Homological Methods in Commutative Algebra

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Contents

CHAPTER 1

Associated primes

Basic references are [**Bou98, Bou06, Bou07**], [**Ser00**], and [**Mat89**].

All rings are commutative, with unit, and noetherian. A local ring is always nonzero.

We will use the convention that R will denote a (noetherian, commutative, unital) ring, A a local ring, $\mathfrak{m}$ its maximal ideal, and k its residue field. The letter M will either denote a R-module, or an A-module. A prime will mean a prime ideal of R, or of A. When $\mathfrak{p}$ is a prime, we denote by $\kappa(\mathfrak{p})$ the field $R_{\mathfrak{p}}/(\mathfrak{p}R_{\mathfrak{p}})$, or $A_{\mathfrak{p}}/(\mathfrak{p}A_{\mathfrak{p}})$.

1. Support of a module

Definition 1.1.1. Let M be an R-module, and $m \in M$. The *annihilator* $\mathrm{Ann}(m)$ is the set of elements $x \in R$ such that $xm = 0$. This is an ideal of R. We write $\mathrm{Ann}(M)$, or $\mathrm{Ann}_R(M)$, for the intersection of the ideals $\mathrm{Ann}(m)$, where $m \in M$.

Definition 1.1.2. The set of prime ideals of R is denoted $\mathrm{Spec}(R)$. The *support* of an R-module M, denoted $\mathrm{Supp}(M)$, or $\mathrm{Supp}_R(M)$, is the subset of of $\mathrm{Spec}(R)$ consisting of those primes $\mathfrak{p}$ such that $M_{\mathfrak{p}} \neq 0$.

Observe that if $\mathfrak{p} \in \mathrm{Supp}(M)$ and $\mathfrak{q} \in \mathrm{Spec}(R)$ with $\mathfrak{p} \subset \mathfrak{q}$, then $\mathfrak{q} \in \mathrm{Supp}(M)$.

Lemma 1.1.3. *The support of M is the set of primes containing the annihilator of some element of M.*

Proof. Let $\mathfrak{p} \in \mathrm{Spec}(R)$. Then $M_{\mathfrak{p}} \neq 0$ if and only if there exists $m \in M$ such that $tm \neq 0$ for all $t \notin \mathfrak{p}$, or equivalently $\mathrm{Ann}(m) \subset \mathfrak{p}$. □

Lemma 1.1.4. *Let M be a finitely generated R-module. Then* $\mathrm{Supp}(M)$ *is the set of primes containing* $\mathrm{Ann}(M)$.

Proof. Since for any $m \in M$, we have $\mathrm{Ann}(M) \subset \mathrm{Ann}(m)$, it follows from Lemma 1.1.3 that any element of $\mathrm{Supp}(M)$ contains $\mathrm{Ann}(M)$ (we did not use the assumption that M is finitely generated).

Conversely assume that M is finitely generated, and let $\mathfrak{p}$ be a prime containing $\mathrm{Ann}(M)$. We claim that there is $m \in M$ such that $\mathrm{Ann}(m) \subset \mathfrak{p}$; by Lemma 1.1.3 this will show that $\mathfrak{p} \in \mathrm{Supp}(M)$. Assuming the contrary, let $m_1, \cdots, m_n$ be a finite generating family for M. We can find $s_i \in \mathrm{Ann}(m_i)$ such that $s_i \notin \mathfrak{p}$, for $i = 1, \cdots, n$. Then the product $s_1 \cdots s_n$ belongs to $\mathrm{Ann}(M)$, hence to $\mathfrak{p}$. Since $\mathfrak{p}$ is prime, it follows that $s_j \in \mathfrak{p}$ for some j, a contradiction. □

Lemma 1.1.5. *Consider an exact sequence of R-modules:*

$$0 \to M' \to M \to M'' \to 0.$$

Then $\mathrm{Supp}(M) = \mathrm{Supp}(M') \cup \mathrm{Supp}(M'')$.

PROOF. For every prime $\mathfrak{p}$, we have an exact sequence

$$0 \to M'_{\mathfrak{p}} \to M_{\mathfrak{p}} \to M''_{\mathfrak{p}} \to 0,$$

and therefore $M_{\mathfrak{p}} = 0$ if and only if $M'_{\mathfrak{p}} = 0$ and $M''_{\mathfrak{p}} = 0$. □

LEMMA 1.1.6 (Nakayama's Lemma). *Let $(A, \mathfrak{m})$ be a local ring, and M a finitely generated A-module. If $\mathfrak{m}M = M$ then $M = 0$.*

PROOF. Assume that $M \neq 0$. Let M' be a maximal proper (i.e. $\neq M$) submodule of M, and $M'' = M/M'$ (if no proper submodule were maximal, then we could build an infinite ascending chain of submodules in M, a contradiction since A is noetherian and M finitely generated). Then by maximality of M, the module M'' is simple, i.e. has exactly two submodules (0 and M''). But a simple module is isomorphic to $A/\mathfrak{m}$ (it is generated by a single element, hence is of the type A/I for an ideal I; but A/I is simple if and only if $I = \mathfrak{m}$). Therefore $\mathfrak{m}M'' = 0$, hence $\mathfrak{m}M \subset M'$. This is a contradiction with $\mathfrak{m}M = M$. □

DEFINITION 1.1.7. If $(A, \mathfrak{m})$ and $(B, \mathfrak{n})$ are two local rings, a ring morphism $\phi\colon A \to B$ is called a *local morphism* if $\phi(\mathfrak{m}) \subset \mathfrak{n}$.

LEMMA 1.1.8. *Let $A \to B$ be a local morphism of local rings, and M a finitely generated A-module. If $M \otimes_A B = 0$, then $M = 0$.*

PROOF. Assume that $M \neq 0$ and let k be the residue field of A. By Nakayama's Lemma 1.1.6, the k-vector space $M \otimes_A k$ is nonzero hence admits a one-dimensional quotient. This gives a surjective morphism of A-modules $M \to k$. Then $k \otimes_A B$ vanishes, being a quotient of $M \otimes_A B$. But since $A \to B$ is local, the residue field of B is a quotient of $k \otimes_A B$, a contradiction. □

PROPOSITION 1.1.9. *Let $\varphi\colon R \to S$ be a ring morphism, and M a finitely generated R-module. Then*

$$\mathrm{Supp}_S(M \otimes_R S) = \{\mathfrak{q} \in \mathrm{Spec}(S) \mid \varphi^{-1}\mathfrak{q} \in \mathrm{Supp}_R(M)\}.$$

PROOF. Let $\mathfrak{q} \in \mathrm{Spec}(S)$ and $\mathfrak{p} = \varphi^{-1}\mathfrak{q}$. Then the morphism $R_{\mathfrak{p}} \to S_{\mathfrak{q}}$ is local. We have an isomorphism of $S_{\mathfrak{q}}$-modules $(M \otimes_R S)_{\mathfrak{q}} \simeq M_{\mathfrak{p}} \otimes_{R_{\mathfrak{p}}} S_{\mathfrak{q}}$, and the result follows from Lemma 1.1.8. □

COROLLARY 1.1.10. *Let M be a finitely generated R-module, and I an ideal of R. Then*

$$\mathrm{Supp}_R(M/IM) = \{\mathfrak{p} \in \mathrm{Supp}(M) \mid I \subset \mathfrak{p}\}.$$

PROOF. Let $\varphi\colon R \to R/I$ be the quotient morphism. Any prime $\mathfrak{p}$ containing I may be written as $\varphi^{-1}\mathfrak{q}$ for some $\mathfrak{q} \in \mathrm{Spec}(R/I)$. If in addition $\mathfrak{p} \in \mathrm{Supp}(M)$, then by Proposition 1.1.9 we have $\mathfrak{q} \in \mathrm{Supp}_{R/I}(M/IM)$. By Lemma 1.1.3 there is $m \in M/IM$ such that $\mathrm{Ann}_{R/I}(m) \subset \mathfrak{q}$, hence $\mathrm{Ann}_R(m) = \varphi^{-1}\mathrm{Ann}_{R/I}(m) \subset \varphi^{-1}\mathfrak{q} = \mathfrak{p}$, proving that $\mathfrak{p} \in \mathrm{Supp}_R(M/IM)$. This proves one inclusion. The other inclusion is clear. □

2. Associated primes

Definition 1.2.1. A prime $\mathfrak{p}$ of R is an *associated prime of* M if there is $m \in M$ such that $\mathfrak{p} = \mathrm{Ann}(m)$. The set of associated primes is written $\mathrm{Ass}(M)$, or $\mathrm{Ass}_R(M)$.

In other words we have $\mathfrak{p} \in \mathrm{Ass}(M)$ if and only if there is an injective R-module morphism $R/\mathfrak{p} \to M$.

Proposition 1.2.2. *Any maximal element of the set* $\{\mathrm{Ann}(m) | m \in M, m \neq 0\}$, *ordered by inclusion, is prime.*

Proof. Let $I = \mathrm{Ann}(m)$ be such a maximal element. Let $x, y \in R$, and assume that $xy \in I$. If $y \notin I$, then $ym \neq 0$. Then $I = \mathrm{Ann}(m) \subset \mathrm{Ann}(ym)$. By maximality $I = \mathrm{Ann}(ym)$. Since $xym = 0$, we have $x \in \mathrm{Ann}(ym)$, hence $x \in I$. □

Corollary 1.2.3. *We have* $M \neq 0$ *if and only if* $\mathrm{Ass}(M) \neq \varnothing$.

Proof. Since R is noetherian, the set of Proposition 1.2.2 admits a maximal element as soon as it is not empty. □

Lemma 1.2.4. *Let* $\mathfrak{p}$ *be a prime in* R. *Then* $\mathrm{Ass}_R(R/\mathfrak{p}) = \{\mathfrak{p}\}$.

Proof. Let $m \in R/\mathfrak{p}$ be a nonzero element. Then $\mathfrak{p} \subset \mathrm{Ann}_R(m)$. Conversely, let $x \in \mathrm{Ann}_R(m)$. If $r \in R - \mathfrak{p}$ is the preimage of $m \in R/\mathfrak{p}$, we have $xr \in \mathfrak{p}$, and since $\mathfrak{p}$ is prime, it follows that $x \in \mathfrak{p}$. Thus $\mathfrak{p} = \mathrm{Ann}_R(m)$. □

Proposition 1.2.5. *Consider an exact sequence of* R*-modules:*

$$0 \to M' \to M \to M'' \to 0.$$

Then $\mathrm{Ass}(M') \subset \mathrm{Ass}(M) \subset \mathrm{Ass}(M') \cup \mathrm{Ass}(M'')$.

Proof. If $\mathfrak{p} \in \mathrm{Ass}(M')$, then M' contains a module isomorphic to $R/\mathfrak{p}$. Since $M' \subset M$, it follows that M also contains such a module, hence $\mathfrak{p} \in \mathrm{Ass}(M)$.

Now let $\mathfrak{p} \in \mathrm{Ass}(M)$. Then M contains a submodule E isomorphic to $R/\mathfrak{p}$. By Lemma 1.2.4 we have $\mathrm{Ass}(E) = \{\mathfrak{p}\}$. Let $F = M' \cap E$. The inclusion proved above implies that

$$\mathrm{Ass}(F) \subset \mathrm{Ass}(E) = \{\mathfrak{p}\} \quad \text{and} \quad \mathrm{Ass}(F) \subset \mathrm{Ass}(M').$$

If $F \neq 0$, we have $\mathrm{Ass}(F) \neq \varnothing$ by Corollary 1.2.3, so that $\mathrm{Ass}(F) = \{\mathfrak{p}\}$, and therefore $\mathfrak{p} \in \mathrm{Ass}(M')$. If $F = 0$, then the morphism $E \to M''$ is injective, so that $\{\mathfrak{p}\} = \mathrm{Ass}(E) \subset \mathrm{Ass}(M'')$. □

Lemma 1.2.6. *Let* M_α *be a family of submodules of* M *such that* $M = \cup_\alpha M_\alpha$. *Then*

$$\mathrm{Ass}(M) = \bigcup_\alpha \mathrm{Ass}(M_\alpha).$$

Proof. Since $M_\alpha \subset M$, we have $\mathrm{Ass}(M_\alpha) \subset \mathrm{Ass}(M)$. Conversely if $\mathfrak{p} = \mathrm{Ann}(m) \in \mathrm{Ass}(M)$, then there is α such that $m \in M_\alpha$. Then $\mathfrak{p} \in \mathrm{Ass}(M_\alpha)$. □

Proposition 1.2.7. *Let* $\Phi \subset \mathrm{Ass}(M)$. *Then there is a submodule* N *of* M *such that* $\mathrm{Ass}(N) = \Phi$ *and* $\mathrm{Ass}(M/N) = \mathrm{Ass}(M) - \Phi$.

Proof. Consider the set Σ of submodules P of M such that $\operatorname{Ass}(P) \subset \Phi$. This set is non-empty since $0 \in \Sigma$, and ordered by inclusion. Moreover Σ is stable under taking reunions of totally ordered subsets by Lemma 1.2.6. By Zorn's lemma, we can find a maximal element $N \in \Sigma$ (when M is finitely generated over the noetherian ring R, we do not need Zorn's lemma). Let $\mathfrak{p} \in \operatorname{Ass}(M/N)$. Then M/N contains a submodule isomorphic to $R/\mathfrak{p}$, of the form N'/N with $N \subsetneq N' \subset M$. By Proposition 1.2.5 and Lemma 1.2.4, we have

$$\operatorname{Ass}(N') \subset \operatorname{Ass}(N) \cup \operatorname{Ass}(N'/N) \subset \Phi \cup \{\mathfrak{p}\}.$$

By maximality of N, we have $\operatorname{Ass}(N') \not\subset \Phi$. It follows that $\mathfrak{p} \not\in \Phi$ and $\mathfrak{p} \in \operatorname{Ass}(N')$. Since N' is a submodule of M, we have $\operatorname{Ass}(N') \subset \operatorname{Ass}(M)$, and therefore $\mathfrak{p} \in \operatorname{Ass}(M) - \Phi$. Thus we have inclusions

$$\operatorname{Ass}(M/N) \subset \operatorname{Ass}(M) - \Phi \quad \text{and} \quad \operatorname{Ass}(N) \subset \Phi.$$

Since $\operatorname{Ass}(M) \subset \operatorname{Ass}(N) \cup \operatorname{Ass}(M/N)$ by Proposition 1.2.5, the above inclusions are in fact equalities. ☐

Definition 1.2.8. An element of R is called a *zerodivisor in M* if it annihilates a nonzero element of M, a *nonzerodivisor* otherwise.

