M)$ . Let  $N$  be a finite  $A$ -module annihilated by a power of  $I$ . Then we can choose a short exact sequence

$$0 \rightarrow N' \rightarrow (A/I^n)^{\oplus m} \rightarrow N \rightarrow 0$$

for some  $n, m \geq 0$ . Then  $\text{Hom}_A(N, M) \subset \text{Hom}_A((A/I^n)^{\oplus m}, M)$  and  $\text{Ext}_A^i(N, M) \subset \text{Ext}_A^{i-1}(N', M)$  for  $i < \text{depth}_I(M)$ . Thus a simply induction argument shows that the final statement of the lemma holds.

Finally, we prove that (3) is equal to (1) and (2). We have  $H_I^p(M) = \text{colim} \text{Ext}_A^p(A/I^n, M)$  by Lemma 8.2. Thus we see that  $H_I^i(M) = 0$  for  $i < \text{depth}_I(M)$ . For  $i = \text{depth}_I(M)$ , using the vanishing of  $\text{Ext}_A^{i-1}(A/I^n, M)$  we see that the map  $\text{Ext}_A^i(A/I, M) \rightarrow H_I^i(M)$  is injective which proves nonvanishing in the correct degree.  $\square$

0BUV **Lemma 11.2.** *Let  $A$  be a Noetherian ring. Let  $0 \rightarrow N' \rightarrow N \rightarrow N'' \rightarrow 0$  be a short exact sequence of finite  $A$ -modules. Let  $I \subset A$  be an ideal.*

- (1)  $\text{depth}_I(N) \geq \min\{\text{depth}_I(N'), \text{depth}_I(N'')\}$
- (2)  $\text{depth}_I(N'') \geq \min\{\text{depth}_I(N), \text{depth}_I(N') - 1\}$
- (3)  $\text{depth}_I(N') \geq \min\{\text{depth}_I(N), \text{depth}_I(N'') + 1\}$

**Proof.** Assume  $IN \neq N$ ,  $IN' \neq N'$ , and  $IN'' \neq N''$ . Then we can use the characterization of depth using the Ext groups  $\text{Ext}_A^i(A/I, N)$ , see Lemma 11.1, and use the long exact cohomology sequence

$$\begin{aligned} 0 \rightarrow \text{Hom}_A(A/I, N') \rightarrow \text{Hom}_A(A/I, N) \rightarrow \text{Hom}_A(A/I, N'') \\ \rightarrow \text{Ext}_A^1(A/I, N') \rightarrow \text{Ext}_A^1(A/I, N) \rightarrow \text{Ext}_A^1(A/I, N'') \rightarrow \dots \end{aligned}$$

from Algebra, Lemma 70.6. This argument also works if  $IN = N$  because in this case  $\text{Ext}_A^i(A/I, N) = 0$  for all  $i$ . Similarly in case  $IN' \neq N'$  and/or  $IN'' \neq N''$ .  $\square$

0BUW **Lemma 11.3.** *Let  $A$  be a Noetherian ring, let  $I \subset A$  be an ideal, and let  $M$  a finite  $A$ -module with  $IM \neq M$ .*

- (1) If  $x \in I$  is a nonzerodivisor on  $M$ , then  $\text{depth}_I(M/xM) = \text{depth}_I(M) - 1$ .  
(2) Any  $M$ -regular sequence  $x_1, \dots, x_r$  in  $I$  can be extended to an  $M$ -regular sequence in  $I$  of length  $\text{depth}_I(M)$ .

**Proof.** Part (2) is a formal consequence of part (1). Let  $x \in I$  be as in (1). By the short exact sequence  $0 \rightarrow M \rightarrow M \rightarrow M/xM \rightarrow 0$  and Lemma 11.2 we see that  $\text{depth}_I(M/xM) \geq \text{depth}_I(M) - 1$ . On the other hand, if  $x_1, \dots, x_r \in I$  is a regular sequence for  $M/xM$ , then  $x, x_1, \dots, x_r$  is a regular sequence for  $M$ . Hence (1) holds.  $\square$

0BUX **Lemma 11.4.** *Let  $R$  be a Noetherian local ring. If  $M$  is a finite Cohen-Macaulay  $R$ -module and  $I \subset R$  a nontrivial ideal. Then*

$$\text{depth}_I(M) = \dim(\text{Supp}(M)) - \dim(\text{Supp}(M/IM)).$$

**Proof.** We will prove this by induction on  $\text{depth}_I(M)$ .

If  $\text{depth}_I(M) = 0$ , then  $I$  is contained in one of the associated primes  $\mathfrak{p}$  of  $M$  (Algebra, Lemma 62.18). Then  $\mathfrak{p} \in \text{Supp}(M/IM)$ , hence  $\dim(\text{Supp}(M/IM)) \geq \dim(R/\mathfrak{p}) = \dim(\text{Supp}(M))$  where equality holds by Algebra, Lemma 102.7. Thus the lemma holds in this case.

If  $\text{depth}_I(M) > 0$ , we pick  $x \in I$  which is a nonzerodivisor on  $M$ . Note that  $(M/xM)/I(M/xM) = M/IM$ . On the other hand we have  $\text{depth}_I(M/xM) = \text{depth}_I(M) - 1$  by Lemma 11.3 and  $\dim(\text{Supp}(M/xM)) = \dim(\text{Supp}(M)) - 1$  by Algebra, Lemma 62.10. Thus the result by induction hypothesis.  $\square$

0BUY **Lemma 11.5.** *Let  $R \rightarrow S$  be a flat local ring homomorphism of Noetherian local rings. Denote  $\mathfrak{m} \subset R$  the maximal ideal. Let  $I \subset S$  be an ideal. If  $S/\mathfrak{m}S$  is Cohen-Macaulay, then*

$$\text{depth}_I(S) \geq \dim(S/\mathfrak{m}S) - \dim(S/\mathfrak{m}S + I)$$

**Proof.** By Algebra, Lemma 98.3 any sequence in  $S$  which maps to a regular sequence in  $S/\mathfrak{m}S$  is a regular sequence in  $S$ . Thus it suffices to prove the lemma in case  $R$  is a field. This is a special case of Lemma 11.4.  $\square$

0AWO **Lemma 11.6.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. Let  $M$  be an  $A$ -module. Let  $Z = V(I)$ . Then  $H_I^0(M) = H_Z^0(M)$ . Let  $N$  be the common value and set  $M' = M/N$ . Then*

- (1)  $H_I^0(M') = 0$  and  $H_I^p(M) = H_I^p(M')$  and  $H_I^p(N) = 0$  for all  $p > 0$ ,  
(2)  $H_Z^0(M') = 0$  and  $H_Z^p(M) = H_Z^p(M')$  and  $H_Z^p(N) = 0$  for all  $p > 0$ .

**Proof.** By definition  $H_I^0(M) = M[I^\infty]$  is  $I$ -power torsion. By Lemma 9.1 we see that

$$H_Z^0(M) = \text{Ker}(M \longrightarrow M_{f_1} \times \dots \times M_{f_r})$$

if  $I = (f_1, \dots, f_r)$ . Thus  $H_I^0(M) \subset H_Z^0(M)$  and conversely, if  $x \in H_Z^0(M)$ , then it is annihilated by a  $f_i^{e_i}$  for some  $e_i \geq 1$  hence annihilated by some power of  $I$ . This proves the first equality and moreover  $N$  is  $I$ -power torsion. By Lemma 8.1 we see that  $R\Gamma_I(N) = N$ . By Lemma 9.1 we see that  $R\Gamma_Z(N) = N$ . This proves the higher vanishing of  $H_I^p(N)$  and  $H_Z^p(N)$  in (1) and (2). The vanishing of  $H_I^0(M')$  and  $H_Z^0(M')$  follow from the preceding remarks and the fact that  $M'$  is  $I$ -power torsion free by More on Algebra, Lemma 77.4. The equality of higher cohomologies for  $M$  and  $M'$  follow immediately from the long exact cohomology sequence.  $\square$

**12. Torsion versus complete modules**

0A6V Let  $A$  be a ring and let  $I$  be a finitely generated ideal. In this case we can consider the derived category  $D_{I^\infty\text{-torsion}}(A)$  of complexes with  $I$ -power torsion cohomology modules (Section 9) and the derived category  $D_{\text{comp}}(A, I)$  of derived complete complexes (More on Algebra, Section 80). In this section we show these categories are equivalent. A more general statement can be found in [DG02].

0A6W **Lemma 12.1.** *Let  $A$  be a ring and let  $I$  be a finitely generated ideal. Let  $R\Gamma_Z$  be as in Lemma 9.1. Let  $\wedge$  denote derived completion as in More on Algebra, Lemma 80.9. For an object  $K$  in  $D(A)$  we have*

$$R\Gamma_Z(K^\wedge) = R\Gamma_Z(K) \quad \text{and} \quad (R\Gamma_Z(K))^\wedge = K^\wedge$$

in  $D(A)$ .

**Proof.** Choose  $f_1, \dots, f_r \in A$  generating  $I$ . Recall that

$$K^\wedge = R\text{Hom}_A \left( (A \rightarrow \prod A_{f_{i_0}} \rightarrow \prod A_{f_{i_0 i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}), K \right)$$

by More on Algebra, Lemma 80.9. Hence the cone  $C = \text{Cone}(K \rightarrow K^\wedge)$  is given by

$$R\text{Hom}_A \left( (\prod A_{f_{i_0}} \rightarrow \prod A_{f_{i_0 i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r}), K \right)$$

which can be represented by a complex endowed with a finite filtration whose successive quotients are isomorphic to

$$R\text{Hom}_A(A_{f_{i_0 \dots f_{i_p}}}, K), \quad p > 0$$

These complexes vanish on applying  $R\Gamma_Z$ , see Lemma 9.4. Applying  $R\Gamma_Z$  to the distinguished triangle  $K \rightarrow K^\wedge \rightarrow C \rightarrow K[1]$  we see that the first formula of the lemma is correct.

Recall that

$$R\Gamma_Z(K) = K \otimes^{\mathbf{L}} (A \rightarrow \prod A_{f_{i_0}} \rightarrow \prod A_{f_{i_0 i_1}} \rightarrow \dots \rightarrow A_{f_1 \dots f_r})$$

by Lemma 9.1. Hence the cone  $C = \text{Cone}(R\Gamma_Z(K) \rightarrow K)$  can be represented by a complex endowed with a finite filtration whose successive quotients are isomorphic to

$$K \otimes_A A_{f_{i_0 \dots f_{i_p}}}, \quad p > 0$$

These complexes vanish on applying  $\wedge$ , see More on Algebra, Lemma 80.10. Applying derived completion to the distinguished triangle  $R\Gamma_Z(K) \rightarrow K \rightarrow C \rightarrow R\Gamma_Z(K)[1]$  we see that the second formula of the lemma is correct.  $\square$

The following result is a special case of a very general phenomenon concerning admissible subcategories of a triangulated category.

0A6X **Proposition 12.2.** *Let  $A$  be a ring and let  $I \subset A$  be a finitely generated ideal. The functors  $R\Gamma_Z$  and  $\wedge$  define quasi-inverse equivalences of categories*

$$D_{I^\infty\text{-torsion}}(A) \leftrightarrow D_{\text{comp}}(A, I)$$

**Proof.** Follows immediately from Lemma 12.1.  $\square$

The following addendum of the proposition above makes the correspondence on morphisms more precise.

0A6Y **Lemma 12.3.** *With notation as in Lemma 12.1. For objects  $K, L$  in  $D(A)$  there is a canonical isomorphism*

$$R\mathrm{Hom}_A(K^\wedge, L^\wedge) \longrightarrow R\mathrm{Hom}_A(R\Gamma_Z(K), R\Gamma_Z(L))$$

in  $D(A)$ .

**Proof.** Say  $I = (f_1, \dots, f_r)$ . Denote  $C = (A \rightarrow \prod A_{f_i} \rightarrow \dots \rightarrow A_{f_1 \dots f_r})$  the alternating Čech complex. Then derived completion is given by  $R\mathrm{Hom}_A(C, -)$  (More on Algebra, Lemma 80.9) and local cohomology by  $C \otimes^{\mathbf{L}} -$  (Lemma 9.1). Combining the isomorphism

$$R\mathrm{Hom}_A(K \otimes^{\mathbf{L}} C, L \otimes^{\mathbf{L}} C) = R\mathrm{Hom}_A(K, R\mathrm{Hom}(C, L \otimes^{\mathbf{L}} C))$$

(More on Algebra, Lemma 66.1) and the map

$$L \rightarrow R\mathrm{Hom}_A(C, L \otimes^{\mathbf{L}} C)$$

(More on Algebra, Lemma 66.6) we obtain a map

$$\gamma : R\mathrm{Hom}_A(K, L) \longrightarrow R\mathrm{Hom}_A(K \otimes^{\mathbf{L}} C, L \otimes^{\mathbf{L}} C)$$

On the other hand, the right hand side is derived complete as it is equal to

$$R\mathrm{Hom}_A(C, R\mathrm{Hom}_A(K, L \otimes^{\mathbf{L}} C)).$$

Thus  $\gamma$  factors through the derived completion of  $R\mathrm{Hom}_A(K, L)$  by the universal property of derived completion. However, the derived completion goes inside the  $R\mathrm{Hom}_A$  by More on Algebra, Lemma 80.11 and we obtain the desired map.

To show that the map of the lemma is an isomorphism we may assume that  $K$  and  $L$  are derived complete, i.e.,  $K = K^\wedge$  and  $L = L^\wedge$ . In this case we are looking at the map

$$\gamma : R\mathrm{Hom}_A(K, L) \longrightarrow R\mathrm{Hom}_A(R\Gamma_Z(K), R\Gamma_Z(L))$$

By Proposition 12.2 we know that the cohomology groups of the left and the right hand side coincide. In other words, we have to check that the map  $\gamma$  sends a morphism  $\alpha : K \rightarrow L$  in  $D(A)$  to the morphism  $R\Gamma_Z(\alpha) : R\Gamma_Z(K) \rightarrow R\Gamma_Z(L)$ . We omit the verification (hint: note that  $R\Gamma_Z(\alpha)$  is just the map  $\alpha \otimes \mathrm{id}_C : K \otimes^{\mathbf{L}} C \rightarrow L \otimes^{\mathbf{L}} C$  which is almost the same as the construction of the map in More on Algebra, Lemma 66.6).  $\square$

### 13. Trivial duality for a ring map

0A6Z Let  $A \rightarrow B$  be a ring homomorphism. Consider the functor

$$\mathrm{Hom}_A(B, -) : \mathrm{Mod}_A \longrightarrow \mathrm{Mod}_B, \quad M \longmapsto \mathrm{Hom}_A(B, M)$$

This functor is left exact and has a derived extension  $R\mathrm{Hom}(B, -) : D(A) \rightarrow D(B)$ . If  $f_* : D(B) \rightarrow D(A)$  is the restriction functor, then  $f_* R\mathrm{Hom}(B, K) = R\mathrm{Hom}_A(B, K)$  for every  $K \in D(A)$ . Since  $R\mathrm{Hom}_A(A, K) = K$ , the map  $A \rightarrow B$  induces a canonical map  $f_* R\mathrm{Hom}(B, K) \rightarrow K$  in  $D(A)$  functorial in  $K$ .