Any element of an associated prime of M is a zerodivisor in M. The converse is true:

Lemma 1.2.9. *The set of zerodivisors in M is the union of the associated primes of M.*

Proof. Assume that $r \in \operatorname{Ann}(x)$ with $x \in M - 0$. Then $\operatorname{Ann}(x)$ is contained in a maximal element of the set $\{\operatorname{Ann}(m) | m \in M, m \neq 0\}$ (otherwise we could construct an ascending chain of ideals in the noetherian ring R). Proposition 1.2.2 says that this maximal element is an associated prime of M. ☐

Recall that when S is a multiplicatively closed subset of R, the map $\mathfrak{p} \mapsto S^{-1}\mathfrak{p}$ induces a bijection

$$\{\mathfrak{p} \in \operatorname{Spec}(R) \mid \mathfrak{p} \cap S = \varnothing\} \xrightarrow{\sim} \operatorname{Spec}(S^{-1}R).$$

Proposition 1.2.10. *Let S be a multiplicatively closed subset of R. Then*

$$\operatorname{Ass}_{S^{-1}R}(S^{-1}M) = \{S^{-1}\mathfrak{p} \mid \mathfrak{p} \in \operatorname{Ass}_R(M) \text{ and } \mathfrak{p} \cap S = \varnothing\}.$$

Proof. If M contains an R-submodule isomorphic to $R/\mathfrak{p}$, then (by exactness of the localisation) $S^{-1}M$ contains an $(S^{-1}R)$-submodule isomorphic to $S^{-1}(R/\mathfrak{p})$. The latter is isomorphic to $(S^{-1}R)/(S^{-1}\mathfrak{p})$.

Conversely, as recalled above any element of $\operatorname{Ass}_{S^{-1}R}(S^{-1}M)$ is of the form $S^{-1}\mathfrak{p}$ for a unique $\mathfrak{p} \in \operatorname{Spec}(R)$ satisfying $S \cap \mathfrak{p} = \varnothing$. We need to prove that $\mathfrak{p} \in \operatorname{Ass}_R(M)$. Let $m \in M$ and $s \in S$ be such that $S^{-1}\mathfrak{p} = \operatorname{Ann}_{S^{-1}R}(m/s)$. Let $p_1, \cdots, p_n$ be a set of generators of the R-module $\mathfrak{p}$. For every $i = 1, \cdots, n$, we have $p_i m/s = 0$ in $S^{-1}M$, which means that we can find $t_i \in S$ such that $t_i p_i m = 0$ in M. Let $m' = t_1 \cdots t_n m \in M$. Since each p_i belongs to $\operatorname{Ann}_R(m')$, it follows that $\mathfrak{p} \subset \operatorname{Ann}_R(m')$. Conversely if $x \in \operatorname{Ann}_R(m')$, then $xt_1 \cdots t_n/1 \in \operatorname{Ann}_{S^{-1}R}(m/s) = S^{-1}\mathfrak{p}$. Thus $uxt_1 \cdots t_n \in \mathfrak{p}$ for some $u \in S$. Since $ut_1 \cdots t_n \in S$ and $S \cap \mathfrak{p} = \varnothing$, it follows from the primality of $\mathfrak{p}$ that $x \in \mathfrak{p}$. Therefore $\operatorname{Ann}_R(m') = \mathfrak{p}$, and $\mathfrak{p} \in \operatorname{Ass}_R(M)$. ☐

3. Support and associated primes

PROPOSITION 1.3.1. *The set* $\operatorname{Supp}(M)$ *is the set of primes of* R *containing an element of* $\operatorname{Ass}(M)$.

PROOF. If $\mathfrak{p}$ contains an associated prime $\operatorname{Ann}(m)$ for some $m \in M$, then $\mathfrak{p} \in \operatorname{Supp}(M)$ by Lemma 1.1.3.

Let now $\mathfrak{p} \in \operatorname{Supp}(M)$. Then $M_{\mathfrak{p}} \neq 0$, hence by Corollary 1.2.3 we can find a prime in $\operatorname{Ass}_{R_{\mathfrak{p}}}(M_{\mathfrak{p}})$, which corresponds by Proposition 1.2.10 to a prime $\mathfrak{q} \in \operatorname{Ass}_R(M)$ such that $\mathfrak{q} \subset \mathfrak{p}$. □

COROLLARY 1.3.2. *We have* $\operatorname{Ass}(M) \subset \operatorname{Supp}(M)$, *and these sets have the same minimal elements.*

COROLLARY 1.3.3. *Minimal elements of* $\operatorname{Supp}(M)$ *consist of zerodivisors in* M.

PROOF. Combine Proposition 1.3.1 with Lemma 1.2.9. □

DEFINITION 1.3.4. The non-minimal elements of $\operatorname{Ass}(M)$ are called *embedded primes of* M.

PROPOSITION 1.3.5. *Assume that* M *is finitely generated. Then there is a chain of submodules*

$$0 = M_0 \subsetneq M_1 \subsetneq \cdots \subsetneq M_n = M$$

such that $M_i/M_{i-1} \simeq R/\mathfrak{p}_i$ *with* $\mathfrak{p}_i \in \operatorname{Spec}(R)$ *for* $i = 1, \cdots, n$. *We have*

$$\operatorname{Ass}(M) \subset \{\mathfrak{p}_1, \cdots, \mathfrak{p}_n\} \subset \operatorname{Supp}(M),$$

and these sets have the same minimal elements.

PROOF. Assume that we have constructed a chain

$$0 = M_0 \subsetneq M_1 \subsetneq \cdots \subsetneq M_j \subset M$$

such that $M_i/M_{i-1} \simeq R/\mathfrak{p}_i$ with $\mathfrak{p}_i$ prime, for $i = 1, \cdots, j$. If $M_j = M$, then the first part of the statement is proved. Otherwise, by Corollary 1.2.3 we can find $\mathfrak{p}_{j+1} \in \operatorname{Ass}(M/M_j)$. Thus M/M_j contains a submodule isomorphic to $R/\mathfrak{p}_{j+1}$, which is necessarily of the form M_{j+1}/M_j with $M_j \subsetneq M_{j+1} \subset M$. This process must stop, since R is noetherian and M finitely generated. This proves the first part.

By Proposition 1.2.5, we have $\operatorname{Ass}(M_i) \subset \operatorname{Ass}(M_{i-1}) \cup \operatorname{Ass}(R/\mathfrak{p}_i)$. We obtain that $\operatorname{Ass}(M) \subset \{\mathfrak{p}_1, \cdots, \mathfrak{p}_n\}$ using Lemma 1.2.4 and induction on i.

By Lemma 1.1.5, we have $\operatorname{Supp}(R/\mathfrak{p}_i) \cup \operatorname{Supp}(M_{i-1}) \subset \operatorname{Supp}(M_i)$. In particular $\mathfrak{p}_i \in \operatorname{Supp}(R/\mathfrak{p}_i) \subset \operatorname{Supp}(M_i)$. Since $M_i \subset M$, we have $\operatorname{Supp}(M_i) \subset \operatorname{Supp}(M)$. This proves that $\{\mathfrak{p}_1, \cdots, \mathfrak{p}_n\} \subset \operatorname{Supp}(M)$.

The last statement follows from Proposition 1.3.1. □

COROLLARY 1.3.6. *Assume that* M *is finitely generated. Then:*

(i) The set $\operatorname{Ass}(M)$ *is finite.*
(ii) The set of minimal elements of $\operatorname{Supp}(M)$ *is finite.*

COROLLARY 1.3.7. *Assume that* M *is finitely generated and nonzero. Then* $\operatorname{Supp}(M)$ *possesses at least one minimal element.*

REMARK 1.3.8. Corollary 1.3.7 may also be proved directly using Zorn's Lemma.

CHAPTER 2

Krull dimension

1. Dimension of a module

DEFINITION 2.1.1. The length of a chain of primes $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ in R is the integer n. The *dimension* of a finitely generated R-module M is the supremum of the lengths of the chains of primes in $\operatorname{Supp}(M)$. It is denoted $\dim M$, or $\dim_R M$. The *height* of a prime $\mathfrak{p}$ of R is the supremum of the lengths n of chains $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n = \mathfrak{p}$ of primes in R. In other words:

$$\operatorname{height} \mathfrak{p} = \dim R_{\mathfrak{p}}.$$

The dimension of the zero module is $-\infty$. By Lemma 1.1.4, we have $\dim M = \dim R/\operatorname{Ann}(M)$.

REMARK 2.1.2. Note that $\dim R/\mathfrak{p} + \dim R_{\mathfrak{p}}$ is the supremum of the lengths of chains of primes of R with $\mathfrak{p}$ appearing in the chain, so that

$$\dim R/\mathfrak{p} + \dim R_{\mathfrak{p}} \leq \dim R.$$

Later we will provide conditions on R ensuring that it is an equality.

PROPOSITION 2.1.3. *Let $R \to S$ be a ring homomorphism. Let M be an S-module, finitely generated as an R-module. Then*

$$\dim_R M = \dim_S M.$$

PROOF. Let $m_1, \cdots, m_n$ be generators of the S-module M. The morphism of S-modules $S \to M^n$ sending s to $(sm_1, \cdots, sm_n)$ has kernel $\operatorname{Ann}_S(M)$. This makes $S/\operatorname{Ann}_S(M)$ an S-submodule of M^n, which is therefore finitely generated as an R-module (R is noetherian). The ring morphism $R/\operatorname{Ann}_R(M) \to S/\operatorname{Ann}_S(M)$ is injective, and, as we have just seen, integral. In this situation chains of primes are in bijective correspondence (see e.g. [**AM69**, Corollary 5.9 and Theorem 5.10]). $\square$

PROPOSITION 2.1.4. *Let M be a finitely generated R-module. Then*

$$\dim M = \max_{\mathfrak{p} \in \operatorname{Ass}(M)} \dim R/\mathfrak{p} = \max_{\mathfrak{p} \in \operatorname{Supp}(M)} \dim R/\mathfrak{p}.$$

PROOF. This follows from Lemma 1.1.4 and Proposition 1.3.1. $\square$

2. Length of a module

DEFINITION 2.2.1. The length of a chain of submodules $0 = M_0 \subsetneq \cdots \subsetneq M_n = M$ is the integer n. The chain is called *maximal* if for each i there is no submodule N satisfying $M_i \subsetneq N \subsetneq M_{i+1}$. The *length* of an R-module M is the supremum of the lengths of the chains of submodules of M. It is denoted $\operatorname{length} M$.

The zero module is the only module of length zero.

Lemma 2.2.2. *Consider an exact sequence of R-modules*

$$0 \to M' \to M \to M'' \to 0.$$

Then we have $\operatorname{length} M = \operatorname{length} M' + \operatorname{length} M''$*.*

Proof. If $\operatorname{length} M' = \infty$ or $\operatorname{length} M'' = \infty$, then $\operatorname{length} M = \infty$. Assume that $\operatorname{length} M' = e < \infty$ and $\operatorname{length} M = \infty$. Let n be an integer. We may find a chain $M_0 \subsetneq \cdots \subsetneq M_{n+e}$ in M. Let $M'_i = M_i \cap M'$ and $M''_i = M_i/M'_i$. There are at least n indices i such that $M'_i = M'_{i+1}$, and for such i we have $M''_i \subsetneq M''_{i+1}$. Thus from the family M''_i we may extract a chain of length n of submodules of M''. This proves that $\operatorname{length} M'' \geq n$. Since n was arbitrary, we deduce that $\operatorname{length} M'' = \infty$.

So we may assume that all modules have finite length. The statement is true if $\operatorname{length} M' = \operatorname{length} M$ or if $\operatorname{length} M'' = \operatorname{length} M$, for then $M = M'$ or $M = M''$. Thus we may assume that $\operatorname{length} M' < \operatorname{length} M$ and $\operatorname{length} M'' < \operatorname{length} M$, and proceed by induction on $\operatorname{length} M$. Let $0 = M_0 \subsetneq \cdots \subsetneq M_r = M$ be a chain of maximal length, so that $r = \operatorname{length} M$. Let $N = M_{r-1}$. Then $\operatorname{length} N = \operatorname{length} M - 1$, and $\operatorname{length} M/N = 1$. Form the commutative diagram with exact rows and columns

$$\begin{tikzcd}
 & 0 \arrow[d] & 0 \arrow[d] & 0 \arrow[d] & \\
0 \arrow[r] & N' \arrow[r] \arrow[d] & N \arrow[r] \arrow[d] & N'' \arrow[r] \arrow[d] & 0 \\
0 \arrow[r] & M' \arrow[r] \arrow[d] & M \arrow[r] \arrow[d] & M'' \arrow[r] \arrow[d] & 0 \\
0 \arrow[r] & P' \arrow[r] \arrow[d] & P \arrow[r] \arrow[d] & P'' \arrow[r] \arrow[d] & 0 \\
 & 0 & 0 & 0 &
\end{tikzcd}$$

Then $\operatorname{length} P = 1$, hence either $P' = 0$ or $P' = P$. In any case, we have

$$\operatorname{length} P' + \operatorname{length} P'' = 1.$$

Then, using induction

$$\begin{aligned}
\operatorname{length} M &= \operatorname{length} N + 1 \\
&= \operatorname{length} N' + \operatorname{length} N'' + \operatorname{length} P' + \operatorname{length} P'' \\
&= \operatorname{length} M' + \operatorname{length} M''.
\end{aligned}$$

□

Proposition 2.2.3. *The length of any maximal chain of submodules of M is equal to the length of M.*

Proof. If M contains an infinite chain, then $\operatorname{length} M = \infty$. Let $0 = M_0 \subsetneq \cdots \subsetneq M_r = M$ be a maximal chain. We prove that $r = \operatorname{length} M$ by induction on r. If $r = 0$, then $M = 0$, hence $\operatorname{length} M = 0$. Assume that $r > 0$, and let $N = M_{r-1}$. We have $\operatorname{length} M/N = 1$ by maximality of the chain. In addition, the chain $0 = M_0 \subsetneq \cdots \subsetneq$

$M_{r-1} = N$ is maximal in N, so that $\operatorname{length} N = r - 1$ by induction. Therefore, by Lemma 2.2.2

$$\operatorname{length} M = \operatorname{length} N + \operatorname{length} M/N = r - 1 + 1 = r. \qquad \square$$

Lemma 2.2.4. *Let R be an integral domain. Then R has finite length as an R-module if and only if it is a field.*

Proof. If R is a field, it has exactly two ideals (0 and R), and thus has length 1.

Now assume that R has finite length, and let $x \in R - \{0\}$. The sequence of ideals $\cdots \subset x^{i+1}R \subset x^i R \subset \cdots \subset R$ must stabilise, hence $x^n = ax^{n+1}$ for some $n \in \mathbb{N}$ and some $a \in R$. Thus $x^n(1 - ax) = 0$. If R is an integral domain then $ax = 1$, showing that x is invertible in R. $\square$

Lemma 2.2.5. *Assume that M is finitely generated. Then* $\dim M = 0$ *if and only if M is nonzero and has finite length.*

Proof. We may assume that $M \neq 0$. Let us choose $M_i, \mathfrak{p}_i$ as in Proposition 1.3.5. Then by induction M has finite length if and only if each $R/\mathfrak{p}_i$ has finite length. This is so if and only if each $\mathfrak{p}_i$ is a maximal ideal of R by Lemma 2.2.4. Since $\{\mathfrak{p}_1, \cdots, \mathfrak{p}_n\}$ and $\operatorname{Supp}(M)$ have the same minimal elements, each $\mathfrak{p}_i$ is maximal if and only if $\operatorname{Supp}(M)$ consists of maximal ideals of R, or equivalently $\dim M = 0$. $\square$

3. Principal ideal Theorem

Definition 2.3.1. When S is a subset of R, and $\mathfrak{p} \in \operatorname{Spec}(R)$, we say that $\mathfrak{p}$ is *minimal over S* if it is a minimal element of the set of primes containing S.

Theorem 2.3.2 (Krull). *Assume that R is an integral domain. Let $x \in R - \{0\}$, and $\mathfrak{p}$ be a prime minimal over $\{x\}$. Then* $\operatorname{height} \mathfrak{p} = 1$.

Proof. The ring $R_{\mathfrak{p}}$ is an integral domain, and the image of x in $R_{\mathfrak{p}}$ is nonzero. Thus we may replace R with $R_{\mathfrak{p}}$, and assume that R is local with maximal ideal $\mathfrak{p}$. Let $\mathfrak{q}$ be a prime such that $\mathfrak{q} \subsetneq \mathfrak{p}$. It will suffice to prove that $\mathfrak{q} = 0$. We view R as a subring of $R_{\mathfrak{q}}$. For each integer $n \geq 0$, we consider the ideal of R defined as

$$\mathfrak{q}_n = (\mathfrak{q}^n R_{\mathfrak{q}}) \cap R = \{u \in R \mid su \in \mathfrak{q}^n \text{ for some } s \in R - \mathfrak{q}\},$$

(and called the n-th symbolic power of the ideal $\mathfrak{q}$). The ring R/xR has dimension zero by minimality of $\mathfrak{p}$, hence finite length by Lemma 2.2.5. It follows that the chain of ideals $\cdots \subset \mathfrak{q}_{n+1}/(\mathfrak{q}_{n+1} \cap xR) \subset \mathfrak{q}_n/(\mathfrak{q}_n \cap xR) \subset \cdots$ of R/xR must stabilise. Therefore we can find an integer n such that $\mathfrak{q}_n \subset \mathfrak{q}_{n+1} + xR$. Thus for any $y \in \mathfrak{q}_n$, we may find $a \in R$ such that $y - ax \in \mathfrak{q}_{n+1}$. Note that $x \notin \mathfrak{q}$ by minimality of $\mathfrak{p}$, hence x becomes invertible in $R_{\mathfrak{q}}$. But $ax \in \mathfrak{q}_n \subset \mathfrak{q}^n R_{\mathfrak{q}}$, and therefore $a = axx^{-1} \in \mathfrak{q}^n R_{\mathfrak{q}}$. Since $a \in R$, it follows that $a \in \mathfrak{q}_n$. We have proved that

$$\mathfrak{q}_n = \mathfrak{q}_{n+1} + x\mathfrak{q}_n.$$

Consider the finitely generated R-module $N = \mathfrak{q}_n/\mathfrak{q}_{n+1}$. We have $xN = N$ with x in the maximal ideal $\mathfrak{p}$ of R. Applying Nakayama's Lemma 1.1.6 we obtain that $N = 0$, or equivalently $\mathfrak{q}_n = \mathfrak{q}_{n+1}$. Observe that $\mathfrak{q}_m R_{\mathfrak{q}} = \mathfrak{q}^m R_{\mathfrak{q}} = (\mathfrak{q}R_{\mathfrak{q}})^m$ for any m. Thus $(\mathfrak{q}R_{\mathfrak{q}})^n = (\mathfrak{q}R_{\mathfrak{q}})^{n+1}$. We now apply Nakayama's Lemma 1.1.6 to the finitely generated $R_{\mathfrak{q}}$-module $(\mathfrak{q}R_{\mathfrak{q}})^n$ and conclude that $(\mathfrak{q}R_{\mathfrak{q}})^n = 0$. This shows that any element of the maximal ideal $\mathfrak{q}R_{\mathfrak{q}}$ of $R_{\mathfrak{q}}$ is nilpotent; but $R_{\mathfrak{q}}$ is a domain, so that $\mathfrak{q}R_{\mathfrak{q}} = 0$, and finally $\mathfrak{q} = 0$. $\square$

Lemma 2.3.3. *Let $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ be a chain of primes, and let $x \in \mathfrak{p}_n$. Then we can find a chain of primes $\mathfrak{p}'_0 \subsetneq \cdots \subsetneq \mathfrak{p}'_n$ with $\mathfrak{p}_0 = \mathfrak{p}'_0$, $\mathfrak{p}_n = \mathfrak{p}'_n$, and $x \in \mathfrak{p}'_1$.*

Proof. We proceed by induction on n, and we may assume that $n \geq 2$. It will suffice to find a prime $\mathfrak{p}'_{n-1}$ containing x and such that $\mathfrak{p}_{n-2} \subsetneq \mathfrak{p}'_{n-1} \subsetneq \mathfrak{p}_n$ (then we find by induction a chain of primes $\mathfrak{p}'_0 \subsetneq \cdots \subsetneq \mathfrak{p}'_{n-2}$ such that $\mathfrak{p}_0 = \mathfrak{p}'_0$, $\mathfrak{p}'_{n-2} \subsetneq \mathfrak{p}'_{n-1}$, and $x \in \mathfrak{p}'_1$). If $x \in \mathfrak{p}_{n-1}$, we may take $\mathfrak{p}'_{n+1} = \mathfrak{p}_{n+1}$. Thus we assume that $x \notin \mathfrak{p}_{n-1}$. Then we can find a prime $\mathfrak{p}'_{n-1}$ containing $\{x\} \cup \mathfrak{p}_{n-2}$, contained in $\mathfrak{p}_n$, and minimal for these properties (it corresponds to a minimal element of the support of the $R_{\mathfrak{p}_n}$-module $R_{\mathfrak{p}_n}/(\mathfrak{p}_{n-2}R_{\mathfrak{p}_n} + xR_{\mathfrak{p}_n})$, which exists by Corollary 1.3.7 since $\mathfrak{p}_{n-2}R_{\mathfrak{p}_n} + xR_{\mathfrak{p}_n} \subset \mathfrak{p}_n R_{\mathfrak{p}_n} \neq R_{\mathfrak{p}_n}$). Then the prime ideal $\mathfrak{p}'_{n-1}/\mathfrak{p}_{n-2}$ of $R/\mathfrak{p}_{n-2}$ is minimal over the image of x in $R/\mathfrak{p}_{n-2}$, and therefore has height 1 by Theorem 2.3.2. Since the prime ideal $\mathfrak{p}_n/\mathfrak{p}_{n-2}$ of $R/\mathfrak{p}_{n-2}$ has height ≥ 2, it cannot be equal to $\mathfrak{p}'_{n-1}/\mathfrak{p}_{n-2}$. Thus we have $\mathfrak{p}_{n-2} \subsetneq \mathfrak{p}'_{n-1} \subsetneq \mathfrak{p}_n$, with $x \in \mathfrak{p}'_{n-1}$, as required. $\square$

Proposition 2.3.4. *Let $(A, \mathfrak{m})$ be a local ring, $x \in \mathfrak{m}$, and M a finitely generated A-module. Then*

$$\dim M/xM \geq \dim M - 1,$$

with equality if and only x belongs to no prime $\mathfrak{p} \in \operatorname{Supp}(M)$ such that $\dim A/\mathfrak{p} = \dim M$.

Proof. Let $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ be a chain of primes in $\operatorname{Supp}(M)$. Replacing $\mathfrak{p}_n$ with $\mathfrak{m}$, we may assume that $\mathfrak{p}_n = \mathfrak{m}$. By Lemma 2.3.3 we can assume that $x \in \mathfrak{p}_1$. This gives a chain of primes $\mathfrak{p}_1 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ of length $n-1$ in $\operatorname{Supp}(M) \cap \operatorname{Supp}(A/xA) = \operatorname{Supp}(M/xM)$ (the last equality follows from Corollary 1.1.10), which proves that $\dim M/xM \geq n-1$.

Now a prime $\mathfrak{p} \in \operatorname{Supp}(M)$ contains x if and only if $\mathfrak{p} \in \operatorname{Supp}(M/xM)$ by Corollary 1.1.10. Thus the second statement follows from Proposition 2.1.4 applied to the module M/xM. $\square$

Corollary 2.3.5. *Let $(A, \mathfrak{m})$ be a local ring and M a finitely generated A-module. Let $x \in \mathfrak{m}$ be a nonzerodivisor in M. Then $\dim M/xM = \dim M - 1$.*

Proof. This follows from Corollary 1.3.3 and Proposition 2.3.4. $\square$

4. Flat base change

Definition 2.4.1. An R-module M is called *flat* if for every exact sequence of R-modules $N_1 \to N_2 \to N_3$ the induced sequence $M \otimes_R N_1 \to M \otimes_R N_2 \to M \otimes_R N_3$ is exact. We say that a ring morphism $R \to S$ is flat if S is flat as an R-module.

Lemma 2.4.2. *Let $\varphi\colon (A, \mathfrak{m}) \to (B, \mathfrak{n})$ be a flat local morphism. Then*

(i) For any A-module M, the morphism $M \to B \otimes_A M$ is injective.
(ii) The morphism $\operatorname{Spec} B \to \operatorname{Spec} A$ is surjective.

Proof. (i): Let $m \in M - \{0\}$. The ideal $I = \operatorname{Ann}(m)$ is contained in $\mathfrak{m}$. The exact sequence $I \to A \xrightarrow{m} M$ induces by flatness an exact sequence $B \otimes_A I \to B \xrightarrow{1 \otimes m} B \otimes_A M$. The image of $B \otimes_A I \to B$ is the ideal J generated by $\varphi(I)$ in B. Since φ is local and $I \subset \mathfrak{m}$, we have $J \subset \mathfrak{n}$. If $1 \otimes m = 0 \in B \otimes_A M$, then $B = J$, a contradiction.

(ii): Let $\mathfrak{p} \in \operatorname{Spec}(A)$. Then $\kappa(\mathfrak{p}) \to B \otimes_A \kappa(\mathfrak{p})$ is injective by (i), hence $B \otimes_A \kappa(\mathfrak{p}) \neq 0$. Thus $\operatorname{Spec}(B \otimes_A \kappa(\mathfrak{p})) \neq \varnothing$, which means that there is $\mathfrak{q} \in \operatorname{Spec} B$ such that $\varphi^{-1}\mathfrak{q} = \mathfrak{p}$ (by the description of the set of primes in a quotient or a localisation). $\square$

Proposition 2.4.3 (Going down). *Let $\rho\colon R \to S$ be a flat ring morphism. Let $\mathfrak{q} \in \operatorname{Spec}(S)$ and $\mathfrak{p}' \in \operatorname{Spec}(R)$ be such that $\mathfrak{p}' \subset \rho^{-1}\mathfrak{q}$. Then we may find $\mathfrak{q}' \in \operatorname{Spec}(S)$ such that $\mathfrak{q}' \subset \mathfrak{q}$ and $\rho^{-1}\mathfrak{q}' = \mathfrak{p}'$.*

Proof. The morphism $R_{\mathfrak{p}} \to S_{\mathfrak{q}}$ is flat and local. Therefore by Lemma 2.4.2 (ii) the prime $\mathfrak{p}'R_{\mathfrak{p}}$ has a preimage in $\operatorname{Spec}(S_{\mathfrak{q}})$, necessarily of the form $\mathfrak{q}'S_{\mathfrak{q}}$ with $\mathfrak{q}' \subset \mathfrak{q}$. The primes $\rho^{-1}\mathfrak{q}'$ and $\mathfrak{p}'$ coincide because they are contained in $\mathfrak{p}$ and localise to the same prime of $R_{\mathfrak{p}}$. □

Corollary 2.4.4. *Let $R \to S$ be a flat ring morphism and M a finitely generated R-module. Then the morphism $\operatorname{Spec} S \to \operatorname{Spec} R$ sends minimal elements of $\operatorname{Supp}_S(S \otimes_R M)$ to minimal elements of $\operatorname{Supp}_R(M)$.*

Proof. Let $\mathfrak{q}$ be a minimal element $\operatorname{Supp}_S(S \otimes_R M)$. Then its image $\mathfrak{p} \in \operatorname{Spec}(R)$ belongs to $\operatorname{Supp}_R(M)$ by Proposition 1.1.9. If $\mathfrak{p}' \in \operatorname{Supp}_R(M)$ is such that $\mathfrak{p}' \subset \mathfrak{p}$, then by Proposition 2.4.3 we may find a preimage $\mathfrak{q}'$ of $\mathfrak{p}'$ such that $\mathfrak{q}' \subset \mathfrak{q}$. Then $\mathfrak{q}' \in \operatorname{Supp}_S(S \otimes_R M)$ by Proposition 1.1.9, hence $\mathfrak{q}' = \mathfrak{q}$ by minimality of $\mathfrak{q}$. Thus $\mathfrak{p}' = \mathfrak{p}$, proving that $\mathfrak{p}$ is a minimal element of $\operatorname{Supp}_R(M)$. □

Proposition 2.4.5 (Prime avoidance). *Let $I, \mathfrak{p}_1, \cdots, \mathfrak{p}_n$ be ideals of R. Assume that $\mathfrak{p}_i$ is prime for $i \geq 3$. If $I \subset \mathfrak{p}_1 \cup \cdots \cup \mathfrak{p}_n$ then $I \subset \mathfrak{p}_i$ for some $i \in \{1, \cdots, n\}$.*

Proof. We assume that I is contained in no $\mathfrak{p}_i$ and find $x \in I$ belonging to no $\mathfrak{p}_i$. This is clear for $n = 0, 1$. If $n = 2$, we $x_i \in I - \mathfrak{p}_i$ for $i = 1, 2$. We may assume that $x_1 \in \mathfrak{p}_2$ and $x_2 \in \mathfrak{p}_1$ (otherwise the statement is proved). Then $x = x_1 + x_2$ works.