0A70 **Lemma 13.1.** *Let  $A \rightarrow B$  be a ring homomorphism. The functor  $R\mathrm{Hom}(B, -)$  constructed above is the right adjoint to the restriction functor  $f_* : D(B) \rightarrow D(A)$ .*

**Proof.** This is a consequence of the fact that  $f_*$  and  $\mathrm{Hom}_A(B, -)$  are adjoint functors by Algebra, Lemma 13.3. See Derived Categories, Lemma 28.5.  $\square$

0C0F **Lemma 13.2.** *Let  $A \rightarrow B \rightarrow C$  be ring maps. Then  $R\mathrm{Hom}(C, -) \circ R\mathrm{Hom}(B, -) : D(A) \rightarrow D(C)$  is the functor  $R\mathrm{Hom}(C, -) : D(A) \rightarrow D(C)$ .*

**Proof.** Follows from uniqueness of right adjoints and Lemma 13.1. □

0A71 **Lemma 13.3.** *Let  $A \rightarrow B$  be a ring homomorphism. For  $K$  in  $D(A)$  we have  $f_* R\mathrm{Hom}(B, K) = R\mathrm{Hom}_A(B, K)$  where  $f_* : D(B) \rightarrow D(A)$  is restriction. In particular  $R^q \mathrm{Hom}(B, K) = \mathrm{Ext}_A^q(B, K)$ .*

**Proof.** Omitted, but see above. □

Let  $A$  be a Noetherian ring. We will denote

$$D_{\mathrm{Coh}}(A) \subset D(A)$$

the full subcategory consisting of those objects  $K$  of  $D(A)$  whose cohomology modules are all finite  $A$ -modules. This makes sense by Derived Categories, Section 13 because as  $A$  is Noetherian, the subcategory of finite  $A$ -modules is a Serre subcategory of  $\mathrm{Mod}_A$ .

0A72 **Lemma 13.4.** *With notation as above, assume  $A \rightarrow B$  is a finite ring map of Noetherian rings. Then  $R\mathrm{Hom}(B, -)$  maps  $D_{\mathrm{Coh}}^+(A)$  into  $D_{\mathrm{Coh}}^+(B)$ .*

**Proof.** We have to show: if  $K \in D^+(A)$  has finite cohomology modules, then the complex  $R\mathrm{Hom}(B, K)$  has finite cohomology modules too. This follows for example from Lemma 13.3 if we can show the ext modules  $\mathrm{Ext}_A^i(B, K)$  are finite  $A$ -modules. Since  $K$  is bounded below there is a convergent spectral sequence

$$\mathrm{Ext}_A^p(B, H^q(K)) \Rightarrow \mathrm{Ext}_A^{p+q}(B, K)$$

This finishes the proof as the modules  $\mathrm{Ext}_A^p(B, H^q(K))$  are finite by Algebra, Lemma 70.9. □

0A73 **Remark 13.5.** Let  $A$  be a ring and let  $I \subset A$  be an ideal. Set  $B = A/I$ . In this case the functor  $\mathrm{Hom}_A(B, -)$  is equal to the functor

$$\mathrm{Mod}_A \longrightarrow \mathrm{Mod}_B, \quad M \longmapsto M[I]$$

which sends  $M$  to the submodule of  $I$ -torsion.

0BZB **Situation 13.6.** Let  $R \rightarrow A$  be a ring map. We will give an alternative construction of  $R\mathrm{Hom}(A, -)$  which will stand us in good stead later in this chapter. Namely, suppose we have a differential graded algebra  $(E, d)$  over  $R$  and a quasi-isomorphism  $E \rightarrow A$  where we view  $A$  as a differential graded algebra over  $R$  with zero differential. Then we have commutative diagrams

$$\begin{array}{ccc} D(E, d) & \xleftarrow{\quad} & D(A) \\ & \searrow & \swarrow \\ & & D(R) \end{array} \quad \text{and} \quad \begin{array}{ccc} D(E, d) & \xrightarrow{\quad} & D(A) \\ & \swarrow \scriptstyle -\otimes_R^L E & \searrow \scriptstyle -\otimes_E^L A \\ & & D(R) \end{array}$$

where the horizontal arrows are equivalences of categories (Differential Graded Algebra, Lemma 28.1). It is clear that the first diagram commutes. The second diagram commutes because the first one does and our functors are their left adjoints (Differential Graded Algebra, Example 24.5) or because we have  $E \otimes_E^L A = E \otimes_E A$  and we can use Differential Graded Algebra, Lemma 25.1.

0BZC **Lemma 13.7.** *In Situation 13.6 the functor  $R\mathrm{Hom}(A, -)$  is equal to the composition of  $R\mathrm{Hom}(E, -) : D(R) \rightarrow D(E, d)$  and the equivalence  $-\otimes_E^{\mathbf{L}} A : D(E, d) \rightarrow D(A)$ .*

**Proof.** This is true because  $R\mathrm{Hom}(E, -)$  is the right adjoint to  $-\otimes_R^{\mathbf{L}} E$ , see Differential Graded Algebra, Lemma 24.4. Hence this functor plays the same role as the functor  $R\mathrm{Hom}(A, -)$  for the map  $R \rightarrow A$  (Lemma 13.1), whence these functors must correspond via the equivalence  $-\otimes_E^{\mathbf{L}} A : D(E, d) \rightarrow D(A)$ .  $\square$

0BZD **Lemma 13.8.** *In Situation 13.6 assume that*

- (1)  *$E$  viewed as an object of  $D(R)$  is compact, and*
- (2)  *$N = \mathrm{Hom}_R^\bullet(E^\bullet, R)$  computes  $R\mathrm{Hom}(E, R)$ .*

*Then  $R\mathrm{Hom}(E, -) : D(R) \rightarrow D(E)$  is isomorphic to  $K \mapsto K \otimes_R^{\mathbf{L}} N$ .*

**Proof.** Special case of Differential Graded Algebra, Lemma 24.9.  $\square$

0BZE **Lemma 13.9.** *In Situation 13.6 assume  $A$  is a perfect  $R$ -module. Then*

$$R\mathrm{Hom}(A, -) : D(R) \rightarrow D(A)$$

*is given by  $K \mapsto K \otimes_R^{\mathbf{L}} M$  where  $M = R\mathrm{Hom}(A, R) \in D(A)$ .*

**Proof.** We apply Divided Power Algebra, Lemma 6.9 to choose a Tate resolution  $(E, d)$  of  $A$  over  $R$ . Note that  $E^i = 0$  for  $i > 0$ ,  $E^0 = R[x_1, \dots, x_n]$  is a polynomial algebra, and  $E^i$  is a finite free  $E^0$ -module for  $i < 0$ . It follows that  $E$  viewed as a complex of  $R$ -modules is a bounded above complex of free  $R$ -modules. We check the assumptions of Lemma 13.8. The first holds because  $A$  is perfect (hence compact by More on Algebra, Proposition 70.3) and the second by More on Algebra, Lemma 66.2. From the lemma conclude that  $K \mapsto R\mathrm{Hom}(E, K)$  is isomorphic to  $K \mapsto K \otimes_R^{\mathbf{L}} N$  for some differential graded  $E$ -module  $N$ . Observe that

$$(R \otimes_R E) \otimes_E^{\mathbf{L}} A = R \otimes_E E \otimes_E A$$

in  $D(A)$ . Hence by Differential Graded Algebra, Lemma 25.2 we conclude that the composition of  $-\otimes_R^{\mathbf{L}} N$  and  $-\otimes_R^{\mathbf{L}} A$  is of the form  $-\otimes_R M$  for some  $M \in D(A)$ . To finish the proof we apply Lemma 13.7.  $\square$

0BZH **Lemma 13.10.** *Let  $R \rightarrow A$  be a surjective ring map whose kernel  $I$  is an invertible  $R$ -module. The functor  $R\mathrm{Hom}(A, -) : D(R) \rightarrow D(A)$  is isomorphic to  $K \mapsto K \otimes_R^{\mathbf{L}} N[-1]$  where  $N$  is inverse of the invertible  $A$ -module  $I \otimes_R A$ .*

**Proof.** Since  $A$  has the finite projective resolution

$$0 \rightarrow I \rightarrow R \rightarrow A \rightarrow 0$$

we see that  $A$  is a perfect  $R$ -module. By Lemma 13.9 it suffices to prove that  $R\mathrm{Hom}(A, R)$  is represented by  $N[-1]$  in  $D(A)$ . This means  $R\mathrm{Hom}(A, R)$  has a unique nonzero cohomology module, namely  $N$  in degree 1. As  $\mathrm{Mod}_A \rightarrow \mathrm{Mod}_R$  is fully faithful it suffice to prove this after applying the restriction functor  $i_* : D(A) \rightarrow D(R)$ . By Lemma 13.3 we have

$$i_* R\mathrm{Hom}(A, R) = R\mathrm{Hom}_R(A, R)$$

Using the finite projective resolution above we find that the latter is represented by the complex  $R \rightarrow I^{\otimes -1}$  with  $R$  in degree 0. The map  $R \rightarrow I^{\otimes -1}$  is injective and the cokernel is  $N$ .  $\square$

### 14. Dualizing complexes

0A7A In this section we define dualizing complexes for Noetherian rings.

0A7B **Definition 14.1.** Let  $A$  be a Noetherian ring. A *dualizing complex* is a complex of  $A$ -modules  $\omega_A^\bullet$  such that

- (1)  $\omega_A^\bullet$  has finite injective dimension,
- (2)  $H^i(\omega_A^\bullet)$  is a finite  $A$ -module for all  $i$ , and
- (3)  $A \rightarrow R\mathrm{Hom}_A(\omega_A^\bullet, \omega_A^\bullet)$  is a quasi-isomorphism.

This definition takes some time getting used to. It is perhaps a good idea to prove some of the following lemmas yourself without reading the proofs.

0A7C **Lemma 14.2.** *Let  $A$  be a Noetherian ring. If  $\omega_A^\bullet$  is a dualizing complex, then the functor*

$$D : K \longmapsto R\mathrm{Hom}_A(K, \omega_A^\bullet)$$

*is an anti-equivalence  $D_{\mathrm{Coh}}(A) \rightarrow D_{\mathrm{Coh}}(A)$  which exchanges  $D_{\mathrm{Coh}}^+(A)$  and  $D_{\mathrm{Coh}}^-(A)$  and induces an equivalence  $D_{\mathrm{Coh}}^b(A) \rightarrow D_{\mathrm{Coh}}^b(A)$ . Moreover  $D \circ D$  is isomorphic to the identity functor.*

**Proof.** Let  $K$  be an object of  $D_{\mathrm{Coh}}(A)$ . Pick an integer  $n$  and consider the distinguished triangle

$$\tau_{\leq n}K \rightarrow K \rightarrow \tau_{\geq n+1}K \rightarrow \tau_{\leq n}K[1]$$

see Derived Categories, Remark 12.4. Since  $\omega_A^\bullet$  has finite injective dimension we see that  $R\mathrm{Hom}_A(\tau_{\geq n+1}K, \omega_A^\bullet)$  has vanishing cohomology in degrees  $\geq n - c$  for some constant  $c$ . On the other hand, we obtain a spectral sequence

$$\mathrm{Ext}_A^p(H^{-q}(\tau_{\leq n}K), \omega_A^\bullet) \Rightarrow \mathrm{Ext}_A^{p+q}(\tau_{\leq n}K, \omega_A^\bullet) = H^{p+q}(R\mathrm{Hom}_A(\tau_{\leq n}K, \omega_A^\bullet))$$

which shows that these cohomology modules are finite. Since for  $n > p + q + c$  this is equal to  $H^{p+q}(R\mathrm{Hom}_A(K, \omega_A^\bullet))$  we see that  $R\mathrm{Hom}_A(K, \omega_A^\bullet)$  is indeed an object of  $D_{\mathrm{Coh}}(A)$ . By More on Algebra, Lemma 84.2 and the assumptions on the dualizing complex we obtain a canonical isomorphism

$$K = R\mathrm{Hom}_A(\omega_A^\bullet, \omega_A^\bullet) \otimes_A^{\mathbf{L}} K \longrightarrow R\mathrm{Hom}_A(R\mathrm{Hom}_A(K, \omega_A^\bullet), \omega_A^\bullet)$$

Thus our functor has a quasi-inverse and the proof is complete.  $\square$

0A7D **Lemma 14.3.** *Let  $A$  be a Noetherian ring. Let  $K \in D_{\mathrm{Coh}}^b(A)$ . Let  $\mathfrak{m}$  be a maximal ideal of  $A$ . If  $H^i(K)/\mathfrak{m}H^i(K) \neq 0$ , then there exists a finite  $A$ -module  $E$  annihilated by a power of  $\mathfrak{m}$  and a map  $K \rightarrow E[-i]$  which is nonzero on  $H^i(K)$ .*

**Proof.** Let  $I$  be the injective hull of the residue field of  $\mathfrak{m}$ . If  $H^i(K)/\mathfrak{m}H^i(K) \neq 0$ , then there exists a nonzero map  $H^i(K) \rightarrow I$ . Since  $I$  is injective, we can lift this to a nonzero map  $K \rightarrow I[-i]$ . Recall that  $I = \bigcup I[\mathfrak{m}^n]$ , see Lemma 7.2 and that each of the modules  $E = I[\mathfrak{m}^n]$  is of the desired type. Thus it suffices to prove that

$$\mathrm{Hom}_{D(A)}(K, I) = \mathrm{colim} \mathrm{Hom}_{D(A)}(K, I[\mathfrak{m}^n])$$

This would be immediate if  $K$  were a compact object (or a perfect object) of  $D(A)$ . This is not the case, but  $K$  is a pseudo-coherent object which is enough here. Namely, we can represent  $K$  by a bounded above complex of finite free  $R$ -modules  $K^\bullet$ . In this case the Hom groups above are computed by using  $\mathrm{Hom}_{K(A)}(K^\bullet, -)$ . As each  $K^n$  is finite free the limit statement holds and the proof is complete.  $\square$



Let  $R$  be a ring. We will say that an object  $L$  of  $D(R)$  is *invertible* if there is an open covering  $\text{Spec}(R) = \bigcup D(f_i)$  such that  $L \otimes_R R_{f_i} \cong R_{f_i}[-n_i]$  for some integers  $n_i$ . In this case, the function

$$\mathfrak{p} \mapsto n_{\mathfrak{p}}, \quad \text{where } n_{\mathfrak{p}} \text{ is the unique integer such that } H^{n_{\mathfrak{p}}}(L \otimes \kappa(\mathfrak{p})) \neq 0$$

is locally constant on  $\text{Spec}(R)$ . In particular, it follows that  $L = \bigoplus H^n(L)[-n]$  which gives a well defined complex of  $R$ -modules (with zero differentials) representing  $L$ . Since each  $H^n(L)$  is finite projective and nonzero for only a finite number of  $n$  we also see that  $L$  is a perfect object of  $D(R)$ .