Now assume that $n > 2$, and proceed by induction on n. For each $j = 1, \cdots, n$, we can find by induction $x_j \in I$ which is in none of the $\mathfrak{p}_i$ for $i \neq j$, and we may assume as above that $x_j \in \mathfrak{p}_j$. Then $x = x_n + x_1x_2 \cdots x_{n-1}$ works, since $\mathfrak{p}_n$ is prime ($n \geq 3$). □

Proposition 2.4.6. *Let $\varphi\colon A \to B$ be a local morphism of local rings and M a finitely generated A-module. Let $\mathfrak{m}$ be the maximal ideal of A, and k its residue field. Then*

$$\dim_B B \otimes_A M \leq \dim_A M + \dim_B B \otimes_A k,$$

with equality if B is flat as an A-module.

Proof. We may assume that $M \neq 0$, and proceed by induction on $\dim_A M$. First assume that $\dim_A M = 0$. Then $\{\mathfrak{m}\} = \operatorname{Supp}_A(M) = \operatorname{Supp}_A(k)$, hence $\operatorname{Supp}_B(B \otimes_A M) = \operatorname{Supp}_B(B \otimes_A k)$ by Proposition 1.1.9 and thus $\dim_B B \otimes_A M = \dim B \otimes_A k$, proving the statement in this case.

Assume that $\dim_A M > 0$. Then $\mathfrak{m}$ is not a minimal element of $\operatorname{Supp}_A(M)$. By prime avoidance (Proposition 2.4.5) and finiteness of the set of minimal primes (Corollary 1.3.6), we may find $x \in \mathfrak{m}$ belonging to no minimal primes of $\operatorname{Supp}_A(M)$. By Proposition 2.3.4 we have $\dim_A M/xM = \dim_A M - 1$, so that we may use the induction hypothesis for the module M/xM and obtain

$$\dim_B B \otimes_A (M/xM) \leq \dim_A M - 1 + \dim_B B \otimes_A k, \tag{2.4.a}$$

with equality if φ is flat. Applying Proposition 2.3.4 to the B-module $B \otimes_A M$ and the element $\varphi(x) \in B$, we obtain

$$\dim_B B \otimes_A M \leq \dim_B B \otimes_A (M/xM) + 1, \tag{2.4.b}$$

with equality if $\varphi(x)$ belongs to no minimal primes of $\mathrm{Supp}_B(B \otimes_A M)$. The latter condition is fulfilled if φ is flat by Corollary 2.4.4. The statement follows by combining (2.4.a) and (2.4.b). $\square$

CHAPTER 3

Systems of parameters

1. Alternative definition of the dimension

In this section $(A, \mathfrak{m}, k)$ is a local ring, and M a finitely generated A-module.

LEMMA 3.1.1. *The following conditions are equivalent:*

(i) $\dim M = 0$.
(ii) $\mathrm{Supp}(M) = \{\mathfrak{m}\}$.
(iii) $\mathrm{Ass}(M) = \{\mathfrak{m}\}$.
(iv) *The A-module M has finite length and is nonzero.*
(v) $M \neq 0$ *and there is an integer n such that* $\mathfrak{m}^n M = 0$.

PROOF. (i) $\Leftrightarrow$ (ii): Indeed, $\dim M$ is the supremum of the lengths of chains of primes in $\mathrm{Supp}(M)$, and $\mathfrak{m} \in \mathrm{Supp}(M)$ as soon as $\mathrm{Supp}(M) \neq \varnothing$.

(ii) $\Leftrightarrow$ (iii): This follows from Proposition 1.3.1.

(iv) $\Leftrightarrow$ (i): This was proved in Lemma 2.2.5.

(iv) $\Rightarrow$ (v): The sequence of submodules $\mathfrak{m}^{i+1}M \subset \mathfrak{m}^i M \subset \cdots$ must stabilise, hence there is n such that $\mathfrak{m}^{n+1}M = \mathfrak{m}^n M$. By Nakayama's Lemma 1.1.6 (applied to $\mathfrak{m}^n M$) we obtain $\mathfrak{m}^n M = 0$.

(v) $\Rightarrow$ (ii): If $\mathfrak{p} \in \mathrm{Supp}(M)$, then $\mathfrak{m}^n \subset \mathrm{Ann}(M) \subset \mathfrak{p}$. Thus for any $x \in \mathfrak{m}$ we have $x^n \in \mathfrak{p}$. Since $\mathfrak{p}$ is prime, this implies $x \in \mathfrak{p}$, proving that $\mathfrak{m} = \mathfrak{p}$. □

PROPOSITION 3.1.2. *Assume that $M \neq 0$. Then $\dim M$ is finite, and coincides with the smallest integer n for which there exists elements $x_1, \cdots, x_n \in \mathfrak{m}$ such that the module $M/\{x_1, \cdots, x_n\}M$ satisfies the conditions of Lemma 3.1.1.*

PROOF. If $x_1, \cdots, x_m \in \mathfrak{m}$ are such that $\dim M/\{x_1, \cdots, x_m\}M = 0$, then $\dim M \leq m$ by Proposition 2.3.4.

If $x_1, \cdots, x_m$ is a finite set of generators of the ideal $\mathfrak{m}$ (which exists since A is noetherian), then the module $M/\{x_1, \cdots, x_m\}M = M/\mathfrak{m}M$ satisfies the condition (v) of Lemma 3.1.1, hence $\dim M \leq m < \infty$.

We prove by induction on $n = \dim M$ that we may find $x_1, \cdots, x_n \in \mathfrak{m}$ such that $\dim M/\{x_1, \cdots, x_n\}M = 0$. The case $n = 0$ being clear, let us assume that $n > 0$. By prime avoidance (Proposition 2.4.5), we may find an element $x_n \in \mathfrak{m}$ belonging to no $\mathfrak{p} \in \mathrm{Supp}(M)$ such that $\dim A/\mathfrak{p} = n$ (by Corollary 1.3.6 there are only finitely many such $\mathfrak{p}$, since they are among the minimal elements of $\mathrm{Supp}(M)$). Then $\dim M/x_n M = n - 1$ by Proposition 2.3.4. Applying the induction hypothesis to the module $N = M/x_n M$, we find $x_1, \cdots, x_{n-1} \in \mathfrak{m}$ such that $N/\{x_1, \cdots, x_{n-1}\}N = M/\{x_1, \cdots, x_n\}M$ satisfies the conditions of Lemma 3.1.1. □

DEFINITION 3.1.3. A set $\{x_1, \cdots, x_n\}$ as in Proposition 3.1.2 (with $n = \dim M$) is called a *system of parameters for M*.

If V is a k-vector space, we denote by $\dim_{k-\text{vect}} V$ its dimension in the sense of linear algebra (that is, the cardinality of a k-basis).

Proposition 3.1.4. *The minimal number of generators of the ideal* $\mathfrak{m}$ *is equal to* $\dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2)$.

Proof. Let $n = \dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2)$, and $x_1, \cdots, x_n \in \mathfrak{m}$ a family which reduces modulo $\mathfrak{m}^2$ to a k-basis of $\mathfrak{m}/\mathfrak{m}^2$. Let $I \subset \mathfrak{m}$ be the ideal generated by $x_1, \cdots, x_n$. Then $\mathfrak{m} = I + \mathfrak{m}^2$. Thus the finitely generated A-module $M = \mathfrak{m}/I$ satisfies $\mathfrak{m}M = M$, hence vanishes by Nakayama's Lemma 1.1.6. This prove that $\mathfrak{m} = I$ can be generated by n elements.

Conversely if the A-module $\mathfrak{m}$ is generated by m elements, then the k-vector space $\mathfrak{m}/\mathfrak{m}^2$ is generated by their images modulo $\mathfrak{m}^2$, so that $\dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2) \leq m$. □

Corollary 3.1.5. *We have* $\dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2) \geq \dim A$.

Proof. Since the A-module $k = A/\mathfrak{m}A$ satisfies the conditions of Lemma 3.1.1, this follows from Proposition 3.1.2 applied with $M = A$, and Proposition 3.1.4. □

2. Regular local rings

Definition 3.2.1. We will say that a local (noetherian) ring A is *regular* if $\dim A = \dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2)$, or equivalently (Proposition 3.1.4) if $\mathfrak{m}$ can be generated by $\dim A$ elements. A system of parameters for A generating the maximal ideal is called a *regular system of parameters.*

Example 3.2.2. A local ring of dimension zero is a regular local ring if and only if it is a field. Indeed let $\mathfrak{m}$ be its maximal ideal. Then $\dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2) = 0$ if and only if $\mathfrak{m} = \mathfrak{m}^2$. By Nakayama's Lemma 1.1.6, this condition is equivalent to $\mathfrak{m} = 0$.

Example 3.2.3. (Exercise) A local ring of dimension one is a regular local ring if and only if it is a discrete valuation ring.

Lemma 3.2.4. *Let* $(A, \mathfrak{m})$ *be a regular local ring, and* $x \in \mathfrak{m} - \mathfrak{m}^2$. *Then* A/xA *is a regular local ring of dimension* $\dim A - 1$.

Proof. Consider the local ring $B = A/xA$, and let $\mathfrak{n} = \mathfrak{m}/xA$ be its maximal ideal. Note that $k = A/\mathfrak{m} = B/\mathfrak{n}$. There is a surjective morphism $\mathfrak{m}/\mathfrak{m}^2 \to \mathfrak{n}/\mathfrak{n}^2$ of k-vector spaces whose kernel contains the 1-dimensional k-vector space generated by $x \mod \mathfrak{m}^2$. It follows that

$$\dim_{k-\text{vect}}(\mathfrak{n}/\mathfrak{n}^2) \leq \dim_{k-\text{vect}}(\mathfrak{m}/\mathfrak{m}^2) - 1 = \dim A - 1 \leq \dim B,$$

where we use Proposition 2.3.4 for the last inequality. Since $\dim_{k-\text{vect}}(\mathfrak{n}/\mathfrak{n}^2) \geq \dim B$ by Corollary 3.1.5, we conclude that $\dim_{k-\text{vect}}(\mathfrak{n}/\mathfrak{n}^2) = \dim B = \dim A - 1$. □

A partial converse is given by the following.

Lemma 3.2.5. *Let* $(A, \mathfrak{m})$ *be a local ring, and* $x \in \mathfrak{m}$ *a nonzerodivisor in* A. *If* A/xA *is a regular local ring then so is* A.

Proof. Let $n = \dim A$. By Corollary 2.3.5 we have $\dim A/xA = n - 1$. Let $x_1, \cdots, x_{n-1}$ be elements of $\mathfrak{m}$ reducing modulo xA to a regular system of parameters for the local ring A/xA. Then the n elements $x, x_1, \cdots, x_{n-1}$ generate the ideal $\mathfrak{m}$, and thus form a regular system of parameters for A. □

Proposition 3.2.6. *A regular local ring is an integral domain.*

Proof. Let $(A, \mathfrak{m})$ be a regular local ring. We prove that A is an integral domain by induction on $\dim A$. If $\dim A = 0$, then A is a field by Example 3.2.2, and in particular an integral domain. If $\dim A > 0$, then $\mathfrak{m} \neq 0$, hence $\mathfrak{m} \neq \mathfrak{m}^2$ by Nakayama's Lemma 1.1.6. Thus by prime avoidance (Proposition 2.4.5) we may find an element $x \in \mathfrak{m}$ not belonging to $\mathfrak{m}^2$ nor to any of the finitely many minimal primes of A (Corollary 1.3.6). The local ring A/xA is regular and has dimension $\dim A - 1$ by Lemma 3.2.4. By the induction hypothesis it is an integral domain, which means that xA is a prime ideal of A. So xA contains a minimal prime $\mathfrak{q}$; by the choice of x we have $x \notin \mathfrak{q}$. For any $y \in \mathfrak{q}$, we can write $y = xa$ for some $a \in A$. Since $\mathfrak{q}$ is prime and $x \notin \mathfrak{q}$ we have $a \in \mathfrak{q}$. Thus $\mathfrak{q} = x\mathfrak{q}$, hence $\mathfrak{q} = \mathfrak{m}\mathfrak{q}$ and by Nakayama's Lemma 1.1.6 we have $\mathfrak{q} = 0$, proving that A is an integral domain. $\square$

CHAPTER 4

Tor **and** Ext

In this section R is a commutative unital ring.

1. Chain complexes

DEFINITION 4.1.1. A *chain complex (of R-modules) C* is a collection of R-modules C_i and morphisms of R-modules $d_i^C : C_i \to C_{i-1}$ for $i \in \mathbb{Z}$ satisfying $d_{i-1}^C \circ d_i^C = 0$. The R-module

$$H_i(C) = \ker d_i^C \,/\, \operatorname{im} d_{i+1}^C$$

is called the *i-th homology* of the chain complex C. The chain complex C is called *exact* if $H_i(C) = 0$ for all i.

A morphism of chain complexes $f\colon C \to C'$ is a collection of morphisms $f_i\colon C_i \to C_i'$ such that $f_{i-1} \circ d_i = d_i \circ f_i$. Such a morphism induces a morphism of the homology modules $H_i(C) \to H_i(C')$. We say that the morphism $C \to C'$ is a *quasi-isomorphism* if the induced morphism $H_i(C) \to H_i(C')$ is an isomorphism for all i.

DEFINITION 4.1.2. We say that two morphisms of chain complexes $f, g\colon C \to C'$ are *homotopic* if there is a collection of morphisms $s_i\colon C_i \to C_{i+1}'$ such that

$$f_i - g_i = d_{i+1}^{C'} \circ s_i + s_{i-1} \circ d_i^C.$$

A morphism of chain complexes $f\colon M \to N$ is a *homotopy equivalence* if there is a morphism of chain complexes $g\colon N \to M$ such that $f \circ g$ is homotopic to id_N and $g \circ f$ is homotopic to id_M. We say that two chain complexes are *homotopy equivalent* if there is a homotopy equivalence between them.

PROPOSITION 4.1.3. *Homotopic morphisms induce the same morphism in homology.*

PROOF. In the notations of Definition 4.1.2, the morphism $d_i^{C'} \circ s_i$ has image contained in $\operatorname{im} d_{i+1}^{C'}$ and the morphism $s_{i-1} \circ d_i^C$ has kernel contained in $\ker d_i^C$. They induce the zero morphism in homology by construction. □

COROLLARY 4.1.4. *Homotopy equivalent chain complexes are quasi-isomorphic.*

DEFINITION 4.1.5. A sequence of chain complexes

$$0 \to C' \to C \to C'' \to 0$$

is called *exact* if the sequence

$$0 \to C_i' \to C_i \to C_i'' \to 0$$

is exact for each i.

Proposition 4.1.6. *An exact sequence of chain complexes*

$$0 \to C' \to C \to C'' \to 0$$

induces an exact sequence of modules

$$\cdots \to H_{i+1}(C'') \to H_i(C') \to H_i(C) \to H_i(C'') \to H_{i-1}(C) \to \cdots$$

Proof. We only describe the morphism $\partial \colon H_{i+1}(C'') \to H_i(C')$. Any element $x''_{i+1} \in \ker d^{C''}_{i+1}$ lifts to $x_{i+1} \in C_{i+1}$. Let $x_i = d^C_{i+1}(x_{i+1}) \in C_i$. The image of x_i in C''_i is $d^{C''}_{i+1}(x''_{i+1}) = 0$, hence x_i is the image of some $x'_i \in C'_i$. In addition the image of $d^{C'}_i(x'_i) \in C'_{i-1}$ in C_{i-1} is $d^C_i \circ d^C_{i+1}(x_i) = 0$. Since $C'_{i-1} \to C_{i-1}$ is injective, it follows that $x'_i \in \ker d^{C'}_i$. We define $\partial(x)$ as the class of $x'_i \in H_i(C') = \ker d^{C'}_i / \operatorname{im} d^{C'}_{i+1}$.

We leave it as an exercise to check that ∂ is well-defined and that the sequence is exact. □

2. Projective Resolutions

Lemma 4.2.1. *Let M be a module. Then there is a surjective morphism $F \to M$ with F free. If M finitely generated, then F may be chosen to be finitely generated.*

Proof. First assume that $\mathcal{G} \subset M$ is a generating set for the R-module M, and let F be the free module on the basis $\{e_g | g \in \mathcal{G}\}$. Then there is a surjective morphism $F \to M$ given by $e_g \mapsto g$.

We may always take $\mathcal{G} = M$. If M is finitely generated, we may find a finite generating set $\mathcal{G}$; in this case F is finitely generated. □

Definition 4.2.2. An R-module P is *projective* if for every surjective R-module morphism $M \to M''$, the natural morphism $\operatorname{Hom}_R(P, M) \to \operatorname{Hom}_R(P, M'')$ is surjective.

Lemma 4.2.3. *A module is projective if and only if it is a direct summand of a free module.*

Proof. If P is a projective R-module, we may find a surjective R-module morphism $p \colon F \to P$ with F free by Lemma 4.2.1. Since P is projective, there is an R-module morphism $s \colon P \to F$ such that $p \circ s = \mathrm{id}_P$. This gives a decomposition $F = P \oplus \ker p$.

Let L be a free module with basis l_α, and $M \to M''$ be a surjective morphism. Let $g \colon L \to M''$ be a morphism. For each α, choose an element of $m_\alpha \in M$ mapping to $g(l_\alpha)$. Then the unique morphism $L \to M$ mapping l_α to m_α is a lifting of g. This proves that L is projective. Let now A be a direct summand of a free module L, which means that there are morphisms $A \to L$ and $L \to A$ such that the composite $A \to L \to A$ is the identity. Let $A \to M$ be a morphism. As we have just seen, the morphism $L \to A \to M$ lifts to a morphism $L \to M''$. The composite $A \to L \to M$ is then a lifting of the morphism $A \to M$. This proves that the module A is projective. □

Lemma 4.2.4. *A projective module is flat.*

Proof. Using the fact that tensor products commutes with (possibly infinite) direct sums, we see that a direct summand of a flat module is flat, and that a free module is flat. The lemma then follows from Lemma 4.2.3. □

Definition 4.2.5. Let M be an R-module. A *resolution* $C \to M$ is a chain complex C such that $C_i = 0$ for $i < 0$, together with a morphism $C_0 \to M$ such that the augmented chain complex
$$\cdots \to C_1 \to C_0 \to M \to 0$$
is exact.

This may be reformulated as follows. We denote by $C(M)$ the chain complex such that $C(M)_i = 0$ for $i \neq 0$ and $C(M)_0 = M$ (and thus $d_i^{C(M)} = 0$ for all i). A resolution of M is a chain complex C such that $C_i = 0$ for $i < 0$, together with a quasi-isomorphism $C \to C(M)$.

A resolution $C \to M$ is said to be projective, resp. free, resp. finitely generated, if each C_i is so.

Proposition 4.2.6. *Every module admits a free resolution. If R is noetherian, any finitely generated R-module admits a finitely generated free resolution.*

Proof. Let M be a module. We construct a chain complex D as follows. We let $D_i = 0$ for $i < 0$ and $D_{-1} = M$. Assuming that $D_{i-1} \to D_{i-2} \to \cdots$ is constructed for some $i \geq 0$, by Lemma 4.2.1 we may find a surjection $D_i \to \ker(D_{i-1} \to D_{i-2})$ with D_i free (resp. free and finitely generated). Then the sequence of modules $D_i \to D_{i-1} \to D_{i-2}$ is exact. The resolution $C \to M$ is obtained by letting $C_i = D_i$ for $i \neq 0$ and $C_0 = 0$. □

Proposition 4.2.7. *Let E and P be two chain complexes. Assume that*

- *$P_i = E_i = 0$ for $i < -1$.*
- *P_i is projective for $i \geq 0$.*
- *E is exact.*

Let $g\colon P_{-1} \to E_{-1}$ be a morphism of modules. Then there is a morphism of chain complexes $f\colon P \to E$ such that $f_{-1} = g$. This morphism is unique up to homotopy.

Proof. We construct f_i inductively, starting with $f_{-1} = g$. Assume that $i \geq 0$ and that f_{i-1} is constructed. The composite $f_{i-1} \circ d_i^P\colon P_i \to E_{i-1}$ lands into $\ker d_{i-1}^E$, because $d_{i-1}^E \circ f_{i-1} \circ d_i^P = d_i^E \circ d_{i-1}^E = 0$. By exactness of the complex E, the morphism $E_i \to \ker d_{i-1}^E$ induced by d_i^E is surjective, hence by projectivity of P_i, we may find a morphism $f_i\colon P_i \to E_i$ such that $d_i^E \circ f_i = f_{i-1} \circ d_i^P$.

Now let $f, f'\colon P \to E$ be two morphisms of chain complexes extending g. We construct for each i a morphism $s_i\colon P_i \to E_{i+1}$ such that
$$f_i - f'_i = d_{i+1}^E \circ s_i + s_{i-1} \circ d_i^P$$
by induction on i. We let $s_i = 0$ for $i < -1$. Assume that s_{i-1} is constructed. Then
$$\begin{aligned} d_i^E \circ (f_i - f'_i) &= (f_{i-1} - f'_{i-1}) \circ d_i^P \\ &= d_i^E \circ s_{i-1} \circ d_i^P + s_{i-2} \circ d_{i-1}^P \circ d_i^P \\ &= d_i^E \circ s_{i-1} \circ d_i^P, \end{aligned}$$
so that $(f_i - f'_i) - s_{i-1} \circ d_i^P\colon P_i \to E_i$ has image in $\ker d_i^E$. By exactness of the complex E, the morphism $E_{i+1} \to \ker d_i^E$ is surjective. By projectivity of P_i, we obtain a morphism $s_i\colon P_i \to E_{i+1}$ such that $d_{i+1}^E \circ s_i = (f_i - f'_i) - s_{i-1} \circ d_i^P$, as required. □

Corollary 4.2.8. *Let M be an R-module, and $P \to M, P' \to M$ projective resolutions. Then there exists a morphism of chain complexes $P \to P'$ such that $P_0 \to$*

$P_0' \to M = P_0 \to M$. Such a morphism is unique up to homotopy, and is a homotopy equivalence.

Proof. The identity of M extends to morphisms of chain complexes $P \to P'$ and $g\colon P' \to P$ by the existence part of Proposition 4.2.7. The composite $P \to P' \to P$ and the identity of C are both extensions of the identity of M. They must be homotopic by the unicity part of Proposition 4.2.7. For the same reason, the composite $P' \to P \to P'$ is homotopic to the identity of P'. $\square$

Lemma 4.2.9. *Let C' and C'' be two chain complexes. Assume that*

- *$C_i' = C_i'' = 0$ for $i < -1$*
- *C_i'' is projective for $i \geq 0$.*
- *C' is exact.*

Then any exact sequence of modules

$$0 \to C'_{-1} \to M \to C''_{-1} \to 0$$

is the degree -1 part of an exact sequence of chain complexes

$$0 \to C' \to C \to C'' \to 0.$$

In addition:

(i) If the chain complex C'' is exact, then so is C.

(ii) For each $i \geq 0$, the exact sequence of modules

$$0 \to C_i' \to C_i \to C_i'' \to 0$$

splits (i.e. induces a decomposition $C_i = C_i' \oplus C_i''$).

(iii) If C_i' is projective, then so is C_i.

Proof. Let us first prove (i) (ii) (iii) assume the first part of lemma.

(i): This follows from the homology long exact sequence Proposition 4.1.6.

(ii): This follows from the fact that C_i'' is projective.

(iii): This follows from (ii), since a direct sum of projective modules is projective (e.g. by Lemma 4.2.3).

Let us now prove the first part of the lemma. We let $C_i = C_i' \oplus C_i''$ with the natural morphisms $C_i' \to C_i \to C_i''$. We construct by induction a morphism $d_i^C : C_i \to C_{i-1}$ such that $d_{i-1}^C \circ d_i^C = 0$ making the following diagram commute

$$\begin{tikzcd}
C_i' \arrow[r] \arrow[d] & C_i \arrow[r] \arrow[d] & C_i'' \arrow[d] \\
C_{i-1}' \arrow[r] & C_{i-1} \arrow[r] & C_{i-1}''
\end{tikzcd}$$

and moreover such that the sequence

$$0 \to Z_i' \to Z_i \to Z_i'' \to 0$$

is exact, where $Z_i = \ker d_i^C$, $Z_i' = \ker d_i^{C'}$, $Z_i'' = \ker d_i^{C''}$.

We let $d_{-1}^C = 0$. Assume d_{i-1}^C constructed for some $i \geq 0$. The morphism $d_i^C : C_i \to Z_{i-1} \subset C_{i-1}$ is the sum of the morphism $C_i' \to Z_{i-1}' \to Z_{i-1}$ and a morphism $C_i'' \to Z_{i-1}$ lifting the morphism $C_i'' \to Z_{i-1}''$, which exists since C_i'' is projective and $Z_{i-1} \to Z_{i-1}''$ is surjective.

It only remains to prove that $Z_i \to Z_i''$ is surjective. Any $x_i'' \in Z_i'' \subset C_i''$ lifts to an element $x_i \in C_i$. Let $x_{i-1} = d_i^C(x_i) \in C_{i-1}$. Then the image of x_{i-1} in C_{i-1}'' is $d_i^{C''}(x_i'') = 0$, hence x_{i-1} is the image of some element of $x_{i-1}' \in C_{i-1}'$. In addition, the image of $d_{i-1}^{C'}(x_{i-1}')$ in C_{i-2}'' is $d_{i-1}^C(x_{i-1}) = d_{i-1}^C \circ d_i^C(x_i) = 0$, hence $d_{i-1}^{C'}(x_{i-1}') = 0$ by injectivity of $C_{i-2}' \to C_{i-2}$. Since the complex C' is exact, we may find $x_i' \in C_i'$ such that $d_i^{C'}(x_i') = x_{i-1}'$. Let $y_i \in C_i$ be the image of x_i'. Then $x_i - y_i \in C_i$ maps to x_i'' in C_i'', and satisfies $d_i(x_i - y_i) = 0$, i.e. belongs to Z_i. □

3. The Tor functor

When C is a chain complex, and N a module, we denote by $C \otimes_R N$ the chain complex such that that $(C \otimes_R N)_i = C_i \otimes_R N$ and $d_i^{C\otimes_R N} = d_i^C \otimes \mathrm{id}_N$. A morphism of chain complexes $f: C \to C'$ induces a morphism of chain complexes $f \otimes_R N: C \otimes_R N \to C' \otimes_R N$. If f is homotopic to g, then $f \otimes_R N$ is homotopic to $g \otimes_R N$. Thus a homotopy equivalence $C \to C'$ induces a homotopy equivalence $C \otimes_R N \to C' \otimes_R N$, and in particular a quasi-isomorphism by Corollary 4.1.4.

Definition 4.3.1. Let M, N be two modules and n an integer. Let $C \to M$ be a projective resolution. Then the module $H_n(C \otimes_R N)$ is independent of the choice of C, up to a canonical isomorphism by Corollary 4.2.8 and the discussion above. We denote this module by $\mathrm{Tor}_n(M, N)$, or $\mathrm{Tor}_n^R(M, N)$. A morphism $g: N \to N'$ induces a morphism $\mathrm{Tor}_n(M, g): \mathrm{Tor}_n(M, N) \to \mathrm{Tor}_n(M, N')$. Let now M' be another module, and $C' \to M'$ be a projective resolution. By Proposition 4.2.7 any morphism of modules $f: M \to M'$ extends to a morphism of complexes $C \to C'$. The latter induces a morphism $\mathrm{Tor}_n(f, N): \mathrm{Tor}_n(M, N) \to \mathrm{Tor}_n(M', N)$ which does not depend on any choice by the unicity part of Proposition 4.2.7 and Proposition 4.1.3.

Proposition 4.3.2. *(i)* $\mathrm{Tor}_0(M, N) \simeq M \otimes_R N$.

(ii) $\mathrm{Tor}_n(M, N) = 0$ *for* $n < 0$.

(iii) If N is flat, then $\mathrm{Tor}_n(M, N) = 0$ *for* $n > 0$.

(iv) If M is projective, then $\mathrm{Tor}_n(M, N) = 0$ *for* $n > 0$.

(v) If $f, g: M \to M'$ are two morphisms and $\lambda \in R$, then

$$\mathrm{Tor}_n(f + \lambda g, N) = \mathrm{Tor}_n(f, N) + \lambda \,\mathrm{Tor}_n(g, N).$$

(vi) If $a, b: N \to N'$ are two morphisms and $\mu \in R$, then

$$\mathrm{Tor}_n(M, a + \mu b) = \mathrm{Tor}_n(M, a) + \mu \,\mathrm{Tor}_n(M, b).$$

Proof. If $C \to M$ is a projective resolution of M, then $M = \mathrm{coker}(C_1 \to C_0)$, hence by right-exactness of the tensor product, we have

$$M \otimes_R N = \mathrm{coker}(C_1 \otimes_R N \to C_0 \otimes_R N) = H_0(C \otimes_R N).$$

This proves (i). Since $C_n = 0$ for $n < 0$, we have $C_n \otimes_R N = 0$, and thus $H_n(C \otimes_R N) = 0$, proving (ii). If N is flat, then $C \otimes_R N \to M \otimes_R N$ is a resolution, hence $H_n(C \otimes_R N) = 0$ for $n > 0$. This proves (iii).