0A7E **Lemma 14.4.** *Let  $A$  be a Noetherian ring. Let  $F : D_{\text{Coh}}^b(A) \rightarrow D_{\text{Coh}}^b(A)$  be an  $A$ -linear equivalence of categories. Then  $F(A)$  is an invertible object of  $D(A)$ .*

**Proof.** Let  $\mathfrak{m} \subset A$  be a maximal ideal with residue field  $\kappa$ . Consider the object  $F(\kappa)$ . Since  $\kappa = \text{Hom}_{D(A)}(\kappa, \kappa)$  we find that all cohomology groups of  $F(\kappa)$  are annihilated by  $\mathfrak{m}$ . We also see that

$$\text{Ext}_A^i(\kappa, \kappa) = \text{Ext}_A^i(F(\kappa), F(\kappa)) = \text{Hom}_{D(A)}(F(\kappa), F(\kappa)[-i])$$

is zero for  $i < 0$ . Say  $H^a(F(\kappa)) \neq 0$  and  $H^b(F(\kappa)) \neq 0$  with  $a$  minimal and  $b$  maximal (so in particular  $a \leq b$ ). Then there is a nonzero map

$$F(\kappa) \rightarrow H^b(F(\kappa))[-b] \rightarrow H^a(F(\kappa))[-b] \rightarrow F(\kappa)[a-b]$$

in  $D(A)$  (nonzero because it induces a nonzero map on cohomology). This proves that  $b = a$ . We conclude that  $F(\kappa) = \kappa[-a]$ .

Let  $G$  be a quasi-inverse to our functor  $F$ . Arguing as above we find an integer  $b$  such that  $G(\kappa) = \kappa[-b]$ . On composing we find  $a + b = 0$ . Let  $E$  be a finite  $A$ -module which is annihilated by a power of  $\mathfrak{m}$ . Arguing by induction on the length of  $E$  we find that  $G(E) = E'[-b]$  for some finite  $A$ -module  $E'$  annihilated by a power of  $\mathfrak{m}$ . Then  $E[-a] = F(E')$ . Next, we consider the groups

$$\text{Ext}_A^i(A, E') = \text{Ext}_A^i(F(A), F(E')) = \text{Hom}_{D(A)}(F(A), E[-a+i])$$

The left hand side is nonzero if and only if  $i = 0$  and then we get  $E'$ . Applying this with  $E = E' = \kappa$  and using Nakayama's lemma this implies that  $H^j(F(A))_{\mathfrak{m}}$  is zero for  $j > a$  and generated by 1 element for  $j = a$ . On the other hand, if  $H^j(F(A))_{\mathfrak{m}}$  is not zero for some  $j < a$ , then there is a map  $F(A) \rightarrow E[-a+i]$  for some  $i < 0$  and some  $E$  (Lemma 14.3) which is a contradiction. Thus we see that  $F(A)_{\mathfrak{m}} = M[-a]$  for some  $A_{\mathfrak{m}}$ -module  $M$  generated by 1 element. However, since

$$A_{\mathfrak{m}} = \text{Hom}_{D(A)}(A, A)_{\mathfrak{m}} = \text{Hom}_{D(A)}(F(A), F(A))_{\mathfrak{m}} = \text{Hom}_{A_{\mathfrak{m}}}(M, M)$$

we see that  $M \cong A_{\mathfrak{m}}$ . We conclude that there exists an element  $f \in A$ ,  $f \notin \mathfrak{m}$  such that  $F(A)_f$  is isomorphic to  $A_f[-a]$ . This finishes the proof.  $\square$

0A7F **Lemma 14.5.** *Let  $A$  be a Noetherian ring. If  $\omega_A^\bullet$  and  $(\omega'_A)^\bullet$  are dualizing complexes, then  $(\omega'_A)^\bullet$  is quasi-isomorphic to  $\omega_A^\bullet \otimes_A^{\mathbf{L}} L$  for some invertible object  $L$  of  $D(A)$ .*

**Proof.** By Lemmas 14.2 and 14.4 the functor  $K \mapsto R\text{Hom}_A(R\text{Hom}_A(K, \omega_A^\bullet), (\omega'_A)^\bullet)$  maps  $A$  to an invertible object  $L$ . In other words, there is an isomorphism

$$L \longrightarrow R\text{Hom}_A(\omega_A^\bullet, (\omega'_A)^\bullet)$$

Since  $L$  has finite tor dimension, this means that we can apply More on Algebra, Lemma 84.2 to see that

$$R\mathrm{Hom}_A(\omega_A^\bullet, (\omega'_A)^\bullet) \otimes_A^{\mathbf{L}} K \longrightarrow R\mathrm{Hom}_A(R\mathrm{Hom}_A(K, \omega_A^\bullet), (\omega'_A)^\bullet)$$

is an isomorphism for  $K$  in  $D_{\mathrm{Coh}}^b(A)$ . In particular, setting  $K = \omega_A^\bullet$  finishes the proof.  $\square$

0A7G **Lemma 14.6.** *Let  $A$  be a Noetherian ring. Let  $B = S^{-1}A$  be a localization. If  $\omega_A^\bullet$  is a dualizing complex, then  $\omega_A^\bullet \otimes_A B$  is a dualizing complex for  $B$ .*

**Proof.** Let  $\omega_A^\bullet \rightarrow I^\bullet$  be a quasi-isomorphism with  $I^\bullet$  a bounded complex of injectives. Then  $S^{-1}I^\bullet$  is a bounded complex of injective  $B = S^{-1}A$ -modules (Lemma 3.9) representing  $\omega_A^\bullet \otimes_A B$ . Thus  $\omega_A^\bullet \otimes_A B$  has finite injective dimension. Since  $H^i(\omega_A^\bullet \otimes_A B) = H^i(\omega_A^\bullet) \otimes_A B$  by flatness of  $A \rightarrow B$  we see that  $\omega_A^\bullet \otimes_A B$  has finite cohomology modules. Finally, the map

$$B \longrightarrow R\mathrm{Hom}_A(\omega_A^\bullet \otimes_A B, \omega_A^\bullet \otimes_A B)$$

is a quasi-isomorphism as formation of internal hom commutes with flat base change in this case, see More on Algebra, Lemma 84.3.  $\square$

0A7H **Lemma 14.7.** *Let  $A$  be a Noetherian ring. Let  $f_1, \dots, f_n \in A$  generate the unit ideal. If  $\omega_A^\bullet$  is a complex of  $A$ -modules such that  $(\omega_A^\bullet)_{f_i}$  is a dualizing complex for  $A_{f_i}$  for all  $i$ , then  $\omega_A^\bullet$  is a dualizing complex for  $A$ .*

**Proof.** Consider the double complex

$$\prod_{i_0} (\omega_A^\bullet)_{f_{i_0}} \rightarrow \prod_{i_0 < i_1} (\omega_A^\bullet)_{f_{i_0} f_{i_1}} \rightarrow \dots$$

The associated total complex is quasi-isomorphic to  $\omega_A^\bullet$  for example by Descent, Remark 3.10 or by Derived Categories of Schemes, Lemma 8.4. By assumption the complexes  $(\omega_A^\bullet)_{f_i}$  have finite injective dimension as complexes of  $A_{f_i}$ -modules. This implies that each of the complexes  $(\omega_A^\bullet)_{f_{i_0} \dots f_{i_p}}$ ,  $p > 0$  has finite injective dimension over  $A_{f_{i_0} \dots f_{i_p}}$ , see Lemma 3.9. This in turn implies that each of the complexes  $(\omega_A^\bullet)_{f_{i_0} \dots f_{i_p}}$ ,  $p > 0$  has finite injective dimension over  $A$ , see Lemma 3.2. Hence  $\omega_A^\bullet$  has finite injective dimension as a complex of  $A$ -modules (as it can be represented by a complex endowed with a finite filtration whose graded parts have finite injective dimension). Since  $H^n(\omega_A^\bullet)_{f_i}$  is a finite  $A_{f_i}$  module for each  $i$  we see that  $H^i(\omega_A^\bullet)$  is a finite  $A$ -module, see Algebra, Lemma 23.2. Finally, the (derived) base change of the map  $A \rightarrow R\mathrm{Hom}_A(\omega_A^\bullet, \omega_A^\bullet)$  to  $A_{f_i}$  is the map  $A_{f_i} \rightarrow R\mathrm{Hom}_A((\omega_A^\bullet)_{f_i}, (\omega_A^\bullet)_{f_i})$  by More on Algebra, Lemma 84.3. Hence we deduce that  $A \rightarrow R\mathrm{Hom}_A(\omega_A^\bullet, \omega_A^\bullet)$  is an isomorphism and the proof is complete.  $\square$

0AX0 **Lemma 14.8.** *Let  $A \rightarrow B$  be a finite ring map of Noetherian rings. Let  $\omega_A^\bullet$  be a dualizing complex. Then  $R\mathrm{Hom}(B, \omega_A^\bullet)$  is a dualizing complex for  $B$ .*

**Proof.** Let  $\omega_A^\bullet \rightarrow I^\bullet$  be a quasi-isomorphism with  $I^\bullet$  a bounded complex of injectives. Then  $\mathrm{Hom}_A(B, I^\bullet)$  is a bounded complex of injective  $B$ -modules (Lemma 3.4) representing  $R\mathrm{Hom}(B, \omega_A^\bullet)$ . Thus  $R\mathrm{Hom}(B, \omega_A^\bullet)$  has finite injective dimension. By Lemma 13.4 it is an object of  $D_{\mathrm{Coh}}(B)$ . Finally, we compute

$$\mathrm{Hom}_{D(B)}(R\mathrm{Hom}(B, \omega_A^\bullet), R\mathrm{Hom}(B, \omega_A^\bullet)) = \mathrm{Hom}_{D(A)}(R\mathrm{Hom}(B, \omega_A^\bullet), \omega_A^\bullet) = B$$

and for  $n \neq 0$  we compute

$$\mathrm{Hom}_{D(B)}(R\mathrm{Hom}(B, \omega_A^\bullet), R\mathrm{Hom}(B, \omega_A^\bullet)[n]) = \mathrm{Hom}_{D(A)}(R\mathrm{Hom}(B, \omega_A^\bullet), \omega_A^\bullet[n]) = 0$$

which proves the last property of a dualizing complex. In the displayed equations, the first equality holds by Lemma 13.1 and the second equality holds by Lemma 14.2.  $\square$

0A7I **Lemma 14.9.** *Let  $A \rightarrow B$  be a surjective homomorphism of Noetherian rings. Let  $\omega_A^\bullet$  be a dualizing complex. Then  $R\mathrm{Hom}(B, \omega_A^\bullet)$  is a dualizing complex for  $B$ .*

**Proof.** Special case of Lemma 14.8.  $\square$

0A7J **Lemma 14.10.** *Let  $A$  be a Noetherian ring. If  $\omega_A^\bullet$  is a dualizing complex, then  $\omega_A^\bullet \otimes_A A[x]$  is a dualizing complex for  $A[x]$ .*

**Proof.** Set  $B = A[x]$  and  $\omega_B^\bullet = \omega_A^\bullet \otimes_A B$ . It follows from Lemma 3.11 and More on Algebra, Lemma 64.4 that  $\omega_B^\bullet$  has finite injective dimension. Since  $H^i(\omega_B^\bullet) = H^i(\omega_A^\bullet) \otimes_A B$  by flatness of  $A \rightarrow B$  we see that  $\omega_A^\bullet \otimes_A B$  has finite cohomology modules. Finally, the map

$$B \longrightarrow R\mathrm{Hom}_B(\omega_B^\bullet, \omega_B^\bullet)$$

is a quasi-isomorphism as formation of internal hom commutes with flat base change in this case, see More on Algebra, Lemma 84.3.  $\square$

0A7K **Proposition 14.11.** *Let  $A$  be a Noetherian ring which has a dualizing complex. Then any  $A$ -algebra essentially of finite type over  $A$  has a dualizing complex.*

**Proof.** This follows from a combination of Lemmas 14.6, 14.9, and 14.10.  $\square$

0A7L **Lemma 14.12.** *Let  $A$  be a Noetherian ring. Let  $\omega_A^\bullet$  be a dualizing complex. Let  $\mathfrak{m} \subset A$  be a maximal ideal and set  $\kappa = A/\mathfrak{m}$ . Then  $R\mathrm{Hom}_A(\kappa, \omega_A^\bullet) \cong \kappa[n]$  for some  $n \in \mathbf{Z}$ .*

**Proof.** This is true because  $R\mathrm{Hom}_A(\kappa, \omega_A^\bullet)$  is a dualizing complex over  $\kappa$  (Lemma 14.9), because dualizing complexes over  $\kappa$  are unique up to shifts (Lemma 14.5), and because  $\kappa$  is a dualizing complex over  $\kappa$ .  $\square$

## 15. Dualizing complexes over local rings

0A7M In this section  $(A, \mathfrak{m}, \kappa)$  will be a Noetherian local ring endowed with a dualizing complex  $\omega_A^\bullet$  such that the integer  $n$  of Lemma 14.12 is zero. More precisely, we assume that  $R\mathrm{Hom}_A(\kappa, \omega_A^\bullet) = \kappa[0]$ . In this case we will say that the dualizing complex is *normalized*. Observe that a normalized dualizing complex is unique up to isomorphism and that any other dualizing complex for  $A$  is isomorphic to a shift of a normalized one (Lemma 14.5).

0AX1 **Lemma 15.1.** *Let  $(A, \mathfrak{m}, \kappa) \rightarrow (B, \mathfrak{m}', \kappa')$  be a finite local map of Noetherian local rings. Let  $\omega_A^\bullet$  be a normalized dualizing complex. Then  $\omega_B^\bullet = R\mathrm{Hom}(B, \omega_A^\bullet)$  is a normalized dualizing complex for  $B$ .*

**Proof.** By Lemma 14.8 the complex  $\omega_B^\bullet$  is dualizing for  $B$ . We have

$$R\mathrm{Hom}_B(\kappa', \omega_B^\bullet) = R\mathrm{Hom}_B(\kappa', R\mathrm{Hom}(B, \omega_A^\bullet)) = R\mathrm{Hom}_A(\kappa', \omega_A^\bullet)$$

by Lemma 13.1. Since  $\kappa'$  is isomorphic to a finite direct sum of copies of  $\kappa$  as an  $A$ -module and since  $\omega_A^\bullet$  is normalized, we see that this complex only has cohomology placed in degree 0. Thus  $\omega_B^\bullet$  is a normalized dualizing complex as well.  $\square$

0A7N **Lemma 15.2.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $A \rightarrow B$  be surjective. Then  $\omega_B^\bullet = R\mathrm{Hom}_A(B, \omega_A^\bullet)$  is a normalized dualizing complex for  $B$ .*

**Proof.** Special case of Lemma 15.1.  $\square$

0A7P **Lemma 15.3.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $F$  be an  $A$ -linear self-equivalence of the category of finite length  $A$ -modules. Then  $F$  is isomorphic to the identity functor.*

**Proof.** Since  $\kappa$  is the unique simple object of the category we have  $F(\kappa) \cong \kappa$ . Since our category is abelian, we find that  $F$  is exact. Hence  $F(E)$  has the same length as  $E$  for all finite length modules  $E$ . Since  $\mathrm{Hom}(E, \kappa) = \mathrm{Hom}(F(E), F(\kappa)) \cong \mathrm{Hom}(F(E), \kappa)$  we conclude from Nakayama's lemma that  $E$  and  $F(E)$  have the same number of generators. Hence  $F(A/\mathfrak{m}^n)$  is a cyclic  $A$ -module. Pick a generator  $e \in F(A/\mathfrak{m}^n)$ . Since  $F$  is  $A$ -linear we conclude that  $\mathfrak{m}^n e = 0$ . The map  $A/\mathfrak{m}^n \rightarrow F(A/\mathfrak{m}^n)$  has to be an isomorphism as the lengths are equal. Pick an element

$$e \in \lim F(A/\mathfrak{m}^n)$$

which maps to a generator for all  $n$  (small argument omitted). Then we obtain a system of isomorphisms  $A/\mathfrak{m}^n \rightarrow F(A/\mathfrak{m}^n)$  compatible with all  $A$ -module maps  $A/\mathfrak{m}^n \rightarrow A/\mathfrak{m}^{n'}$  (by  $A$ -linearity of  $F$  again). Since any finite length module is a cokernel of a map between direct sums of cyclic modules, we obtain the isomorphism of the lemma.  $\square$

0A7Q **Lemma 15.4.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $E$  be an injective hull of  $\kappa$ . Then there exists a functorial isomorphism*

$$R\mathrm{Hom}_A(N, \omega_A^\bullet) = \mathrm{Hom}_A(N, E)[0]$$

for  $N$  running through the finite length  $A$ -modules.