Now if M is projective, we may use the trivial projective resolution $C(M) \to M$ (see Definition 4.2.5) to compute $\mathrm{Tor}_n(M, N)$, so that $\mathrm{Tor}_n(M, N) = 0$ for $n > 0$. This proves (iv). The two remaining statements follow easily from the construction of the Tor functor. □

Proposition 4.3.3. *Consider an exact sequence of modules*

$$0 \to M' \to M \to M'' \to 0$$

Let N be a module. Then we have an exact sequence

$$\cdots \to \operatorname{Tor}_{n+1}(M'', N) \to \operatorname{Tor}_n(M', N) \to \operatorname{Tor}_n(M, N) \to \operatorname{Tor}_n(M'', N) \to \cdots$$

Proof. Let $C' \to M'$ and $C'' \to M''$ be projective resolutions. By Lemma 4.2.9, we find a projective resolution $C \to M$ and an exact sequence of chain complexes $0 \to C' \to C \to C'' \to 0$ extending the exact sequence of modules $0 \to M' \to M \to M'' \to 0$. Since each exact sequence $0 \to C'_i \to C_i \to C''_i \to 0$ is split, the sequence of chain complexes $0 \to C' \otimes_R N \to C \otimes_R N \to C'' \otimes_R N \to 0$ is exact. The corresponding long exact sequence (Proposition 4.1.6) is the required sequence. ☐

Proposition 4.3.4. *Consider an exact sequence of modules*

$$0 \to N' \to N \to N'' \to 0$$

Let M be a module. Then we have an exact sequence

$$\cdots \to \operatorname{Tor}_{n+1}(M, N'') \to \operatorname{Tor}_n(M, N') \to \operatorname{Tor}_n(M, N) \to \operatorname{Tor}_n(M, N'') \to \cdots$$

Proof. Let $C \to M$ be a projective resolution. Since each C_i is projective, hence flat by Lemma 4.2.4, we have an exact sequence of complexes

$$0 \to C \otimes_R N' \to C \otimes_R N \to C \otimes_R N'' \to 0.$$

The corresponding long exact sequence (Proposition 4.1.6) is the required sequence. ☐

Proposition 4.3.5. *The modules* $\operatorname{Tor}_n(N, M)$ *and* $\operatorname{Tor}_n(M, N)$ *are isomorphic.*

Proof. We proceed by induction on n, the case $n = 0$ being the symmetry of the tensor product. Let $0 \to K \to P \to N \to 0$ be an exact sequence with P projective (this is possible by Lemma 4.2.1). Since P is both projective and flat (Lemma 4.2.4), so that $\operatorname{Tor}_n(P, M) = \operatorname{Tor}(P, M) = 0$ for $n > 0$ by Proposition 4.3.2.

Applying Proposition 4.3.3 and Proposition 4.3.4, we obtain a commutative diagram with exact rows (recall that $\operatorname{Tor}_1(P, M) = \operatorname{Tor}_1(M, P) = 0$)

$$\begin{tikzcd}
0 \arrow[r] & \operatorname{Tor}_1(M, N) \arrow[r] & M \otimes_R K \arrow[r] \arrow[d] & M \otimes_R P \arrow[d] \\
0 \arrow[r] & \operatorname{Tor}_1(N, M) \arrow[r] & K \otimes_R M \arrow[r] & P \otimes_R M
\end{tikzcd}$$

Since horizontal arrows are isomorphisms, we conclude that $\operatorname{Tor}_1(M, N) \simeq \operatorname{Tor}_1(N, M)$.

Let now $n > 1$. Using Proposition 4.3.3 and the vanishing of $\operatorname{Tor}_n(M, P)$ and $\operatorname{Tor}_{n-1}(M, P)$ we deduce that $\operatorname{Tor}_n(M, N) \simeq \operatorname{Tor}_{n-1}(M, K)$. Using Proposition 4.3.4 and the vanishing of $\operatorname{Tor}_n(P, M)$ and $\operatorname{Tor}_{n-1}(P, M)$ we deduce that $\operatorname{Tor}_n(N, M) \simeq \operatorname{Tor}_{n-1}(K, M)$. By induction $\operatorname{Tor}_{n-1}(M, K) \simeq \operatorname{Tor}_{n-1}(K, M)$, and the result follows. ☐

4. Cochain complexes

Definition 4.4.1. A *cochain complex (of R-modules) C* is a collection of R-modules C^i and morphisms of R-modules $d_C^i \colon C^i \to C^{i+1}$ for $i \in \mathbb{Z}$ satisfying $d_C^{i+1} \circ d_C^i = 0$. The R-module

$$H^i(C) = \ker d_C^i / \operatorname{im} d_C^{i-1}$$

is called the *i-th cohomology* of the cochain complex C. A morphism of cochain complexes $f \colon C \to C'$ is a collection of morphisms $f^i \colon C^i \to C'^i$ such that $f^{i+1} \circ d^i = d^i \circ f^i$. Such a morphism induces a morphism of the cohomology modules $H^i(C) \to H^i(C')$. We say that the morphism $C \to C'$ is a *quasi-isomorphism* if the induced morphism $H^i(C) \to H^i(C')$ is an isomorphism for all i.

Definition 4.4.2. We say that two morphisms of cochain complexes $f, g \colon C \to C'$ are *homotopic* if there is a collection of morphisms $s^i \colon C^i \to C'^{i-1}$ such that

$$f^i - g^i = d_{C'}^{i-1} \circ s^i + s^{i+1} \circ d_C^i.$$

A morphism of cochain complexes $f \colon M \to N$ is a *homotopy equivalence* if there is a morphism of cochain complexes $g \colon N \to M$ such that $f \circ g$ is homotopic to id_N and $g \circ f$ is homotopic to id_M.

Proposition 4.4.3. *Homotopic morphisms induce the same morphism in cohomology.*

Proof. In the notations of the definition, the morphism $d_{C'}^{i-1} \circ s^i$ has image contained in $\operatorname{im} d_{i-1}^{C'}$ and the morphism $s^{i+1} \circ d_C^i$ has kernel contained in $\ker d_C^i$. They induce the zero morphism in cohomology by construction. □

Corollary 4.4.4. *Homotopy equivalent cochain complexes are quasi-isomorphic.*

Definition 4.4.5. A sequence of cochain complexes

$$0 \to C' \to C \to C'' \to 0$$

is called *exact* if the sequence

$$0 \to C'^i \to C^i \to C''^i \to 0$$

is exact for each i.

Proposition 4.4.6. *An exact sequence of cochain complexes*

$$0 \to C' \to C \to C'' \to 0$$

induces an exact sequence of modules

$$\cdots \to H^{i-1}(C'') \to H^i(C') \to H^i(C) \to H^i(C'') \to H^{i+1}(C) \to \cdots$$

5. The Ext functor

When M, N are two R-modules, we denote by $\operatorname{Hom}_R(M, N)$ the R-module of R-module morphisms $M \to N$. When C is a chain complex and N a module, we denote by $\operatorname{Hom}_R(C, N)$ the cochain complex such that $(\operatorname{Hom}_R(C, N))^i = \operatorname{Hom}_R(C_i, N)$ and

$$d^i_{\operatorname{Hom}_R(C,N)} \colon \operatorname{Hom}_R(C_i, N) \to \operatorname{Hom}_R(C_{i+1}, N)$$

is the morphism induced by left-composition with d_{i+1}^C.

Definition 4.5.1. Let M, N be two modules and n an integer. Let $C \to M$ be a projective resolution. Then the module $H^n(\mathrm{Hom}_R(C,N))$ is independent of the choice of C, up to a canonical isomorphism. We denote this module by $\mathrm{Ext}^n(M,N)$, or $\mathrm{Ext}^n_R(M,N)$. A morphism $g\colon N \to N'$ induces a morphism $\mathrm{Ext}^n(M,g)\colon \mathrm{Ext}^n(M,N) \to \mathrm{Ext}^n(M,N')$. A morphism $f\colon M \to M'$ induces a morphism $\mathrm{Ext}^n(f,N)\colon \mathrm{Ext}^n(M',N) \to \mathrm{Ext}^n(M,N)$.

Proposition 4.5.2. *(i)* $\mathrm{Ext}^0(M,N) \simeq \mathrm{Hom}_R(M,N)$.

(ii) $\mathrm{Ext}^n(M,N) = 0$ *for* $n < 0$.

(iii) If M *is projective, then* $\mathrm{Ext}^n(M,N) = 0$ *for* $n > 0$.

(iv) If $f, g\colon M \to M'$ *are two morphisms and* $\lambda \in R$*, then*

$$\mathrm{Ext}^n(f+\lambda g, N) = \mathrm{Ext}^n(f,N) + \lambda\,\mathrm{Ext}^n(g,N).$$

(v) If $a, b\colon N \to N'$ *are two morphisms and* $\mu \in R$*, then*

$$\mathrm{Ext}^n(M, a+\mu b) = \mathrm{Ext}^n(M,a) + \mu\,\mathrm{Ext}^n(M,b).$$

Proof. If $C \to M$ is a (projective) resolution of M, then $M = \mathrm{coker}(C_1 \to C_0)$, hence by left-exactness of the contravariant functor $\mathrm{Hom}_R(-,N)$, we have

$$\mathrm{Hom}_R(M,N) = \ker(\mathrm{Hom}_R(C_0,N) \to \mathrm{Hom}_R(C_1,N)) = H^0(\mathrm{Hom}_R(C,N)).$$

This proves the first statement. Since $C_n = 0$ for $n < 0$, we have $\mathrm{Hom}_R(C_n,N) = 0$, and thus $H^n(\mathrm{Hom}_R(C,N)) = 0$, proving the second statement. Now if M is projective, we may use the trivial projective resolution $C(M) \to M$ (see Definition 4.2.5) to compute $\mathrm{Ext}^n(M,N)$, so that $\mathrm{Ext}^n(M,N) = 0$ for $n > 0$. This proves the third statement. The two remaining statements follow easily from the construction of the Ext functor. $\square$

Proposition 4.5.3. *Consider an exact sequence of modules*

$$0 \to M' \to M \to M'' \to 0$$

Let N *be a module. Then we have an exact sequence*

$$\cdots \to \mathrm{Ext}^{n-1}(M',N) \to \mathrm{Ext}^n(M'',N) \to \mathrm{Ext}^n(M,N) \to \mathrm{Ext}^n(M',N) \to \cdots$$

Proof. Let $C' \to M'$ and $C'' \to M''$ be projective resolutions. By Lemma 4.2.9, we find a projective resolution $C \to M$ and an exact sequence of chain complexes $0 \to C' \to C \to C'' \to 0$ extending the exact sequence of modules $0 \to M' \to M \to M'' \to 0$. Since each exact sequence $0 \to C'_i \to C_i \to C''_i \to 0$ is split, the sequence of cochain complexes $0 \to \mathrm{Hom}_R(C'',N) \to \mathrm{Hom}_R(C,N) \to \mathrm{Hom}_R(C',N) \to 0$ is exact. The corresponding long exact sequence (Proposition 4.4.6) is the required sequence. $\square$

Proposition 4.5.4. *Consider an exact sequence of modules*

$$0 \to N' \to N \to N'' \to 0$$

Let M *be a module. Then we have an exact sequence*

$$\cdots \to \mathrm{Ext}^{n-1}(M,N'') \to \mathrm{Ext}^n(M,N') \to \mathrm{Ext}^n(M,N) \to \mathrm{Ext}^n(M,N'') \to \cdots$$

Proof. Let $C \to M$ be a projective resolution. Since each C_i is projective, we have an exact sequence of cochain complexes

$$0 \to \mathrm{Hom}_R(C,N') \to \mathrm{Hom}_R(C,N) \to \mathrm{Hom}_R(C,N'') \to 0.$$

The corresponding long exact sequence (Proposition 4.4.6) is the required sequence. $\square$

CHAPTER 5

Depth

In this chapter $(A, \mathfrak{m})$ is a noetherian local ring, and M a finitely generated A-module.

1. M-regular sequences

DEFINITION 5.1.1. A finite tuple $(x_1, \cdots, x_n)$ of elements of $\mathfrak{m}$ is called an *M-regular sequence* if for all i the element x_i is a nonzerodivisor in $M/\{x_1, \cdots, x_i\}M$. The integer n is the *length* of the M-regular sequence. The M-regular sequence is called *maximal* if there is no $x_{n+1} \in \mathfrak{m}$ such that $(x_1, \cdots, x_{n+1})$ is an M-regular sequence.

LEMMA 5.1.2. *If $M \neq 0$, then a maximal M-regular sequence exists.*

PROOF. If not, we may find $x_i \in \mathfrak{m}$ for $i \in \mathbb{N}$ such that $(x_1, \cdots, x_n)$ is an M-regular sequence for all n. By Nakayama's Lemma 1.1.6, the A-module $M/\{x_1, \cdots, x_{n-1}\}M$ is nonzero, hence we may find an element $m \in M$ such that $m \notin \{x_1, \cdots, x_{n-1}\}M$. Assume that $x_n \in \{x_1, \cdots, x_{n-1}\}A$. Then $x_n m \in \{x_1, \cdots, x_{n-1}\}M$, hence x_n is a zerodivisor in $M/\{x_1, \cdots, x_{n-1}\}M$, a contradiction. It follows that the sequence of ideals

$$\cdots \subset \{x_1, \cdots, x_n\}A \subset \{x_1, \cdots, x_{n+1}\}A \subset \cdots$$

of A is strictly increasing, which is impossible since A is noetherian. □

DEFINITION 5.1.3. A finite subset S of $\mathfrak{m}$ is called *secant for M* if

$$\dim M/SM = \dim M - s,$$

where s is the cardinal of S. We will say that a sequence $(s_1, \cdots, s_n)$ is secant for M if the set $\{s_1, \cdots, s_n\}$ is secant for M.

PROPOSITION 5.1.4. *Any M-regular sequence is secant.*

PROOF. By induction it is enough to consider the case of a sequence of length 1, in which case the statement is Corollary 2.3.5. □

2. Depth

DEFINITION 5.2.1. The depth of M is defined as

$$\operatorname{depth} M = \operatorname{depth}_A M = \inf\{i \in \mathbb{N} \mid \operatorname{Ext}^i(k, M) \neq 0\}.$$

This is an element of $\mathbb{N} \cup \{\infty\}$. When $M = 0$, we have $\operatorname{depth} M = \infty$.

PROPOSITION 5.2.2. *Let $x \in \mathfrak{m}$ be a nonzerodivisor in M. Then*

$$\operatorname{depth} M/xM = \operatorname{depth} M - 1.$$

Proof. From the exact sequence $0 \to M \xrightarrow{x} M \to M/xM \to 0$ we deduce using Proposition 4.5.4 an exact sequence

$$\cdots \to \mathrm{Ext}^{i-1}(k, M/xM) \to \mathrm{Ext}^i(k, M) \xrightarrow{x} \mathrm{Ext}^i(k, M) \to \cdots$$

In view of Proposition 4.5.2 (iv), the A-module $\mathrm{Ext}^i(k, M)$ is annihilated by $\mathrm{Ann}(k) = \mathfrak{m}$, and in particular multiplication by x is zero in this module. We obtain for each i an exact sequence

$$0 \to \mathrm{Ext}^{i-1}(k, M) \to \mathrm{Ext}^{i-1}(k, M/xM) \to \mathrm{Ext}^i(k, M) \to 0.$$

Therefore $\mathrm{Ext}^{i-1}(k, M/xM) \neq 0$ if and only if $\mathrm{Ext}^{i-1}(k, M) \neq 0$ or $\mathrm{Ext}^i(k, M) \neq 0$. The result follows. □

Corollary 5.2.3. *Let $(x_1, \cdots, x_n)$ be an M-regular sequence. Then*

$$\operatorname{depth}(M/\{x_1, \cdots, x_n\}M) = \operatorname{depth} M - n,$$

and in particular $\operatorname{depth} M \geq n$*.*

Lemma 5.2.4. *The following conditions are equivalent:*

(i) $\operatorname{depth} M = 0$.

(ii) Every element of $\mathfrak{m}$ is a zerodivisor in M.

(iii) $\mathfrak{m} \in \mathrm{Ass}(M)$.

Proof. A nonzero A-linear morphism $k \to M$ is necessarily injective, therefore $\mathrm{Ext}^0(k, M) = \mathrm{Hom}_A(k, M)$ is nonzero if and only if there is an injective A-modules morphism $k \to M$. This proves that (i) $\Leftrightarrow$ (iii).

By Lemma 1.2.9, the set of nonzerodivisors in M is the union of the associated primes of M. Since $\mathrm{Ass}(M)$ is finite (Corollary 1.3.6), we see using prime avoidance (Proposition 2.4.5) that (ii) $\Leftrightarrow$ (iii). □

Lemma 5.2.5. *Let $(x_1, \cdots, x_n)$ be an M-regular sequence. The following conditions are equivalent:*

(i) $\operatorname{depth} M = n$.

(ii) The M-regular sequence $(x_1, \cdots, x_n)$ is maximal.

(iii) $\mathfrak{m} \in \mathrm{Ass}(M/\{x_1, \cdots, x_n\}M)$.

Proof. In view of Corollary 5.2.3, we see that (i) is equivalent to the condition $\operatorname{depth}(M/\{x_1, \cdots, x_n\}M) = 0$. On the other hand (ii) means that every element of $\mathfrak{m}$ is a zerodivisor in $M/\{x_1, \cdots, x_n\}M$. So the lemma is just a reformulation of Lemma 5.2.4. □

Proposition 5.2.6. *Assume that $M \neq 0$. Then* $\operatorname{depth} M$ *is finite, and coincides with the length of any maximal M-regular sequence.*

Proof. If $(x_1, \cdots, x_n)$ is a maximal M-regular sequence, then $\operatorname{depth} M = n$ by Lemma 5.2.5. Such a sequence always exists by Lemma 5.1.2. □

Combining Proposition 5.2.6 and Proposition 5.1.4, we obtain:

Corollary 5.2.7. *If $M \neq 0$, then* $\operatorname{depth} M \leq \dim M$*.*

We can be more precise:

Proposition 5.2.8. *We have* $\operatorname{depth} M \leq \dim A/\mathfrak{p}$ *for every* $\mathfrak{p} \in \mathrm{Ass}(M)$*.*

PROOF. We may assume that $M \neq 0$ and proceed by induction on depth M (which is finite by Proposition 5.2.6), the case $\operatorname{depth} M = 0$ being clear. If $\operatorname{depth} M > 0$, then by Lemma 5.2.4 we can find $x \in \mathfrak{m}$, which a nonzerodivisor in M. Let $\mathfrak{p} \in \operatorname{Ass}(M)$, and consider the exact sequence of A-modules

$$0 \to \operatorname{Hom}_A(A/\mathfrak{p}, M) \xrightarrow{x} \operatorname{Hom}_A(A/\mathfrak{p}, M) \to \operatorname{Hom}_A(A/\mathfrak{p}, M/xM).$$

Since $\mathfrak{p} \in \operatorname{Ass}(M)$, the A-module $\operatorname{Hom}_A(A/\mathfrak{p}, M)$ is nonzero. It is also finitely generated, being a submodule of $\operatorname{Hom}_A(A, M) = M$. By Nakayama's Lemma 1.1.6, it follows that $\operatorname{Hom}_A(A/\mathfrak{p}, M)/x \operatorname{Hom}_A(A/\mathfrak{p}, M) \neq 0$, hence by the above exact sequence $\operatorname{Hom}_A(A/\mathfrak{p}, M/xM) \neq 0$. Thus the A-module M/xM contains a nonzero quotient Q of $A/\mathfrak{p}$. Let us choose an element $\mathfrak{q} \in \operatorname{Ass}(Q) \subset \operatorname{Ass}(M/xM)$ (Corollary 1.2.3). Then $\mathfrak{q} \in \operatorname{Supp}(Q) \subset \operatorname{Supp}(A/\mathfrak{p})$ (because Q is a quotient of $A/\mathfrak{p}$), hence $\mathfrak{p} \subset \mathfrak{q}$. Since $x \in \operatorname{Ann}(M/xM) \subset \operatorname{Ann}(Q) \subset \mathfrak{q}$ and $x \notin \mathfrak{p}$ (a nonzerodivisor is in no associated prime), we have $\mathfrak{p} \subsetneq \mathfrak{q}$. Thus

$$\dim A/\mathfrak{p} \geq \dim A/\mathfrak{q} + 1.$$

By Corollary 5.2.3 we have

$$\operatorname{depth} M/xM = \operatorname{depth} M - 1,$$

hence applying the induction hypothesis to the module M/xM, we know that

$$\dim A/\mathfrak{q} \geq \operatorname{depth} M/xM.$$

This concludes the proof. □

Proposition 5.2.8 may be viewed as a special case of:

PROPOSITION 5.2.9. *For any $\mathfrak{p} \in \operatorname{Spec}(R)$, we have*

$$\operatorname{depth}_A M \leq \operatorname{depth}_{A_\mathfrak{p}} M_\mathfrak{p} + \dim A/\mathfrak{p}.$$

PROOF. We may assume that $M \neq 0$, and proceed by induction on depth M (which is finite by Proposition 5.2.6), the case $\operatorname{depth} M = 0$ being clear. If $\mathfrak{p} \subset \mathfrak{q}$ for some $\mathfrak{q} \in \operatorname{Ass}(M)$, then by Proposition 5.2.8 we have

$$\operatorname{depth}_A M \leq \dim A/\mathfrak{q} \leq \dim A/\mathfrak{p} \leq \operatorname{depth}_{A_\mathfrak{p}} M_\mathfrak{p} + \dim A/\mathfrak{p}.$$

Thus we may assume that $\mathfrak{p}$ is contained in no associated prime of M. Then by prime avoidance (Proposition 2.4.5), finiteness of $\operatorname{Ass}(M)$ (Corollary 1.3.6) and Lemma 1.2.9, we may find an element $x \in \mathfrak{p}$ which is a nonzerodivisor in M. The image of x in $A_\mathfrak{p}$ is a nonzerodivisor in $M_\mathfrak{p}$ by flatness of $A \to A_\mathfrak{p}$ (since multiplication with x induces an injective endomorphism of M, multiplication with $1 \otimes x \in A_\mathfrak{p} \otimes_A A = A_\mathfrak{p}$ induces an injective endomorphism of $A_\mathfrak{p} \otimes_A M = M_\mathfrak{p}$). Therefore by Proposition 5.2.2

$$\operatorname{depth}_A M/xM = \operatorname{depth}_A M - 1 \quad \text{and} \quad \operatorname{depth}_{A_\mathfrak{p}} (M/xM)_\mathfrak{p} = \operatorname{depth}_{A_\mathfrak{p}} M_\mathfrak{p} - 1,$$

and we may conclude by applying the induction hypothesis to M/xM. □

The following observation will be used later:

LEMMA 5.2.10. *Let M, M' be two finitely generated A-modules. Then*

$$\operatorname{depth}(M \oplus M') = \min(\operatorname{depth} M, \operatorname{depth} M').$$

In particular we have $\operatorname{depth} F = \operatorname{depth} A$ *for any free finitely generated nonzero A-module F.*

PROOF. Let k be the residue field. Functoriality of Ext^n implies that $\mathrm{Ext}^n(k, M \oplus M') = \mathrm{Ext}^n(k, M) \oplus \mathrm{Ext}^n(k, M')$ (exercise), and the statement follows. □

3. Depth and base change

PROPOSITION 5.3.1. *Let $\phi\colon (A, \mathfrak{m}) \to (B, \mathfrak{n})$ be a local morphism. Let M be a B-module, finitely generated as an A-module. Then*

$$\operatorname{depth}_A M = \operatorname{depth}_B M.$$

PROOF. The statement being true if $M = 0$, let us assume that $M \neq 0$. Let $(a_1, \cdots, a_n)$ be a maximal M-regular sequence, where M is viewed as an A-module, so that $\operatorname{depth}_A M = n$ by Proposition 5.2.6. Then the tuple $(\phi(a_1), \cdots, \phi(a_n))$ is an M-regular sequence, where M is viewed as a B-module. By Corollary 5.2.3, we may replace M with $M/\{a_1, \cdots, a_n\}M$, and thus assume that $\operatorname{depth}_A M = 0$. By Lemma 5.2.4, there is an element $m \in M$ such that $\mathrm{Ann}_A(m) = \mathfrak{m}$. Let N be the B-submodule of M generated by m. This is a nonzero, finitely generated A-module, which is annihilated by $\mathfrak{m}$. Hence N has finite length as an A-module (Lemma 3.1.1), and a fortiori as a B-module. Thus $\mathfrak{n} \in \mathrm{Ass}_B(N) \subset \mathrm{Ass}_B(M)$, showing that $\operatorname{depth}_B M = 0$. □

We will need the following technical lemma:

LEMMA 5.3.2. *Consider an exact sequence of finitely-generated A-modules*

$$0 \to M' \to M \to M'' \to 0.$$

If $\operatorname{depth} M'' \geq \operatorname{depth} M'$, *we have* $\operatorname{depth} M = \operatorname{depth} M'$.

PROOF (EXERCISE). Let $n = \operatorname{depth} M$ and $n' = \operatorname{depth} M'$. We have an exact sequence (Proposition 4.5.4)

$$\mathrm{Ext}^{n'-1}(k, M'') \to \mathrm{Ext}^{n'}(k, M') \to \mathrm{Ext}^{n'}(k, M).$$

By assumption, the group on the left is zero, and the group in the middle is nonzero. Thus the group on the right must be nonzero, showing that $n \leq n'$.

We have an exact sequence (Proposition 4.5.4)

$$\mathrm{Ext}^{n}(k, M') \to \mathrm{Ext}^{n}(k, M) \to \mathrm{Ext}^{n}(k, M'').$$

If $n < n'$, then the group on the left is zero. So is the group on the right by our assumption. It follows that the group in the middle vanishes, a contradiction. □

PROPOSITION 5.3.3. *Let $A \to B$ be a flat local morphism and M a finitely generated A-module. Let $\mathfrak{m}$ be the maximal ideal of A, and k its residue field. Then*

$$\operatorname{depth}_B B \otimes_A M = \operatorname{depth}_A M + \operatorname{depth}_B B \otimes_A k.$$

PROOF. We may assume that $M \neq 0$, and proceed by induction on $\dim_A M$. Assume that $\dim_A M = 0$. Thus $\operatorname{depth}_A M = 0$, and we need to prove that $\operatorname{depth}_B B \otimes_A M = \operatorname{depth}_B B \otimes_A k$. We argue by induction on $\operatorname{length}_A M$ (which is finite by Lemma 2.2.5). If $\operatorname{length}_A M = 1$, then the A-module M is isomorphic to k, and the statement is true. If $\operatorname{length}_A M > 1$, then we can find an exact sequence of A-modules

$$0 \to N \to M \to k \to 0$$

with $\operatorname{length}_A N < \operatorname{length}_A M$. Since the A-module B is flat, this gives an exact sequence of B-modules

$$0 \to B \otimes_A N \to B \otimes_A M \to B \otimes_A k \to 0.$$

In view of Lemma 5.3.2, the statement follows by using the induction hypothesis for the module N.

Assume now that $\dim_A M > 0$. Let us first assume additionally that $\mathfrak{m} \notin \operatorname{Ass}_A(M)$. Then we may find an element $x \in \mathfrak{m}$ which is a nonzerodivisor in M (by Lemma 5.2.4). Its image in B is a nonzerodivisor in $B \otimes_A M$ by flatness of $A \to B$. Thus by Proposition 5.2.2 we have $\operatorname{depth}_A M/xM = \operatorname{depth}_A M - 1$ and $\operatorname{depth}_B B \otimes_A (M/xM) = \operatorname{depth}_B B \otimes_A M - 1$. We may then conclude using the induction hypothesis for the A-module M/xM, whose dimension is $< \dim_A M$ by Corollary 2.3.5.

Thus we may assume that $\mathfrak{m} \in \operatorname{Ass}_A(M)$. Thus $\operatorname{depth}_A M = 0$, and we need to prove that $\operatorname{depth}_B B \otimes_A M = \operatorname{depth}_B B \otimes_A k$. By Proposition 1.2.7, we can find an exact sequence of A-modules

$$0 \to M' \to M \to M'' \to 0$$

such that $\operatorname{Ass}_A(M') = \{\mathfrak{m}\}$, and $\operatorname{Ass}_A(M'') = \operatorname{Ass}_A(M) - \{\mathfrak{m}\}$. Then $\dim_A M'' = \dim_A M$ and $\mathfrak{m} \notin \operatorname{Ass}_A(M'')$; we have just proved that

$$\operatorname{depth}_B B \otimes_A M'' = \operatorname{depth}_A M'' + \operatorname{depth}_B B \otimes_A k.$$

On the other hand, since $\dim_A M' = 0$, we have also proved that

$$\operatorname{depth}_B B \otimes_A M' = \operatorname{depth}_B B \otimes_A k.$$

By flatness of $A \to B$, we have an exact sequence of B-modules

$$0 \to B \otimes_A M' \to B \otimes_A M \to B \otimes_A M'' \to 0,$$

and the statement follows from Lemma 5.3.2. □

CHAPTER 6

Cohen-Macaulay modules

1. Cohen-Macaulay modules

In this section $(A, \mathfrak{m})$ will be a local ring, and M a finitely generated A-module.