**Proof.** By induction on the length of  $N$  we see that  $R\mathrm{Hom}_A(N, \omega_A^\bullet)$  is a module of finite length sitting in degree 0. Thus  $R\mathrm{Hom}_A(-, \omega_A^\bullet)$  induces an anti-equivalence on the category of finite length modules. Since the same is true for  $\mathrm{Hom}_A(-, E)$  by Proposition 7.8 we see that

$$N \longmapsto \mathrm{Hom}_A(R\mathrm{Hom}_A(N, \omega_A^\bullet), E)$$

is an equivalence as in Lemma 15.3. Hence it is isomorphic to the identity functor. Since  $\mathrm{Hom}_A(-, E)$  applied twice is the identity (Proposition 7.8) we obtain the statement of the lemma.  $\square$

0A7U **Lemma 15.5.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $M$  be a finite  $A$ -module and let  $d = \dim(\mathrm{Supp}(M))$ . Then*

- (1) *if  $\mathrm{Ext}_A^i(M, \omega_A^\bullet)$  is nonzero, then  $i \in \{-d, \dots, 0\}$ ,*
- (2) *the dimension of the support of  $\mathrm{Ext}_A^i(M, \omega_A^\bullet)$  is at most  $-i$ ,*
- (3) *depth( $M$ ) is the smallest integer  $\delta \geq 0$  such that  $\mathrm{Ext}_A^{-\delta}(M, \omega_A^\bullet) \neq 0$ .*

**Proof.** We prove this by induction on  $d$ . If  $d = 0$ , this follows from Lemma 15.4 and Matlis duality (Proposition 7.8) which guarantees that  $\mathrm{Hom}_A(M, E)$  is nonzero if  $M$  is nonzero.

Assume the result holds for modules with support of dimension  $< d$  and that  $M$  has depth  $> 0$ . Choose an  $f \in \mathfrak{m}$  which is a nonzerodivisor on  $M$  and consider the short exact sequence

$$0 \rightarrow M \rightarrow M \rightarrow M/fM \rightarrow 0$$

Since  $\dim(\text{Supp}(M/fM)) = d - 1$  (Algebra, Lemma 62.10) we may apply the induction hypothesis. Writing  $E^i = \text{Ext}_A^i(M, \omega_A^\bullet)$  and  $F^i = \text{Ext}_A^i(M/fM, \omega_A^\bullet)$  we obtain a long exact sequence

$$\dots \rightarrow F^i \rightarrow E^i \xrightarrow{f} E^i \rightarrow F^{i+1} \rightarrow \dots$$

By induction  $E^i/fE^i = 0$  for  $i+1 \notin \{-\dim(\text{Supp}(M/fM)), \dots, -\text{depth}(M/fM)\}$ . By Nakayama's lemma (Algebra, Lemma 19.1) and Algebra, Lemma 71.7 we conclude  $E^i = 0$  for  $i \notin \{-\dim(\text{Supp}(M)), \dots, -\text{depth}(M)\}$ . Moreover, in the boundary case  $i = -\text{depth}(M)$  we deduce that  $E^i$  is nonzero as  $F^{i+1}$  is nonzero by induction. Since  $E^i/fE^i \subset F^{i+1}$  we get

$$\dim(\text{Supp}(F^{i+1})) \geq \dim(\text{Supp}(E^i/fE^i)) \geq \dim(\text{Supp}(E^i)) - 1$$

(see lemma used above) we also obtain the dimension estimate (2).

If  $M$  has depth 0 and  $d > 0$  we let  $N = M[\mathfrak{m}^\infty]$  and set  $M' = M/N$  (compare with Lemma 11.6). Then  $M'$  has depth  $> 0$  and  $\dim(\text{Supp}(M')) = d$ . Thus we know the result for  $M'$  and since  $R\text{Hom}_A(N, \omega_A^\bullet) = \text{Hom}_A(N, E)$  (Lemma 15.4) the long exact cohomology sequence of Ext's implies the result for  $M$ .  $\square$

0BUJ **Remark 15.6.** Let  $(A, \mathfrak{m})$  and  $\omega_A^\bullet$  be as in Lemma 15.5. By More on Algebra, Lemma 64.2 we see that  $\omega_A^\bullet$  has injective-amplitude in  $[-d, 0]$  because part (3) of that lemma applies. In particular, for any  $A$ -module  $M$  (not necessarily finite) we have  $\text{Ext}_A^i(M, \omega_A^\bullet) = 0$  for  $i \notin \{-d, \dots, 0\}$ .

0B5A **Lemma 15.7.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $M$  be a finite  $A$ -module. The following are equivalent*

- (1)  $M$  is Cohen-Macaulay,
- (2)  $\text{Ext}_A^i(M, \omega_A^\bullet)$  is nonzero for a single  $i$ ,
- (3)  $\text{Ext}_A^i(M, \omega_A^\bullet)$  is zero for  $i \neq \dim(\text{Supp}(M))$ .

Denote  $CM_d$  the category of finite Cohen-Macaulay  $A$ -modules of depth  $d$ . Then  $M \mapsto \text{Ext}_A^{-d}(M, \omega_A^\bullet)$  defines an anti-auto-equivalence of  $CM_d$ .

**Proof.** We will use the results of Lemma 15.5 without further mention. Fix a finite module  $M$ . If  $M$  is Cohen-Macaulay, then only  $\text{Ext}_A^{-d}(M, \omega_A^\bullet)$  can be nonzero, hence (1)  $\Rightarrow$  (3). The implication (3)  $\Rightarrow$  (2) is immediate. Assume (2) and let  $N = \text{Ext}_A^{-\delta}(M, \omega_A^\bullet)$  be the nonzero Ext where  $\delta = \text{depth}(M)$ . Then, since

$$M[0] = R\text{Hom}_A(R\text{Hom}_A(M, \omega_A^\bullet), \omega_A^\bullet) = R\text{Hom}_A(N[\delta], \omega_A^\bullet)$$

(Lemma 14.2) we conclude that  $M = \text{Ext}_A^{-\delta}(N, \omega_A^\bullet)$ . Thus  $\delta \geq \dim(\text{Supp}(M))$ . However, since we also know that  $\delta \leq \dim(\text{Supp}(M))$  (Algebra, Lemma 71.3) we conclude that  $M$  is Cohen-Macaulay.

To prove the final statement, it suffices to show that  $N = \text{Ext}_A^{-d}(M, \omega_A^\bullet)$  is in  $CM_d$  for  $M$  in  $CM_d$ . Above we have seen that  $M[0] = R\text{Hom}_A(N[d], \omega_A^\bullet)$  and this proves the desired result by the equivalence of (1) and (3).  $\square$

0A7R **Lemma 15.8.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . If  $\dim(A) = 0$ , then  $\omega_A^\bullet \cong E[0]$  where  $E$  is an injective hull of the residue field.*

**Proof.** Immediate from Lemma 15.4.  $\square$

0A7S **Lemma 15.9.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex. Let  $I \subset \mathfrak{m}$  be an ideal of finite length. Set  $B = A/I$ . Then there is a distinguished triangle*

$$\omega_B^\bullet \rightarrow \omega_A^\bullet \rightarrow \mathrm{Hom}_A(I, E)[0] \rightarrow \omega_B^\bullet[1]$$

in  $D(A)$  where  $E$  is an injective hull of  $\kappa$  and  $\omega_B^\bullet$  is a normalized dualizing complex for  $B$ .

**Proof.** Use the short exact sequence  $0 \rightarrow I \rightarrow A \rightarrow B \rightarrow 0$  and Lemmas 15.4 and 15.2.  $\square$

0A7T **Lemma 15.10.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $f \in \mathfrak{m}$  be a nonzerodivisor. Set  $B = A/(f)$ . Then there is a distinguished triangle*

$$\omega_B^\bullet \rightarrow \omega_A^\bullet \rightarrow \omega_A^\bullet \rightarrow \omega_B^\bullet[1]$$

in  $D(A)$  where  $\omega_B^\bullet$  is a normalized dualizing complex for  $B$ .

**Proof.** Use the short exact sequence  $0 \rightarrow A \rightarrow A \rightarrow B \rightarrow 0$  and Lemma 15.2.  $\square$

0A7V **Lemma 15.11.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $\mathfrak{p}$  be a minimal prime of  $A$  with  $\dim(A/\mathfrak{p}) = e$ . Then  $H^i(\omega_A^\bullet)_{\mathfrak{p}}$  is nonzero if and only if  $i = -e$ .*

**Proof.** Since  $A_{\mathfrak{p}}$  has dimension zero, there exists an integer  $n > 0$  such that  $\mathfrak{p}^n A_{\mathfrak{p}}$  is zero. Set  $B = A/\mathfrak{p}^n$  and  $\omega_B^\bullet = R\mathrm{Hom}_A(B, \omega_A^\bullet)$ . Since  $B_{\mathfrak{p}} = A_{\mathfrak{p}}$  we see that  $(\omega_B^\bullet)_{\mathfrak{p}} \cong (\omega_A^\bullet)_{\mathfrak{p}}$  by using More on Algebra, Lemma 84.3. By Lemma 15.2 we may replace  $A$  by  $B$ . After doing so, we see that  $\dim(A) = e$ . Then we see that  $H^i(\omega_A^\bullet)_{\mathfrak{p}}$  can only be nonzero if  $i = -e$  by Lemma 15.5. On the other hand, since  $(\omega_A^\bullet)_{\mathfrak{p}}$  is a dualizing complex for the nonzero ring  $A_{\mathfrak{p}}$  (Lemma 14.6) we see that the remaining module has to be nonzero.  $\square$

## 16. Dualizing complexes and dimension functions

0A7W Our results in the local setting have the following consequence: a Noetherian ring with a dualizing complex is a universally catenary ring of finite dimension.

0A7X **Lemma 16.1.** *Let  $A$  be a Noetherian ring. Let  $\mathfrak{p}$  be a minimal prime of  $A$ . Then  $H^i(\omega_A^\bullet)_{\mathfrak{p}}$  is nonzero for exactly one  $i$ .*

**Proof.** The complex  $\omega_A^\bullet \otimes_A A_{\mathfrak{p}}$  is a dualizing complex for  $A_{\mathfrak{p}}$  (Lemma 14.6). The dimension of  $A_{\mathfrak{p}}$  is zero as  $\mathfrak{p}$  is minimal. Hence the result follows from Lemma 15.8.  $\square$

Let  $A$  be a Noetherian ring and let  $\omega_A^\bullet$  be a dualizing complex. Lemma 14.12 allows us to define a function

$$\delta = \delta_{\omega_A^\bullet} : \mathrm{Spec}(A) \longrightarrow \mathbf{Z}$$

by mapping  $\mathfrak{p}$  to the integer of Lemma 14.12 for the dualizing complex  $(\omega_A^\bullet)_{\mathfrak{p}}$  over  $A_{\mathfrak{p}}$  (Lemma 14.6) and the residue field  $\kappa(\mathfrak{p})$ . To be precise, we define  $\delta(\mathfrak{p})$  to be the unique integer such that

$$(\omega_A^\bullet)_{\mathfrak{p}}[-\delta(\mathfrak{p})]$$

is a normalized dualizing complex over the Noetherian local ring  $A_{\mathfrak{p}}$ .

0A7Y **Lemma 16.2.** *Let  $A$  be a Noetherian ring and let  $\omega_A^\bullet$  be a dualizing complex. Let  $A \rightarrow B$  be a surjective ring map and let  $\omega_B^\bullet = R\mathrm{Hom}(B, \omega_A^\bullet)$  be the dualizing complex for  $B$  of Lemma 14.9. Then we have*

$$\delta_{\omega_B^\bullet} = \delta_{\omega_A^\bullet}|_{\mathrm{Spec}(B)}$$

**Proof.** This follows from the definition of the functions and Lemma 15.2.  $\square$

0A7Z **Lemma 16.3.** *Let  $A$  be a Noetherian ring and let  $\omega_A^\bullet$  be a dualizing complex. The function  $\delta = \delta_{\omega_A^\bullet}$  defined above is a dimension function (Topology, Definition 20.1).*

**Proof.** Let  $\mathfrak{p} \subset \mathfrak{q}$  be an immediate specialization. We have to show that  $\delta(\mathfrak{p}) = \delta(\mathfrak{q}) + 1$ . We may replace  $A$  by  $A/\mathfrak{p}$ , the complex  $\omega_A^\bullet$  by  $\omega_{A/\mathfrak{p}}^\bullet = R\mathrm{Hom}(A/\mathfrak{p}, \omega_A^\bullet)$ , the prime  $\mathfrak{p}$  by  $(0)$ , and the prime  $\mathfrak{q}$  by  $\mathfrak{q}/\mathfrak{p}$ , see Lemma 16.2. Thus we may assume that  $A$  is a domain,  $\mathfrak{p} = (0)$ , and  $\mathfrak{q}$  is a prime ideal of height 1.

Then  $H^i(\omega_A^\bullet)_{(0)}$  is nonzero for exactly one  $i$ , say  $i_0$ , by Lemma 16.1. In fact  $i_0 = -\delta((0))$  because  $(\omega_A^\bullet)_{(0)}[-\delta((0))]$  is a normalized dualizing complex over the field  $A_{(0)}$ .

On the other hand  $(\omega_A^\bullet)_{\mathfrak{q}}[-\delta(\mathfrak{q})]$  is a normalized dualizing complex for  $A_{\mathfrak{q}}$ . By Lemma 15.11 we see that

$$H^e((\omega_A^\bullet)_{\mathfrak{q}}[-\delta(\mathfrak{q})])_{(0)} = H^{e-\delta(\mathfrak{q})}(\omega_A^\bullet)_{(0)}$$

is nonzero only for  $e = -\dim(A_{\mathfrak{q}}) = -1$ . We conclude

$$-\delta((0)) = -1 - \delta(\mathfrak{p})$$

as desired.  $\square$

0A80 **Lemma 16.4.** *Let  $A$  be a Noetherian ring which has a dualizing complex. Then  $A$  is universally catenary of finite dimension.*

**Proof.** Because  $\mathrm{Spec}(A)$  has a dimension function by Lemma 16.3 it is catenary, see Topology, Lemma 20.2. Hence  $A$  is catenary, see Algebra, Lemma 104.2. It follows from Proposition 14.11 that  $A$  is universally catenary.

Because any dualizing complex  $\omega_A^\bullet$  is in  $D_{\mathrm{Coh}}^b(A)$  the values of the function  $\delta_{\omega_A^\bullet}$  in minimal primes are bounded by Lemma 16.1. On the other hand, for a maximal ideal  $\mathfrak{m}$  with residue field  $\kappa$  the integer  $i = -\delta(\mathfrak{m})$  is the unique integer such that  $\mathrm{Ext}_A^i(\kappa, \omega_A^\bullet)$  is nonzero (Lemma 14.12). Since  $\omega_A^\bullet$  has finite injective dimension these values are bounded too. Since the dimension of  $A$  is the maximal value of  $\delta(\mathfrak{p}) - \delta(\mathfrak{m})$  where  $\mathfrak{p} \subset \mathfrak{m}$  are a pair consisting of a minimal prime and a maximal prime we find that the dimension of  $\mathrm{Spec}(A)$  is bounded.  $\square$

0AWE **Lemma 16.5.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Let  $d = \dim(A)$  and  $\omega_A = H^{-d}(\omega_A^\bullet)$ . Then*

- (1) *the support of  $\omega_A$  is the union of the irreducible components of  $\mathrm{Spec}(A)$  of dimension  $d$ ,*

(2)  $\omega_A$  satisfies  $(S_2)$ , see *Algebra, Definition 151.1*.

**Proof.** We will use Lemma 15.5 without further mention. By Lemma 15.11 the support of  $\omega_A$  contains the irreducible components of dimension  $d$ . Let  $\mathfrak{p} \subset A$  be a prime. By Lemma 16.3 the complex  $(\omega_A^\bullet)_{\mathfrak{p}}[-\dim(A/\mathfrak{p})]$  is a normalized dualizing complex for  $A_{\mathfrak{p}}$ . Hence if  $\dim(A/\mathfrak{p}) + \dim(A_{\mathfrak{p}}) < d$ , then  $(\omega_A)_{\mathfrak{p}} = 0$ . This proves the support of  $\omega_A$  is the union of the irreducible components of dimension  $d$ , because the complement of this union is exactly the primes  $\mathfrak{p}$  of  $A$  for which  $\dim(A/\mathfrak{p}) + \dim(A_{\mathfrak{p}}) < d$  as  $A$  is catenary (Lemma 16.4). On the other hand, if  $\dim(A/\mathfrak{p}) + \dim(A_{\mathfrak{p}}) = d$ , then

$$(\omega_A)_{\mathfrak{p}} = H^{-\dim(A_{\mathfrak{p}})}((\omega_A^\bullet)_{\mathfrak{p}}[-\dim(A/\mathfrak{p})])$$

Hence in order to prove  $\omega_A$  has  $(S_2)$  it suffices to show that the depth of  $\omega_A$  is at least  $\min(\dim(A), 2)$ . We prove this by induction on  $\dim(A)$ . The case  $\dim(A) = 0$  is trivial.

Assume  $\text{depth}(A) > 0$ . Choose a nonzerodivisor  $f \in \mathfrak{m}$  and set  $B = A/fA$ . Then  $\dim(B) = \dim(A) - 1$  and we may apply the induction hypothesis to  $B$ . By Lemma 15.10 we see that multiplication by  $f$  is injective on  $\omega_A$  and we get  $\omega_A/f\omega_A \subset \omega_B$ . This proves the depth of  $\omega_A$  is at least 1. If  $\dim(A) > 1$ , then  $\dim(B) > 0$  and  $\omega_B$  has depth  $> 0$ . Hence  $\omega_A$  has depth  $> 1$  and we conclude in this case.

Assume  $\dim(A) > 0$  and  $\text{depth}(A) = 0$ . Let  $I = A[\mathfrak{m}^\infty]$  and set  $B = A/I$ . Then  $B$  has depth  $\geq 1$  and  $\omega_A = \omega_B$  by Lemma 15.8. Since we proved the result for  $\omega_B$  above the proof is done.  $\square$

### 17. The local duality theorem

0A81 The main result in this section is due to Grothendieck.

0A82 **Lemma 17.1.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $\omega_A^\bullet$  be a normalized dualizing complex. Let  $Z = V(\mathfrak{m}) \subset \text{Spec}(A)$ . Then  $E = R^0\Gamma_Z(\omega_A^\bullet)$  is an injective hull of  $\kappa$  and  $R\Gamma_Z(\omega_A^\bullet) = E[0]$ .*

**Proof.** By Lemma 10.1 we have  $R\Gamma_{\mathfrak{m}} = R\Gamma_Z$ . Thus

$$R\Gamma_Z(\omega_A^\bullet) = R\Gamma_{\mathfrak{m}}(\omega_A^\bullet) = \text{hocolim } R\text{Hom}_A(A/\mathfrak{m}^n, \omega_A^\bullet)$$

by Lemma 8.2. Let  $E'$  be an injective hull of the residue field. By Lemma 15.4 we can find isomorphisms

$$R\text{Hom}_A(A/\mathfrak{m}^n, \omega_A^\bullet) \cong \text{Hom}_A(A/\mathfrak{m}^n, E')[0]$$

compatible with transition maps. Since  $E' = \bigcup E'[\mathfrak{m}^n] = \text{colim } \text{Hom}_A(A/\mathfrak{m}^n, E')$  by Lemma 7.3 we conclude that  $E \cong E'$  and that all other cohomology groups of the complex  $R\Gamma_Z(\omega_A^\bullet)$  are zero.  $\square$

0A83 **Remark 17.2.** Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with a normalized dualizing complex  $\omega_A^\bullet$ . By Lemma 17.1 above we see that  $R\Gamma_Z(\omega_A^\bullet)$  is an injective hull of the residue field placed in degree 0. In fact, this gives a “construction” or “realization” of the injective hull which is slightly more canonical than just picking any old injective hull. Namely, a normalized dualizing complex is unique up to isomorphism, with group of automorphisms the group of units of  $A$ , whereas an injective hull of  $\kappa$  is unique up to isomorphism, with group of automorphisms the group of units of the completion  $A^\wedge$  of  $A$  with respect to  $\mathfrak{m}$ .



Here is the main result of this section.

0A84 **Theorem 17.3.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $\omega_A^\bullet$  be a normalized dualizing complex. Let  $E$  be an injective hull of the residue field. Let  $Z = V(\mathfrak{m}) \subset \text{Spec}(A)$ . Denote  $\wedge$  derived completion with respect to  $\mathfrak{m}$ . Then*

$$R\text{Hom}_A(K, \omega_A^\bullet)^\wedge \cong R\text{Hom}_A(R\Gamma_Z(K), E[0])$$

for  $K$  in  $D(A)$ .

**Proof.** Observe that  $E[0] \cong R\Gamma_Z(\omega_A^\bullet)$  by Lemma 17.1. By More on Algebra, Lemma 80.11 completion on the left hand side goes inside. Thus we have to prove

$$R\text{Hom}_A(K^\wedge, (\omega_A^\bullet)^\wedge) = R\text{Hom}_A(R\Gamma_Z(K), R\Gamma_Z(\omega_A^\bullet))$$

This follows from the equivalence between  $D_{\text{comp}}(A, \mathfrak{m})$  and  $D_{\mathfrak{m}^\infty\text{-torsion}}(A)$  given in Proposition 12.2. More precisely, it is a special case of Lemma 12.3.  $\square$

Here is a special case of the theorem above.

0AAK **Lemma 17.4.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $\omega_A^\bullet$  be a normalized dualizing complex. Let  $E$  be an injective hull of the residue field. Let  $K \in D_{\text{Coh}}(A)$ . Then*

$$\text{Ext}_A^{-i}(K, \omega_A^\bullet)^\wedge = \text{Hom}_A(H_{\mathfrak{m}}^i(K), E)$$

where  $\wedge$  denotes  $\mathfrak{m}$ -adic completion.

**Proof.** By Lemma 14.2 we see that  $R\text{Hom}_A(K, \omega_A^\bullet)$  is an object of  $D_{\text{Coh}}(A)$ . It follows that the cohomology modules of the derived completion of  $R\text{Hom}_A(K, \omega_A^\bullet)$  are equal to the usual completions  $\text{Ext}_A^i(K, \omega_A^\bullet)^\wedge$  by More on Algebra, Lemma 82.3. On the other hand, we have  $R\Gamma_{\mathfrak{m}} = R\Gamma_Z$  for  $Z = V(\mathfrak{m})$  by Lemma 10.1. Moreover, the functor  $\text{Hom}_A(-, E)$  is exact hence factors through cohomology. Hence the lemma is consequence of Theorem 17.3.  $\square$

## 18. Dualizing modules

0DW3 If  $(A, \mathfrak{m}, \kappa)$  is a Noetherian local ring and  $\omega_A^\bullet$  is a normalized dualizing complex, then we say the module  $\omega_A = H^{-\dim(A)}(\omega_A^\bullet)$ , described in Lemma 16.5, is a *dualizing module* for  $A$ . This module is a canonical module of  $A$ . It seems generally agreed upon to define a *canonical module* for a Noetherian local ring  $(A, \mathfrak{m}, \kappa)$  to be a finite  $A$ -module  $K$  such that

$$\text{Hom}_A(K, E) \cong H_{\mathfrak{m}}^{\dim(A)}(A)$$

where  $E$  is an injective hull of the residue field. A dualizing module is canonical because

$$\text{Hom}_A(H_{\mathfrak{m}}^{\dim(A)}(A), E) = (\omega_A)^\wedge$$

by Lemma 17.4 and hence applying  $\text{Hom}_A(-, E)$  we get

$$\begin{aligned} \text{Hom}_A(\omega_A, E) &= \text{Hom}_A((\omega_A)^\wedge, E) \\ &= \text{Hom}_A(\text{Hom}_A(H_{\mathfrak{m}}^{\dim(A)}(A), E), E) \\ &= H_{\mathfrak{m}}^{\dim(A)}(A) \end{aligned}$$

the first equality because  $E$  is  $\mathfrak{m}$ -power torsion, the second by the above, and the third by Matlis duality (Proposition 7.8). The utility of the definition of a canonical module given above lies in the fact that it makes sense even if  $A$  does not have a dualizing complex.

### 19. Cohen-Macaulay rings

0DW4 Cohen-Macaulay modules and rings were studied in Algebra, Sections 102 and 103.

0AWR **Lemma 19.1.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$ . Then  $\text{depth}(A)$  is equal to the smallest integer  $\delta \geq 0$  such that  $H^{-\delta}(\omega_A^\bullet) \neq 0$ .*

**Proof.** This follows immediately from Lemma 15.5. Here are two other ways to see that it is true.

First alternative. By Nakayama's lemma we see that  $\delta$  is the smallest integer such that  $\text{Hom}_A(H^{-\delta}(\omega_A^\bullet), \kappa) \neq 0$ . In other words, it is the smallest integer such that  $\text{Ext}_A^{-\delta}(\omega_A^\bullet, \kappa)$  is nonzero. Using Lemma 14.2 and the fact that  $\omega_A^\bullet$  is normalized this is equal to the smallest integer such that  $\text{Ext}_A^\delta(\kappa, A)$  is nonzero. This is equal to the depth of  $A$  by Algebra, Lemma 71.5.

Second alternative. By the local duality theorem (in the form of Lemma 17.4)  $\delta$  is the smallest integer such that  $H_{\mathfrak{m}}^\delta(A)$  is nonzero. This is equal to the depth of  $A$  by Lemma 11.1.  $\square$

0AWS **Lemma 19.2.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring with normalized dualizing complex  $\omega_A^\bullet$  and dualizing module  $\omega_A = H^{-\dim(A)}(\omega_A^\bullet)$ . The following are equivalent*

- (1)  $A$  is Cohen-Macaulay,
- (2)  $\omega_A^\bullet$  is concentrated in a single degree, and
- (3)  $\omega_A^\bullet = \omega_A[\dim(A)]$ .

*In this case  $\omega_A$  is a maximal Cohen-Macaulay module.*

**Proof.** Follows immediately from Lemma 15.7.  $\square$

0DW5 **Lemma 19.3.** *Let  $A$  be a Noetherian ring. If there exists a finite  $A$ -module  $\omega_A$  such that  $\omega_A[0]$  is a dualizing complex, then  $A$  is Cohen-Macaulay.*

**Proof.** We may replace  $A$  by the localization at a prime (Lemma 14.6 and Algebra, Definition 103.6). In this case the result follows immediately from Lemma 19.2.  $\square$

### 20. Gorenstein rings

0DW6 So far, the only explicit dualizing complex we've seen is  $\kappa$  on  $\kappa$  for a field  $\kappa$ , see proof of Lemma 14.12. By Proposition 14.11 this means that any finite type algebra over a field has a dualizing complex. However, it turns out that there are Noetherian (local) rings which do not have a dualizing complex. Namely, we have seen that a ring which has a dualizing complex is universally catenary (Lemma 16.4) but there are examples of Noetherian local rings which are not catenary, see Examples, Section 16.

Nonetheless many rings in algebraic geometry have dualizing complexes simply because they are quotients of Gorenstein rings. This condition is in fact both necessary and sufficient. That is: a Noetherian ring has a dualizing complex if and only if it is a quotient of a finite dimensional Gorenstein ring. This is Sharp's conjecture ([Sha79]) which can be found as [Kaw02, Corollary 1.4] in the literature. Returning to our current topic, here is the definition of Gorenstein rings.

0DW7 **Definition 20.1.** Gorenstein rings.

- (1) Let  $A$  be a Noetherian local ring. We say  $A$  is *Gorenstein* if  $A[0]$  is a dualizing complex for  $A$ .
- (2) Let  $A$  be a Noetherian ring. We say  $A$  is *Gorenstein* if  $A_{\mathfrak{p}}$  is Gorenstein for every prime  $\mathfrak{p}$  of  $A$ .

This definition makes sense, because if  $A[0]$  is a dualizing complex for  $A$ , then  $S^{-1}A[0]$  is a dualizing complex for  $S^{-1}A$  by Lemma 14.6. We will see later that a finite dimensional Noetherian ring is Gorenstein if it has finite injective dimension as a module over itself.

0DW8 **Lemma 20.2.** *A Gorenstein ring is Cohen-Macaulay.*

**Proof.** Follows from Lemma 19.2.  $\square$

An example of a Gorenstein ring is a regular ring.

0AWX **Lemma 20.3.** *A regular local ring is Gorenstein. A regular ring is Gorenstein.*

**Proof.** Let  $A$  be a regular ring of finite dimension  $d$ . Then  $A$  has finite global dimension  $d$ , see Algebra, Lemma 109.8. Hence  $\text{Ext}_A^{d+1}(M, A) = 0$  for all  $A$ -modules  $M$ , see Algebra, Lemma 108.8. Thus  $A$  has finite injective dimension as an  $A$ -module by More on Algebra, Lemma 64.2. It follows that  $A[0]$  is a dualizing complex, hence  $A$  is Gorenstein by the remark following the definition.  $\square$

0DW9 **Lemma 20.4.** *Let  $A$  be a Noetherian ring.*

- (1) *If  $A$  has a dualizing complex  $\omega_A^\bullet$ , then*
  - (a)  *$A$  is Gorenstein  $\Leftrightarrow \omega_A^\bullet$  is an invertible object of  $D(A)$ ,*
  - (b)  *$A_{\mathfrak{p}}$  is Gorenstein  $\Leftrightarrow (\omega_A^\bullet)_{\mathfrak{p}}$  is an invertible object of  $D(A_{\mathfrak{p}})$ ,*
  - (c)  *$\{\mathfrak{p} \in \text{Spec}(A) \mid A_{\mathfrak{p}} \text{ is Gorenstein}\}$  is an open subset.*
- (2) *If  $A$  is Gorenstein, then  $A$  has a dualizing complex if and only if  $A[0]$  is a dualizing complex.*

**Proof.** By Lemma 14.6 for every  $\mathfrak{p}$  the complex  $(\omega_A^\bullet)_{\mathfrak{p}}$  is a dualizing complex over  $A_{\mathfrak{p}}$ . By definition and uniqueness of dualizing complexes (Lemma 14.5) we see that (1)(b) holds.

To see (1)(c) assume that  $A_{\mathfrak{p}}$  is Gorenstein. Let  $n_x$  be the unique integer such that  $H^{n_x}((\omega_A^\bullet)_{\mathfrak{p}})$  is nonzero and isomorphic to  $A_{\mathfrak{p}}$ . Since  $\omega_A^\bullet$  is in  $D_{\text{Coh}}^b(A)$  there are finitely many nonzero finite  $A$ -modules  $H^i(\omega_A^\bullet)$ . Thus there exists some  $f \in A$ ,  $f \notin \mathfrak{p}$  such that only  $H^{n_x}((\omega_A^\bullet)_f)$  is nonzero and generated by 1 element over  $A_f$ . Since dualizing complexes are faithful (by definition) we conclude that  $A_f \cong H^{n_x}((\omega_A^\bullet)_f)$ . In this way we see that  $A_{\mathfrak{q}}$  is Gorenstein for every  $\mathfrak{q} \in D(f)$ . This proves that the set in (1)(c) is open.

Proof of (1)(a). The implication  $\Leftarrow$  follows from (1)(b). The implication  $\Rightarrow$  follows from the discussion in the previous paragraph, where we showed that if  $A_{\mathfrak{p}}$  is Gorenstein, then for some  $f \in A$ ,  $f \notin \mathfrak{p}$  the complex  $(\omega_A^\bullet)_f$  has only one nonzero cohomology module which is invertible.

If  $A[0]$  is a dualizing complex then  $A$  is Gorenstein by part (1). Conversely, we see that part (1) shows that  $\omega_A^\bullet$  is locally isomorphic to a shift of  $A$ . Since being a dualizing complex is local (Lemma 14.7) the result is clear.  $\square$

0BJI **Lemma 20.5.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Then  $A$  is Gorenstein if and only if  $\text{Ext}_A^i(\kappa, A)$  is zero for  $i \gg 0$ .*

**Proof.** Observe that  $A[0]$  is a dualizing complex for  $A$  if and only if  $A$  has finite injective dimension as an  $A$ -module (follows immediately from Definition 14.1). Thus the lemma follows from More on Algebra, Lemma 64.6.  $\square$

0BJJ **Lemma 20.6.** *Let  $(A, \mathfrak{m}, \kappa)$  be a Noetherian local ring. Let  $f \in \mathfrak{m}$  be a nonzero-divisor. Set  $B = A/(f)$ . Then  $A$  is Gorenstein if and only if  $B$  is Gorenstein.*

**Proof.** If  $A$  is Gorenstein, then  $B$  is Gorenstein by Lemma 15.10. Conversely, suppose that  $B$  is Gorenstein. Then  $\text{Ext}_B^i(\kappa, B)$  is zero for  $i \gg 0$  (Lemma 20.5). Recall that  $R\text{Hom}(B, -) : D(A) \rightarrow D(B)$  is a right adjoint to restriction (Lemma 13.1). Hence

$$R\text{Hom}_A(\kappa, A) = R\text{Hom}_B(\kappa, R\text{Hom}(B, A)) = R\text{Hom}_B(\kappa, B[1])$$

The final equality by direct computation or by Lemma 13.10. Thus we see that  $\text{Ext}_A^i(\kappa, A)$  is zero for  $i \gg 0$  and  $A$  is Gorenstein (Lemma 20.5).  $\square$

0DWA **Lemma 20.7.** *If  $A \rightarrow B$  is a local complete intersection homomorphism of rings and  $A$  is a Noetherian Gorenstein ring, then  $B$  is a Gorenstein ring.*

**Proof.** By More on Algebra, Definition 30.2 we can factor  $A \rightarrow B$  as  $A \rightarrow A[x_1, \dots, x_n] \rightarrow A[x_1, \dots, x_n]/(f_1, \dots, f_c) = B$  with  $f_1, \dots, f_c$  is Koszul regular sequence. Since  $A$  is Gorenstein, the polynomial ring  $A[x_1, \dots, x_n]$  is Gorenstein. Thus it suffices to show: if  $R$  is a Noetherian local Gorenstein ring and  $f_1, \dots, f_c \in \mathfrak{m}_R$  is a Koszul regular sequence, then  $R/(f_1, \dots, f_c)$  is Gorenstein. This follows from Lemma 20.6 and the fact that a Koszul regular sequence in  $R$  is just a regular sequence (More on Algebra, Lemma 27.7).  $\square$

0BJL **Lemma 20.8.** *Let  $A \rightarrow B$  be a flat local homomorphism of Noetherian local rings. The following are equivalent*

- (1)  $B$  is Gorenstein, and
- (2)  $A$  and  $B/\mathfrak{m}_A B$  are Gorenstein.

**Proof.** Below we will use without further mention that a local Gorenstein ring has finite injective dimension as well as Lemma 20.5. By More on Algebra, Remark 60.20 we have

$$\text{Ext}_A^i(\kappa_A, A) \otimes_A B = \text{Ext}_B^i(B/\mathfrak{m}_A B, B)$$

for all  $i$ .

Assume (2). Using that  $R\text{Hom}(B/\mathfrak{m}_A B, -) : D(B) \rightarrow D(B/\mathfrak{m}_A B)$  is a right adjoint to restriction (Lemma 13.1) we obtain

$$R\text{Hom}_B(\kappa_B, B) = R\text{Hom}_{B/\mathfrak{m}_A B}(\kappa_B, R\text{Hom}(B/\mathfrak{m}_A B, B))$$

The cohomology modules of  $R\text{Hom}(B/\mathfrak{m}_A B, B)$  are the modules  $\text{Ext}_B^i(B/\mathfrak{m}_A B, B) = \text{Ext}_A^i(\kappa_A, A) \otimes_A B$ . Since  $A$  is Gorenstein, we conclude only a finite number of these are nonzero and each is isomorphic to a direct sum of copies of  $B/\mathfrak{m}_A B$ . Hence since  $B/\mathfrak{m}_A B$  is Gorenstein we conclude that  $R\text{Hom}_B(B/\mathfrak{m}_A B, B)$  has only a finite number of nonzero cohomology modules. Hence  $B$  is Gorenstein.

Assume (1). Since  $B$  has finite injective dimension,  $\text{Ext}_B^i(B/\mathfrak{m}_A B, B)$  is 0 for  $i \gg 0$ . Since  $A \rightarrow B$  is faithfully flat we conclude that  $\text{Ext}_A^i(\kappa_A, A)$  is 0 for  $i \gg 0$ . We conclude that  $A$  is Gorenstein. This implies that  $\text{Ext}_A^i(\kappa_A, A)$  is nonzero for exactly one  $i$ , namely for  $i = \dim(A)$ , and  $\text{Ext}_A^{\dim(A)}(\kappa_A, A) \cong \kappa_A$  (see Lemmas 15.1, 19.2, and 20.2). Thus we see that  $\text{Ext}_B^i(B/\mathfrak{m}_A B, B)$  is zero except for one  $i$ , namely

$i = \dim(A)$  and  $\text{Ext}_B^{\dim(A)}(B/\mathfrak{m}_A B, B) \cong B/\mathfrak{m}_A B$ . Thus  $B/\mathfrak{m}_A B$  is Gorenstein by Lemma 15.1.  $\square$

## 21. The ubiquity of dualizing complexes

0DWB Many Noetherian rings have dualizing complexes.

0AWD **Lemma 21.1.** *Let  $A \rightarrow B$  be a local homomorphism of Noetherian local rings. Let  $\omega_A^\bullet$  be a normalized dualizing complex. If  $A \rightarrow B$  is flat and  $\mathfrak{m}_A B = \mathfrak{m}_B$ , then  $\omega_A^\bullet \otimes_A B$  is a normalized dualizing complex for  $B$ .*

**Proof.** It is clear that  $\omega_A^\bullet \otimes_A B$  is in  $D_{Coh}^b(B)$ . Let  $\kappa_A$  and  $\kappa_B$  be the residue fields of  $A$  and  $B$ . By More on Algebra, Lemma 84.3 we see that

$$R\text{Hom}_B(\kappa_B, \omega_A^\bullet \otimes_A B) = R\text{Hom}_A(\kappa_A, \omega_A^\bullet) \otimes_A B = \kappa_A[0] \otimes_A B = \kappa_B[0]$$

Thus  $\omega_A^\bullet \otimes_A B$  has finite injective dimension by More on Algebra, Lemma 64.6. Finally, we can use the same arguments to see that

$$R\text{Hom}_B(\omega_A^\bullet \otimes_A B, \omega_A^\bullet \otimes_A B) = R\text{Hom}_A(\omega_A^\bullet, \omega_A^\bullet) \otimes_A B = A \otimes_A B = B$$

as desired.  $\square$

0DWC **Lemma 21.2.** *Let  $A \rightarrow B$  be a flat map of Noetherian rings. Let  $I \subset A$  be an ideal such that  $A/I = B/IB$  and such that  $IB$  is contained in the radical of  $B$ . Let  $\omega_A^\bullet$  be a dualizing complex. Then  $\omega_A^\bullet \otimes_A B$  is a dualizing complex for  $B$ .*

**Proof.** It is clear that  $\omega_A^\bullet \otimes_A B$  is in  $D_{Coh}^b(B)$ . By More on Algebra, Lemma 84.3 we see that

$$R\text{Hom}_B(K \otimes_A B, \omega_A^\bullet \otimes_A B) = R\text{Hom}_A(K, \omega_A^\bullet) \otimes_A B$$

for any  $K \in D_{Coh}^b(A)$ . For any ideal  $IB \subset J \subset B$  there is a unique ideal  $I \subset J' \subset A$  such that  $A/J' \otimes_A B = B/J$ . Thus  $\omega_A^\bullet \otimes_A B$  has finite injective dimension by More on Algebra, Lemma 64.5. Finally, we also have

$$R\text{Hom}_B(\omega_A^\bullet \otimes_A B, \omega_A^\bullet \otimes_A B) = R\text{Hom}_A(\omega_A^\bullet, \omega_A^\bullet) \otimes_A B = A \otimes_A B = B$$

as desired.  $\square$

0DWD **Lemma 21.3.** *Let  $A$  be a Noetherian ring and let  $I \subset A$  be an ideal. Let  $\omega_A^\bullet$  be a dualizing complex.*

- (1)  $\omega_A^\bullet \otimes_A A^h$  is a dualizing complex on the henselization  $(A^h, I^h)$  of the pair  $(A, I)$ ,
- (2)  $\omega_A^\bullet \otimes_A A^\wedge$  is a dualizing complex on the  $I$ -adic completion  $A^\wedge$ , and
- (3) if  $A$  is local, then  $\omega_A^\bullet \otimes_A A^h$ , resp.  $\omega_A^\bullet \otimes_A A^{sh}$  is a dualizing complex on the henselization, resp. strict henselization of  $A$ .

**Proof.** Immediate from Lemmas 21.1 and 21.2. See More on Algebra, Sections 10, 40, and 42 and Algebra, Sections 95 and 96 for information on completions and henselizations.  $\square$

0BFR **Lemma 21.4.** *The following types of rings have a dualizing complex:*

- (1) fields,
- (2) Noetherian complete local rings,
- (3)  $\mathbf{Z}$ ,
- (4) Dedekind domains,

- (5) *any ring which is obtained from one of the rings above by taking an algebra essentially of finite type, or by taking an ideal-adic completion, or by taking a henselization, or by taking a strict henselization.*

**Proof.** Part (5) follows from Proposition 14.11 and Lemma 21.3. By Lemma 20.3 a regular local ring has a dualizing complex. A complete Noetherian local ring is the quotient of a regular local ring by the Cohen structure theorem (Algebra, Theorem 154.8). Let  $A$  be a Dedekind domain. Then every ideal  $I$  is a finite projective  $A$ -module (follows from Algebra, Lemma 77.2 and the fact that the local rings of  $A$  are discrete valuation ring and hence PIDs). Thus every  $A$ -module has finite injective dimension at most 1 by More on Algebra, Lemma 64.2. It follows easily that  $A[0]$  is a dualizing complex.  $\square$

## 22. Formal fibres

OBJM This section is a continuation of More on Algebra, Section 48. There we saw there is a (fairly) good theory of Noetherian rings  $A$  whose local rings have Cohen-Macaulay formal fibres. Namely, we proved (1) it suffices to check the formal fibres of localizations at maximal ideals are Cohen-Macaulay, (2) the property is inherited by rings of finite type over  $A$ , (3) the fibres of  $A \rightarrow A^\wedge$  are Cohen-Macaulay for any completion  $A^\wedge$  of  $A$ , and (4) the property is inherited by henselizations of  $A$ . See More on Algebra, Lemma 48.4, Proposition 48.5, Lemma 48.6, and Lemma 48.7. Similarly, for Noetherian rings whose local rings have formal fibres which are geometrically reduced, geometrically normal,  $(S_n)$ , and geometrically  $(R_n)$ . In this section we will see that the same is true for Noetherian rings whose local rings have formal fibres which are Gorenstein or local complete intersections. This is relevant to this chapter because a Noetherian ring which has a dualizing complex is an example.

OBJN **Lemma 22.1.** *Properties (A), (B), (C), (D), and (E) of More on Algebra, Section 48 hold for  $P(k \rightarrow R) = "R \text{ is a Gorenstein ring}"$ .*

**Proof.** Since we already know the result holds for Cohen-Macaulay instead of Gorenstein, we may in each step assume the ring we have is Cohen-Macaulay. This is not particularly helpful for the proof, but psychologically may be useful.

Part (A). Let  $k \subset K$  be a finitely generated field extension. Let  $R$  be a Gorenstein  $k$ -algebra. We can find a global complete intersection  $A = k[x_1, \dots, x_n]/(f_1, \dots, f_c)$  over  $k$  such that  $K$  is isomorphic to the fraction field of  $A$ , see Algebra, Lemma 152.11. Then  $R \rightarrow R \otimes_k A$  is a relative global complete intersection. Hence  $R \otimes_k A$  is Gorenstein by Lemma 20.7. Thus  $R \otimes_k K$  is too as a localization.

Proof of (B). This is clear because a ring is Gorenstein if and only if all of its local rings are Gorenstein.

Part (C). Let  $A \rightarrow B \rightarrow C$  be flat maps of Noetherian rings. Assume the fibres of  $A \rightarrow B$  are Gorenstein and  $B \rightarrow C$  is regular. We have to show the fibres of  $A \rightarrow C$  are Gorenstein. Clearly, we may assume  $A = k$  is a field. Then we may assume that  $B \rightarrow C$  is a regular local homomorphism of Noetherian local rings. Then  $B$  is Gorenstein and  $C/\mathfrak{m}_B C$  is regular, in particular Gorenstein (Lemma 20.3). Then  $C$  is Gorenstein by Lemma 20.8.

Part (D). This follows from Lemma 20.8. Part (E) is immediate as the condition does not refer to the ground field.  $\square$

0AWY **Lemma 22.2.** *Let  $A$  be a Noetherian local ring. If  $A$  has a dualizing complex, then the formal fibres of  $A$  are Gorenstein.*

**Proof.** Let  $\mathfrak{p}$  be a prime of  $A$ . The formal fibre of  $A$  at  $\mathfrak{p}$  is isomorphic to the formal fibre of  $A/\mathfrak{p}$  at  $(0)$ . The quotient  $A/\mathfrak{p}$  has a dualizing complex (Lemma 14.9). Thus it suffices to check the statement when  $A$  is a local domain and  $\mathfrak{p} = (0)$ . Let  $\omega_A^\bullet$  be a dualizing complex for  $A$ . Then  $\omega_A^\bullet \otimes_A A^\wedge$  is a dualizing complex for the completion  $A^\wedge$  (Lemma 21.1). Then  $\omega_A^\bullet \otimes_A f.f.(A)$  is a dualizing complex for  $K = f.f.(A)$  (Lemma 14.6) hence is isomorphic to  $K[n]$  for some  $n \in \mathbf{Z}$ . Similarly, we conclude a dualizing complex for the formal fibre  $A^\wedge \otimes_A K$  is

$$\omega_A^\bullet \otimes_A A^\wedge \otimes_{A^\wedge} (A^\wedge \otimes_A K) = (\omega_A^\bullet \otimes_A K) \otimes_K (A^\wedge \otimes_A K) \cong (A^\wedge \otimes_A K)[n]$$

as desired.  $\square$

Here is the verification promised in Divided Power Algebra, Remark 9.3.

0BJP **Lemma 22.3.** *Properties (A), (B), (C), (D), and (E) of More on Algebra, Section 48 hold for  $P(k \rightarrow R) = \text{“}R \text{ is a local complete intersection”}$ . See Divided Power Algebra, Definition 8.5.*

**Proof.** Part (A). Let  $k \subset K$  be a finitely generated field extension. Let  $R$  be a  $k$ -algebra which is a local complete intersection. We can find a global complete intersection  $A = k[x_1, \dots, x_n]/(f_1, \dots, f_c)$  over  $k$  such that  $K$  is isomorphic to the fraction field of  $A$ , see Algebra, Lemma 152.11. Then  $R \rightarrow R \otimes_k A$  is a relative global complete intersection. It follows that  $R \otimes_k A$  is a local complete intersection by Divided Power Algebra, Lemma 8.9.

Proof of (B). This is clear because a ring is a local complete intersection if and only if all of its local rings are complete intersections.

Part (C). Let  $A \rightarrow B \rightarrow C$  be flat maps of Noetherian rings. Assume the fibres of  $A \rightarrow B$  are local complete intersections and  $B \rightarrow C$  is regular. We have to show the fibres of  $A \rightarrow C$  are Gorenstein. Clearly, we may assume  $A = k$  is a field. Then we may assume that  $B \rightarrow C$  is a regular local homomorphism of Noetherian local rings. Then  $B$  is a complete intersection and  $C/\mathfrak{m}_B C$  is regular, in particular a complete intersection (by definition). Then  $C$  is a complete intersection by Divided Power Algebra, Lemma 8.9.

Part (D). This follows by the same arguments as in (C) from the other implication in Divided Power Algebra, Lemma 8.9. Part (E) is immediate as the condition does not refer to the ground field.  $\square$

### 23. Upper shriek algebraically

0BZI For a finite type homomorphism  $R \rightarrow A$  of Noetherian rings we will construct a functor  $\varphi^! : D(R) \rightarrow D(A)$  well defined up to nonunique isomorphism which as we will see in Duality for Schemes, Remark 15.4 agrees up to isomorphism with the upper shriek functors one encounters in the duality theory for schemes. To motivate the construction we mention two additional properties:

- (1)  $\varphi^!$  sends a dualizing complex for  $R$  (if it exists) to a dualizing complex for  $A$ , and
- (2)  $\omega_{A/R}^\bullet = \varphi^!(R)$  is a kind of relative dualizing complex: it lies in  $D_{\text{Coh}}^b(A)$  and restricts to a dualizing complex on the fibres provided  $R \rightarrow A$  is flat.

These statements are Lemmas 23.3 and 23.14.

Let  $\varphi : R \rightarrow A$  be a finite type homomorphism of Noetherian rings. We will define a functor  $\varphi^! : D(R) \rightarrow D(A)$  in the following way

- (1) If  $\varphi : R \rightarrow A$  is surjective we set  $\varphi^!(K) = R\mathrm{Hom}(A, K)$ . Here we use the functor  $R\mathrm{Hom}(A, -) : D(R) \rightarrow D(A)$  of Section 13, and
- (2) in general we choose a surjection  $\psi : P \rightarrow A$  with  $P = R[x_1, \dots, x_n]$  and we set  $\varphi^!(K) = \psi^!(K \otimes_R^{\mathbf{L}} P)[n]$ . Here we use the functor  $-\otimes_R^{\mathbf{L}} P : D(R) \rightarrow D(P)$  of More on Algebra, Section 56.

Note the shift  $[n]$  by the number of variables in the polynomial ring. This construction is **not** canonical and the functor  $\varphi^!$  will only be well defined up to a (nonunique) isomorphism of functors<sup>1</sup>.

0BZJ **Lemma 23.1.** *Let  $\varphi : R \rightarrow A$  be a finite type homomorphism of Noetherian rings. The functor  $\varphi^!$  is well defined up to isomorphism.*

**Proof.** Suppose that  $\psi_1 : P_1 = R[x_1, \dots, x_n] \rightarrow A$  and  $\psi_2 : P_2 = R[y_1, \dots, y_m] \rightarrow A$  are two surjections from polynomial rings onto  $A$ . Then we get a commutative diagram

$$\begin{array}{ccc} R[x_1, \dots, x_n, y_1, \dots, y_m] & \xrightarrow{y_j \mapsto f_j} & R[x_1, \dots, x_n] \\ \downarrow x_i \mapsto g_i & & \downarrow \\ R[y_1, \dots, y_m] & \xrightarrow{\quad\quad\quad} & A \end{array}$$

where  $f_j$  and  $g_i$  are chosen such that  $\psi_1(f_j) = \psi_2(y_j)$  and  $\psi_2(g_i) = \psi_1(x_i)$ . By symmetry it suffices to prove the functors defined using  $P \rightarrow A$  and  $P[y_1, \dots, y_m] \rightarrow A$  are isomorphic. By induction we may assume  $m = 1$ . This reduces us to the case discussed in the next paragraph.

Here  $\psi : P \rightarrow A$  is given and  $\chi : P[y] \rightarrow A$  induces  $\psi$  on  $P$ . Write  $Q = P[y]$ . Choose  $g \in P$  with  $\psi(g) = \chi(y)$ . Denote  $\pi : Q \rightarrow P$  the  $P$ -algebra map with  $\pi(y) = g$ . Then  $\psi = \chi \circ \pi$  and hence  $\chi^! = \psi^! \circ \pi^!$  as both are adjoint to the restriction functor  $D(A) \rightarrow D(Q)$  by the material in Section 13. Thus

$$\chi^!(K \otimes_R^{\mathbf{L}} Q)[n+1] = \psi^!(\pi^!(K \otimes_R^{\mathbf{L}} Q)[1])[n]$$

Hence it suffices to show that  $\pi^!(K \otimes_R^{\mathbf{L}} Q[1]) = K \otimes_R^{\mathbf{L}} P$ . Thus it suffices to show that the functor  $\pi^!(-) : D(Q) \rightarrow D(P)$  is isomorphic to  $K \mapsto K \otimes_Q^{\mathbf{L}} P[-1]$ . This follows from Lemma 13.10.  $\square$

0BZK **Lemma 23.2.** *Let  $\varphi : R \rightarrow A$  be a finite type homomorphism of Noetherian rings.*

- (1)  $\varphi^!$  maps  $D^+(R)$  into  $D^+(A)$  and  $D_{\mathrm{Coh}}^+(R)$  into  $D_{\mathrm{Coh}}^+(A)$ .
- (2) if  $\varphi$  is perfect, then  $\varphi^!$  maps  $D^-(R)$  into  $D^-(A)$ ,  $D_{\mathrm{Coh}}^-(R)$  into  $D_{\mathrm{Coh}}^-(A)$ , and  $D_{\mathrm{Coh}}^b(R)$  into  $D_{\mathrm{Coh}}^b(A)$ .

**Proof.** Choose a factorization  $R \rightarrow P \rightarrow A$  as in the definition of  $\varphi^!$ . The functor  $-\otimes_R^{\mathbf{L}} : D(R) \rightarrow D(P)$  preserves the subcategories  $D^+, D_{\mathrm{Coh}}^+, D^-, D_{\mathrm{Coh}}^-, D_{\mathrm{Coh}}^b$ . The functor  $R\mathrm{Hom}(A, -) : D(P) \rightarrow D(A)$  preserves  $D^+$  and  $D_{\mathrm{Coh}}^+$  by Lemma 13.4. If  $R \rightarrow A$  is perfect, then  $A$  is perfect as a  $P$ -module, see More on Algebra, Lemma

<sup>1</sup>It is possible to make the construction canonical: use  $\Omega_{P/R}^n[n]$  instead of  $P[n]$  in the construction and use this in Lemma 23.1. The material in this section becomes a lot more involved if one wants to do this.



73.2. Recall that the restriction of  $R\text{Hom}(A, K)$  to  $D(P)$  is  $R\text{Hom}_P(A, K)$ . By More on Algebra, Lemma 67.14 we have  $R\text{Hom}_P(A, K) = E \otimes_P^{\mathbf{L}} K$  for some perfect  $E \in D(P)$ . Since we can represent  $E$  by a finite complex of finite projective  $P$ -modules it is clear that  $R\text{Hom}_P(A, K)$  is in  $D^-(P), D_{\text{Coh}}^-(P), D_{\text{Coh}}^b(P)$  as soon as  $K$  is. Since the restriction functor  $D(A) \rightarrow D(P)$  reflects these subcategories, the proof is complete.  $\square$

0BZL **Lemma 23.3.** *Let  $\varphi$  be a finite type homomorphism of Noetherian rings. If  $\omega_R^\bullet$  is a dualizing complex for  $R$ , then  $\varphi^!(\omega_R^\bullet)$  is a dualizing complex for  $A$ .*

**Proof.** Follows from Lemmas 14.10 and 14.9.  $\square$

0BZM **Lemma 23.4.** *Let  $\varphi : R \rightarrow A$  be a surjective homomorphism of Noetherian rings. Let  $R \rightarrow R'$  be a flat homomorphism of Noetherian rings. Let  $\varphi' : R' \rightarrow A' = A \otimes_R R'$  be the map induced by  $\varphi$ . Then we have a functorial maps*

$$\varphi^!(K) \otimes_A^{\mathbf{L}} A' \longrightarrow (\varphi')^!(K \otimes_R^{\mathbf{L}} R')$$

for  $K$  in  $D(R)$  which are isomorphisms for  $K \in D^+(R)$ .

**Proof.** Let  $K \in D(R)$ . Choose a  $K$ -injective complex  $I^\bullet$  representing  $K$ . Then  $I^\bullet \otimes_R R'$  represents  $K \otimes_R^{\mathbf{L}} R'$ . Choose a quasi-isomorphism  $I^\bullet \otimes_R R' \rightarrow J^\bullet$  where  $J^\bullet$  is a  $K$ -injective complex of  $R'$ -modules. Then there is a canonical map

$$\text{Hom}_R(A, I^\bullet) \otimes_R R' \rightarrow \text{Hom}_{R'}(A \otimes_R R', I^\bullet \otimes_R R') \rightarrow \text{Hom}_{R'}(A', J^\bullet)$$

Since  $R \rightarrow R'$  is flat, the map  $A \rightarrow A'$  is flat and  $D(A) \rightarrow D(A')$  is given by  $L^\bullet \mapsto L^\bullet \otimes_R R'$  on the level of complexes. Hence the source of the arrow, viewed as a complex of  $A'$ -modules represents  $\varphi^!(K) \otimes_A^{\mathbf{L}} A'$ . Similarly, the target viewed as a complex of  $A'$ -modules represents  $(\varphi')^!(K \otimes_R^{\mathbf{L}} R')$ . This defines the natural transformation of the lemma.

To see that the map is an isomorphism for some  $K$  we may do so after applying the restriction functor  $D(A') \rightarrow D(R)$ . Since  $J^\bullet$  is  $K$ -injective as a complex of  $R$ -modules (More on Algebra, Lemma 53.1) and since  $\text{Hom}_{R'}(A', -) = \text{Hom}_R(A, -)$  we see that  $\text{Hom}_{R'}(A', J^\bullet)$  represents  $R\text{Hom}_R(A, K \otimes_R^{\mathbf{L}} R')$  in  $D(R)$ . The right hand side represents  $R\text{Hom}(A, K) \otimes_R^{\mathbf{L}} R'$  in  $D(R)$ . Checking the definitions we see our map is the map

$$R\text{Hom}(A, K) \otimes_R^{\mathbf{L}} R' \rightarrow R\text{Hom}(A, K \otimes_R^{\mathbf{L}} R')$$

of More on Algebra, Lemma 84.4. In this way we conclude the final assertion of the lemma is true.  $\square$

0BZN **Lemma 23.5.** *Let  $R \rightarrow R'$  be a flat homomorphism of Noetherian rings. Let  $\varphi : R \rightarrow A$  be a finite type ring map. Let  $\varphi' : R' \rightarrow A' = A \otimes_R R'$  be the map induced by  $\varphi$ . Then we have a functorial maps*

$$\varphi^!(K) \otimes_A^{\mathbf{L}} A' \longrightarrow (\varphi')^!(K \otimes_R^{\mathbf{L}} R')$$

for  $K$  in  $D(R)$  which are isomorphisms for  $K \in D^+(R)$ .

**Proof.** We can choose a factorization  $R \rightarrow P \rightarrow A$  where  $P$  is a polynomial ring over  $R$ . This gives a corresponding factorization  $R' \rightarrow P' \rightarrow A'$  by base change. Since we have  $(K \otimes_R^{\mathbf{L}} P) \otimes_P^{\mathbf{L}} P' = (K \otimes_R^{\mathbf{L}} R') \otimes_{R'}^{\mathbf{L}} P'$  by More on Algebra, Lemma 56.4 it suffices to prove the statement for  $P \rightarrow A$  and  $P \rightarrow P'$ . This case is proved in Lemma 23.4.  $\square$

0BZP **Lemma 23.6.** *Let  $\varphi : R \rightarrow A$  be a surjective homomorphism of Noetherian rings. Let  $R \rightarrow R'$  be a homomorphism of Noetherian rings. Assume*

- (1)  *$A$  is a perfect  $R$ -module,*
- (2)  *$R'$  and  $A$  are Tor independent over  $R$ .*

*Let  $\varphi' : R' \rightarrow A' = A \otimes_R R'$  be the map induced by  $\varphi$ . Then we have a functorial isomorphism*

$$\varphi'^1(K) \otimes_A^{\mathbf{L}} A' = (\varphi')^1(K \otimes_R^{\mathbf{L}} R')$$

*for  $K$  in  $D(R)$ .*

**Proof.** Because  $A$  is a perfect  $R$ -module, we see that  $A \otimes_R^{\mathbf{L}} R'$  is a perfect object of  $D(R')$ , see More on Algebra, Lemma 67.9. By assumption (2) we have  $A' = A \otimes_R^{\mathbf{L}} R'$  is a perfect  $R'$ -module. Thus it follows from Lemma 13.9 that  $\varphi^1$  and  $(\varphi')^1$  are given by derived tensor product with  $N = R\mathrm{Hom}(A, R)$  and  $N' = R\mathrm{Hom}(A', R')$ . Hence it suffices to show that

$$(K \otimes_R^{\mathbf{L}} N) \otimes_A^{\mathbf{L}} A' = (K \otimes_R^{\mathbf{L}} R') \otimes_{R'}^{\mathbf{L}} N'$$

functorially for  $K \in D(R)$ . By transitivity of tensor functors (More on Algebra, Lemma 56.4) we conclude that it suffices to construct an isomorphism  $N \otimes_A^{\mathbf{L}} A' \rightarrow N'$  in  $D(A')$ .

Choose a Tate resolution  $R \rightarrow (E, d) \rightarrow A$  with  $E^0 = R$  as in Divided Power Algebra, Lemma 6.8. Then  $E^n = 0$  for  $n > 0$  and  $E^n$  is a finite free  $R$ -module for all  $n$ . Write  $E' = E \otimes_R R'$  with induced differential  $d$ . Since  $E^\bullet \rightarrow A$  is a flat resolution of  $A$  as an  $R$ -module, we see that the map  $E' \rightarrow A'$  is a quasi-isomorphism by assumption (2). The diagram

$$\begin{array}{ccc} D(A) & \xrightarrow{\quad} & D(A') \\ \uparrow -\otimes_E^{\mathbf{L}} A & & \uparrow -\otimes_{E'}^{\mathbf{L}} A' \\ D(E, d) & \xrightarrow{\quad} & D(E', d) \end{array}$$

is commutative (each of the functors as well as the compositions are adjoints to restriction the restriction functors satisfy the corresponding commutativity). The vertical arrows are equivalences because  $E \rightarrow A$  and  $E' \rightarrow A'$  are quasi-isomorphisms (Differential Graded Algebra, Lemma 28.1).

Putting this together with Lemma 13.7 we find that it suffices to construct an isomorphism

0BZQ (23.6.1) 
$$R\mathrm{Hom}(E, R) \otimes_E^{\mathbf{L}} E' \longrightarrow R\mathrm{Hom}(E', R')$$

in  $D(E')$ .

By Differential Graded Algebra, Lemma 21.5 the differential graded  $E$ -module

$$H = \mathrm{Hom}_{\mathrm{Mod}_R^{dg}}(E, R)$$

represents  $R\mathrm{Hom}(E, R)$  in  $D(E, d)$ . The underlying complex of  $R$ -modules is  $H^\bullet = \mathrm{Hom}_R^\bullet(E^\bullet, K^\bullet)$ . This is a  $K$ -flat complex of  $R$ -modules by More on Algebra, Lemma 84.5 and our assumption that  $E^\bullet$  is perfect. By Differential Graded Algebra, Lemma 24.8 we see that the LHS of (23.6.1) is represented by  $H \otimes_R R'$  whose underlying complex of  $R'$ -modules is  $H^\bullet \otimes_R R'$ .

Arguing as above we find that

$$H' = \text{Hom}_{\text{Mod}_R^{\text{dg}}}(E', R')$$

represents the RHS of (23.6.1) and that as a complex of  $R'$ -modules we have

$$(H')^\bullet = \text{Hom}_{R'}^\bullet((E')^\bullet, R') = \text{Hom}_{R'}^\bullet(E^\bullet \otimes_R R', R') = \text{Hom}_R^\bullet(E^\bullet, R')$$

The last equality is proved by applying Algebra, Lemma 13.3 to the terms making up the Hom complex.

We define our map (23.6.1) to be the map

$$H \otimes_R R' \longrightarrow H'$$

defined by the following rule. An element  $f$  of  $H^n$  is an  $R$ -linear map from  $E^{-n}$  to  $R$ . Thus we send  $f \otimes \lambda$  to  $\lambda f'$  where  $f' : E^{-n} \rightarrow R'$  is the composition of  $f$  with  $R \rightarrow R'$ . It is immediately clear that this is an isomorphism of  $E'$ -modules which finishes the proof.  $\square$

0BZR **Lemma 23.7.** *Let  $R \rightarrow R'$  be a homomorphism of Noetherian rings. Let  $\varphi : R \rightarrow A$  be a perfect ring map (More on Algebra, Definition 73.1) such that  $R'$  and  $A$  are tor independent over  $R$ . Let  $\varphi' : R' \rightarrow A' = A \otimes_R R'$  be the map induced by  $\varphi$ . Then we have a functorial isomorphism*

$$\varphi^!(K) \otimes_A^{\mathbf{L}} A' = (\varphi')^!(K \otimes_R^{\mathbf{L}} R')$$

for  $K$  in  $D(R)$ .

**Proof.** We can choose a factorization  $R \rightarrow P \rightarrow A$  where  $P$  is a polynomial ring over  $R$  and then  $A$  is a perfect  $P$ -module, see More on Algebra, Lemma 73.2. This gives a corresponding factorization  $R' \rightarrow P' \rightarrow A'$  by base change. Since we have  $(K \otimes_R^{\mathbf{L}} P) \otimes_P^{\mathbf{L}} P' = (K \otimes_R^{\mathbf{L}} R') \otimes_{R'}^{\mathbf{L}} P'$  by More on Algebra, Lemma 56.4 it suffices to prove the statement for  $P \rightarrow A$  and  $P \rightarrow P'$ . By Lemma 23.6 it suffices to prove that  $A$  is a perfect  $P$ -module and that  $A$  and  $P'$  are tor independent over  $P$ . The  $P$ -module  $A$  is a perfect as seen above. For tor independence

$$A \otimes_P^{\mathbf{L}} P' = A \otimes_R^{\mathbf{L}} R' = A'$$

The first equality by More on Algebra, Lemma 57.2 applied to  $R, R', P, P'$ . The second equality because  $A$  and  $R'$  are tor independent over  $R$ .  $\square$

0BZS **Lemma 23.8.** *Let  $R \rightarrow R'$  be a homomorphism of Noetherian rings. Let  $\varphi : R \rightarrow A$  be flat of finite type. Let  $\varphi' : R' \rightarrow A' = A \otimes_R R'$  be the map induced by  $\varphi$ . Then we have a functorial isomorphism*

$$\varphi^!(K) \otimes_A^{\mathbf{L}} A' = (\varphi')^!(K \otimes_R^{\mathbf{L}} R')$$

for  $K$  in  $D(R)$ .

**Proof.** Special case of Lemma 23.7 by More on Algebra, Lemma 73.4.  $\square$

0BZT **Lemma 23.9.** *Let  $A \xrightarrow{a} B \xrightarrow{b} C$  be finite type homomorphisms of Noetherian rings. Then there is a transformation of functors  $b^! \circ a^! \rightarrow (b \circ a)^!$  which is an isomorphism on  $D^+(A)$ .*

**Proof.** Choose a polynomial ring  $P = A[x_1, \dots, x_n]$  over  $A$  and a surjection  $P \rightarrow B$ . Choose elements  $c_1, \dots, c_m \in C$  generating  $C$  over  $B$ . Set  $Q = P[y_1, \dots, y_m]$  and denote  $Q' = Q \otimes_P B = B[y_1, \dots, y_m]$ . Let  $\chi : Q' \rightarrow C$  be the surjection sending  $y_j$  to  $c_j$ . Picture

$$\begin{array}{ccccc} & & Q & \xrightarrow{\quad} & Q' & \xrightarrow{\quad} & C \\ & & \uparrow & \psi' & \uparrow & & \\ A & \longrightarrow & P & \xrightarrow{\quad \psi} & B & & \end{array}$$

By Lemma 23.4 for  $M \in D(P)$  we have an arrow  $\psi^!(M) \otimes_B^{\mathbf{L}} Q' \rightarrow (\psi')^!(M \otimes_P^{\mathbf{L}} Q)$  which is an isomorphism whenever  $M$  is bounded below. Also we have  $\chi^! \circ (\psi')^! = (\chi \circ \psi)^!$  as both functors are adjoint to the restriction functor  $D(C) \rightarrow D(Q)$  by Section 13. Then we see

$$\begin{aligned} b^!(a^!(K)) &= \chi^!(\psi^!(K \otimes_A^{\mathbf{L}} P)[n] \otimes_B^{\mathbf{L}} Q)[m] \\ &\rightarrow \chi^!((\psi')^!(K \otimes_A^{\mathbf{L}} P \otimes_P^{\mathbf{L}} Q))[n+m] \\ &= (\chi \circ \psi)^!(K \otimes_A^{\mathbf{L}} Q)[n+m] \\ &= (b \circ a)^!(K) \end{aligned}$$

where we have used in addition to the above More on Algebra, Lemma 56.4.  $\square$

0C0G **Lemma 23.10.** *Let  $\varphi : R \rightarrow A$  be a finite map of Noetherian rings. Then  $\varphi^!$  is isomorphic to the functor  $R\mathrm{Hom}(A, -) : D(R) \rightarrow D(A)$  from Section 13.*

**Proof.** Suppose that  $A$  is generated by  $n > 1$  elements over  $R$ . Then can factor  $R \rightarrow A$  as a composition of two finite maps where in both steps the number of generators is  $< n$ . Since we have Lemma 23.9 and Lemma 13.2 we conclude that it suffices to prove the lemma when  $A$  is generated by one element over  $R$ . Since  $A$  is finite over  $R$ , it follows that  $A$  is a quotient of  $B = R[x]/(f)$  where  $f$  is a monic polynomial in  $x$  (Algebra, Lemma 35.3). Again using the lemmas on composition and the fact that we have agreement for surjections by definition, we conclude that it suffices to prove the lemma for  $R \rightarrow B = R[x]/(f)$ . In this case, the functor  $\varphi^!$  is isomorphic to  $K \mapsto K \otimes_R^{\mathbf{L}} B$ ; you prove this by using Lemma 13.10 for the map  $R[x] \rightarrow B$  (note that the shift in the definition of  $\varphi^!$  and in the lemma add up to zero). For the functor  $R\mathrm{Hom}(R-, -) : D(R) \rightarrow D(B)$  we can use Lemma 13.9 to see that it suffices to show  $\mathrm{Hom}_R(B, R) \cong B$  as  $B$ -modules. Suppose that  $f$  has degree  $d$ . Then an  $R$ -basis for  $B$  is given by  $1, x, \dots, x^{d-1}$ . Let  $\delta_i : B \rightarrow R, i = 0, \dots, d-1$  be the  $R$ -linear map which picks off the coefficient of  $x^i$  with respect to the given basis. Then  $\delta_0, \dots, \delta_{d-1}$  is a basis for  $\mathrm{Hom}_R(B, R)$ . Finally,  $x^i \delta_{d-1} = \delta_{d-1-i}$  for  $i \leq d-1$ . Hence  $\mathrm{Hom}_R(B, R)$  is a principal  $B$ -module, and by looking at ranks we conclude that it is a free  $B$ -module of rank 1 (with basis element  $\delta_{d-1}$ ).  $\square$

0C0H **Lemma 23.11.** *Let  $R$  be a Noetherian ring and let  $f \in R$ . If  $\varphi$  denotes the map  $R \rightarrow R_f$ , then  $\varphi^!$  is isomorphic to  $-\otimes_R^{\mathbf{L}} R_f$ . More generally, if  $\varphi : R \rightarrow R'$  is a map such that  $\mathrm{Spec}(R') \rightarrow \mathrm{Spec}(R)$  is an open immersion, then  $\varphi^!$  is isomorphic to  $-\otimes_R^{\mathbf{L}} R'$ .*

**Proof.** Choose the presentation  $R \rightarrow R[x] \rightarrow R[x]/(fx-1) = R_f$  and observe that  $fx-1$  is a nonzerodivisor in  $R[x]$ . Thus we can apply using Lemma 13.10 to compute the functor  $\varphi^!$ . Details omitted; note that the shift in the definition of  $\varphi^!$  and in the lemma add up to zero.

In the general case note that  $R' \otimes_R R' = R'$ . Hence the result follows from the base change results above. Either Lemma 23.5 or Lemma 23.7 will do.  $\square$

Let  $\varphi : R \rightarrow A$  be a finite type homomorphism of Noetherian rings. Then we define the *relative dualizing complex of  $A$  over  $R$*  as the object  $\omega_{A/R}^\bullet = \varphi^!(R)$  of  $D(R)$ . It is well defined up to (non-unique) isomorphism.

0BZU **Lemma 23.12.** *Let  $\varphi : R \rightarrow A$  be a perfect homomorphism of Noetherian rings (for example  $\varphi$  is flat of finite type). Then  $\varphi^!(K) = K \otimes_R^L \omega_{A/R}^\bullet$  for  $K \in D(R)$ .*

**Proof.** (The parenthetical statement follows from More on Algebra, Lemma 73.4.) We can choose a factorization  $R \rightarrow P \rightarrow A$  where  $P$  is a polynomial ring in  $n$  variables over  $R$  and then  $A$  is a perfect  $P$ -module, see More on Algebra, Lemma 73.2. Recall that  $\varphi^!(K) = R \operatorname{Hom}(A, K \otimes_R^L P[n])$ . Thus the result follows from Lemma 13.9 and More on Algebra, Lemma 56.4.  $\square$

0BZV **Lemma 23.13.** *Let  $R \rightarrow R'$  be a homomorphism of Noetherian rings. Let  $R \rightarrow A$  be flat and of finite type. There is an isomorphism  $\omega_{A/R}^\bullet \otimes_A^L A' \rightarrow \omega_{A'/R'}^\bullet$  in  $D(A')$ .*

**Proof.** Immediate from Lemma 23.8 and the definitions.  $\square$

0BZW **Lemma 23.14.** *Let  $R \rightarrow A$  be flat, finite type homomorphism of Noetherian rings. Then  $\omega_{A/R}^\bullet$  is in  $D_{Coh}^b(A)$  and for every map  $R \rightarrow k$  to a field the base change  $\omega_{A/R}^\bullet \otimes_A^L (A \otimes_R k)$  is a dualizing complex for  $A \otimes_R k$ .*

**Proof.** Recall that  $R \rightarrow A$  is a perfect ring map by More on Algebra, Lemma 73.4. Hence  $\omega_{A/R}^\bullet$  is in  $D_{Coh}^b(A)$  by Lemma 23.2. By Lemma 23.13 there is an isomorphism

$$\omega_{A/R}^\bullet \otimes_A^L (A \otimes_R k) \cong \omega_{A \otimes_R k/k}^\bullet$$

and the right hand side is a dualizing complex by Lemma 23.3.  $\square$

0E0P **Lemma 23.15.** *Let  $K/k$  be an extension of fields. Let  $A$  be a finite type  $k$ -algebra. Let  $A_K = A \otimes_k K$ . If  $\omega_A^\bullet$  is a dualizing complex for  $A$ , then  $\omega_A^\bullet \otimes_A A_K$  is a dualizing complex for  $A_K$ .*

**Proof.** By the uniqueness of dualizing complexes, it doesn't matter which dualizing complex we pick for  $A$ ; we omit the detailed proof. Denote  $\varphi : k \rightarrow A$  the algebra structure. We may take  $\omega_A^\bullet = \varphi^!(k[0])$  by Lemma 23.3. We conclude by Lemma 23.14.  $\square$

## 24. Other chapters

Preliminaries	(10) Commutative Algebra
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(2) Conventions	(12) Homological Algebra
(3) Set Theory	(13) Derived Categories
(4) Categories	(14) Simplicial Methods
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