Definition 6.1.1. We say that M is *Cohen-Macaulay* if $\operatorname{depth} M \geq \dim M$. By Corollary 5.2.7, the module M is Cohen-Macaulay if and only if $M = 0$ or $\operatorname{depth} M = \dim M$.

Example 6.1.2. Any module of dimension zero is Cohen-Macaulay.

Proposition 6.1.3. *Assume that $M \neq 0$. The following conditions are equivalent:*
(i) *M is Cohen-Macaulay,*
(ii) *There is an M-regular sequence which is also a system of parameters for M.*
(iii) *Every maximal M-regular sequence is a system of parameters for M.*

Proof. (iii) $\Rightarrow$ (ii): Lemma 5.1.2.
(ii) $\Rightarrow$ (i): Assume that there is an M-regular sequence of length n which is a system of parameters. Then $\dim M = n$ by Proposition 3.1.2, and $n \leq \operatorname{depth} M$ by Lemma 5.2.5. It follows that $\dim M \geq \operatorname{depth} M$.
(i) $\Rightarrow$ (iii): Let $(x_1, \cdots, x_n)$ be a maximal M-regular sequence. Then $n = \operatorname{depth} M$ by Proposition 5.2.6, hence $n = \dim M$ by (i). It follows from Proposition 5.1.4 that $\dim M/\{x_1, \cdots, x_n\}M = 0$, proving that the set $\{x_1, \cdots, x_n\}$ is a system of parameters for M. ☐

Proposition 6.1.4. *Assume that M is Cohen-Macaulay. Then $\dim A/\mathfrak{p} = \dim M$ for every $\mathfrak{p} \in \operatorname{Ass}(M)$.*

Proof. Let $\mathfrak{p} \in \operatorname{Ass}(M)$. We have by Proposition 5.2.8 and Proposition 2.1.4

$$\operatorname{depth} M \leq \dim A/\mathfrak{p} \leq \dim M.$$

If M is Cohen-Macaulay, these inequalities must be equalities. ☐

Corollary 6.1.5. *Assume that M is Cohen-Macaulay. Then M is equidimensional ($\dim A/\mathfrak{p} = \dim M$ for every minimal prime $\mathfrak{p}$ of $\operatorname{Supp}(M)$), and has no embedded prime (every element of $\operatorname{Ass}(M)$ is minimal in $\operatorname{Supp}(M)$).*

Lemma 6.1.6. *Let $(x_1, \cdots, x_n)$ be an M-regular sequence. Then $M/\{x_1, \cdots, x_n\}M$ is Cohen-Macaulay if and only if M is so.*

Proof. We have by Corollary 5.2.3

$$\operatorname{depth} M/\{x_1, \cdots, x_n\}M = \operatorname{depth} M - n,$$

and by Proposition 5.1.4

$$\dim M/\{x_1, \cdots, x_n\}M = \dim M - n.$$

☐

Proposition 6.1.7. *The following conditions are equivalent:*

(i) M is Cohen-Macaulay.
(ii) A sequence is secant for M if and only if it is M-regular.

Proof. (i) $\Rightarrow$ (ii): We proceed by induction on the length of the sequence, the case of the empty sequence being clear. Let $(x_1, \cdots, x_n)$ be a secant sequence. Then $\dim M/x_1M = \dim M - 1$, hence x_1 belongs to no $\mathfrak{p} \in \operatorname{Supp}(M)$ such that $\dim A/\mathfrak{p} = \dim M$ by Proposition 2.3.4, hence to no associated prime of M by Proposition 6.1.4. Thus x_1 is a nonzerodivisor in M (Lemma 1.2.9), and M/x_1M is Cohen-Macaulay by Lemma 6.1.6. By induction, the sequence $(x_2, \cdots, x_n)$ is M/x_1M-regular, hence the sequence $(x_1, \cdots, x_n)$ is M-regular.

(ii) $\Rightarrow$ (i): Let $n = \dim M$ and $\{x_1, \cdots, x_n\}$ a system of parameters for M. Then the sequence $(x_1, \cdots, x_n)$ is M-regular by (ii), hence $n \leq \operatorname{depth} M$ by Corollary 5.2.3, proving that M is Cohen-Macaulay. □

Theorem 6.1.8 (Unmixedness theorem). *The following conditions are equivalent:*

(i) M is Cohen-Macaulay.
(ii) For every secant set S for M, the A-module M/SM has no embedded prime.

Proof. Assume that M is Cohen-Macaulay, and let $S = \{s_1, \cdots, s_n\}$ be a secant set. Then $(s_1, \cdots, s_n)$ is an M-regular sequence by Proposition 6.1.7, hence M/SM is Cohen-Macaulay by Lemma 6.1.6, and has no embedded prime by Corollary 6.1.5.

Conversely assume that for every secant subset S of A, the A-module M/SM has no embedded prime. We proceed by induction on $\dim M$, the cases $M = 0$ and $\dim M = 0$ being trivial. We thus assume that $\dim M > 0$. Taking $S = \varnothing$, we see that M has no embedded prime. The prime $\mathfrak{m}$ is not a minimal element of $\operatorname{Supp}(M)$ (because $\dim M > 0$), and therefore $\mathfrak{m} \notin \operatorname{Ass}(M)$. Thus by Lemma 5.2.4, we can find an element $x \in \mathfrak{m}$ which is a nonzerodivisor in M. Then $\dim M/xM < \dim M$ by Corollary 2.3.5. If S is a secant subset for M/xM, then $\{x\} \cup S$ is a secant subset for M; it follows that the A-module M/xM satisfies the condition of the theorem. By induction it is Cohen-Macaulay, hence M is Cohen-Macaulay by Lemma 6.1.6. □

Lemma 6.1.9. *Let $A \to B$ be a local morphism. Let M be a B-module, finitely generated as an A-module. Then M is Cohen-Macaulay as an A-module if and only if it is so as a B-module.*

Proof. This follows from Proposition 5.3.1 and Proposition 2.1.3. □

Proposition 6.1.10. *Let $A \to B$ be a local morphism, and M a nonzero finitely generated A-module. Let k be the residue field of A. Assume that B is flat over A.*

Then the B-module $B \otimes_A M$ is Cohen-Macaulay if and only if the A-module M and the B-module $B \otimes_A k$ are Cohen-Macaulay.

Proof. This follows from Proposition 2.4.6, Proposition 5.3.3 and Corollary 5.2.7. □

2. Cohen-Macaulay rings

Lemma 6.2.1. *Let R be a ring, and M an R-module. For any $\mathfrak{p} \in \operatorname{Spec}(R)$ we have*

$$\dim_R M \geq \dim_{R_\mathfrak{p}} M_\mathfrak{p} + \dim R/\mathfrak{p}.$$

Proof. We may assume that $\mathfrak{p} \in \operatorname{Supp}(M)$. A chain of primes of $R/\mathfrak{p}$ corresponds to a chain of primes of R containing in $\mathfrak{p}$, and thus in $\operatorname{Supp}(M)$. A chain of primes in $\operatorname{Supp}_{R_\mathfrak{p}}(M_\mathfrak{p})$ corresponds to a chain of primes in $\operatorname{Supp}(M)$ contained in $\mathfrak{p}$. The concatenation of the two chains gives a chain in $\operatorname{Supp}(M)$, whose length is the sum of the two lengths. $\square$

Proposition 6.2.2. *Let A be a local ring and M a Cohen-Macaulay A-module. Then:*

(i) For every $\mathfrak{p} \in \operatorname{Spec}(A)$, the $A_\mathfrak{p}$-module $M_\mathfrak{p}$ is Cohen-Macaulay.
(ii) For every $\mathfrak{p} \in \operatorname{Supp}(M)$, we have

$$\dim_A M = \dim_{A_\mathfrak{p}} M_\mathfrak{p} + \dim A/\mathfrak{p}.$$

Proof. If $\mathfrak{p} \notin \operatorname{Supp}(M)$, then $M_\mathfrak{p} = 0$ is a Cohen-Macaulay $A_\mathfrak{p}$-module. Assume that $\mathfrak{p} \in \operatorname{Supp}(M)$. By Proposition 5.2.9 and Lemma 6.2.1, we have

$$\operatorname{depth}_{A_\mathfrak{p}} M_\mathfrak{p} + \dim A/\mathfrak{p} \geq \operatorname{depth}_A M = \dim_A M \geq \dim_{A_\mathfrak{p}} M_\mathfrak{p} + \dim A/\mathfrak{p}.$$

Since $\operatorname{depth}_{A_\mathfrak{p}} M_\mathfrak{p} \leq \dim_{A_\mathfrak{p}} M_\mathfrak{p}$ by Corollary 5.2.7, these inequalities must be equalities, whence the statements. $\square$

Definition 6.2.3. A ring R is called *Cohen-Macaulay* if for every $\mathfrak{p} \in \operatorname{Spec}(R)$ the $R_\mathfrak{p}$-module $R_\mathfrak{p}$ is Cohen-Macaulay.

From Proposition 6.2.2 (i) we deduce:

Corollary 6.2.4. *A ring R is Cohen-Macaulay if and only if the $R_\mathfrak{m}$-module $R_\mathfrak{m}$ is Cohen-Macaulay for every maximal ideal $\mathfrak{m}$ of R.*

Proposition 6.2.5. *A regular local ring is Cohen-Macaulay.*

Proof. Let A be a regular local ring with maximal ideal $\mathfrak{m}$. We proceed by induction on $\dim A$. Any ring of dimension zero is Cohen-Macaulay. If $\dim A > 0$, then we can find $x \in \mathfrak{m} - \mathfrak{m}^2$ by Corollary 3.1.5 (or directly by Nakayama's Lemma 1.1.6). Then A/xA is a regular local ring of dimension $< \dim A$ by Lemma 3.2.4, so is a Cohen-Macaulay ring by induction. Therefore A/xA is Cohen-Macaulay as an A/xA-module, hence as an A-module by Lemma 6.1.9. Since A is a domain by Proposition 3.2.6, the nonzero element x is a nonzerodivisor in A. By Lemma 6.1.6, it follows that A is Cohen-Macaulay as an A-module, hence is a Cohen-Macaulay ring by Corollary 6.2.4. $\square$

Proposition 6.2.6. *Let $\rho\colon R \to S$ be a flat ring morphism. Assume that the ring R is Cohen-Macaulay and that for every prime $\mathfrak{p}$ of R, the ring $S \otimes_R \kappa(\mathfrak{p})$ is Cohen-Macaulay. Then the ring S is Cohen-Macaulay.*

Proof. Let $\mathfrak{q} \in \operatorname{Spec}(S)$, and $\mathfrak{p} = \rho^{-1}\mathfrak{q}$. By assumption $(S \otimes_R \kappa(\mathfrak{p}))_\mathfrak{q} = S_\mathfrak{q} \otimes_{R_\mathfrak{p}} \kappa(\mathfrak{p})$ is Cohen-Macaulay as a module over itself, and therefore as an $S_\mathfrak{q}$-module by Lemma 6.1.9. Thus the conditions of Proposition 6.1.10 are satisfied with $A = M = R_\mathfrak{p}$ and $B = S_\mathfrak{q}$, hence $S_\mathfrak{q}$ is Cohen-Macaulay as a module over itself. $\square$

Proposition 6.2.7. *If the ring R is Cohen-Macaulay, then so is $R[t_1, \cdots, t_n]$.*

Proof. By induction it suffices to consider the case $n = 1$. By Proposition 6.2.6, we may assume that R is a field. Let A be the localisation of the ring $R[t_1]$ at a maximal ideal. Then A is an integral domain of dimension one. The only associated prime of A is the zero ideal, which differs from its maximal ideal. Hence $\operatorname{depth} A \geq 1 = \dim A$ by

Lemma 5.2.4, and the ring A is Cohen-Macaulay. It follows from Corollary 6.2.4 that the ring $R[t_1]$ is Cohen-Macaulay. $\square$

3. Catenary rings

Definition 6.3.1. We say that a chain of primes $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ is *saturated* if there is no prime $\mathfrak{q}$ and integer i such that $\mathfrak{p}_{i-1} \subsetneq \mathfrak{q} \subsetneq \mathfrak{p}_i$.

We say that a ring R is *catenary* if for every pair of primes $\mathfrak{p} \subset \mathfrak{q}$ of R, all saturated chains joining $\mathfrak{p}$ to $\mathfrak{q}$ have the same length.

Lemma 6.3.2. *A quotient, or a localisation, of a catenary ring is catenary.*

Proof. This follows from the description of the primes of a quotient or a localisation. $\square$

Lemma 6.3.3. *If for every pair of primes $\mathfrak{p} \subset \mathfrak{q}$ of a ring R we have*

$$\dim R_{\mathfrak{q}} = \dim R_{\mathfrak{p}} + \dim(R_{\mathfrak{q}}/\mathfrak{p}R_{\mathfrak{q}}),$$

then R is catenary.

Proof. Let $\mathfrak{p} \subset \mathfrak{q}$ be a pair of primes of R. Let $\mathfrak{p}_0 \subsetneq \cdots \subsetneq \mathfrak{p}_n$ a saturated chain of primes of R, with $\mathfrak{p}_0 = \mathfrak{p}$ and $\mathfrak{p}_n = \mathfrak{q}$. In order to prove the proposition, it will suffice to prove that $n = \dim(R_{\mathfrak{q}}/\mathfrak{p}R_{\mathfrak{q}})$. For each $i = 1, \cdots, n$ we have $\dim(R_{\mathfrak{p}_i}/\mathfrak{p}_{i-1}R_{\mathfrak{p}_i}) = 1$. Using the condition of the lemma for the pair $\mathfrak{p}_{i-1} \subset \mathfrak{p}_i$, we obtain

$$\dim R_{\mathfrak{p}_i} = \dim R_{\mathfrak{p}_{i-1}} + 1.$$

This gives by induction

$$\dim R_{\mathfrak{q}} = \dim R_{\mathfrak{p}} + n.$$

Now we use the condition for the pair $\mathfrak{p} \subset \mathfrak{q}$, and get

$$\dim R_{\mathfrak{p}} = \dim R_{\mathfrak{q}} + \dim(R_{\mathfrak{q}}/\mathfrak{p}R_{\mathfrak{q}}).$$

Therefore $\dim(R_{\mathfrak{q}}/\mathfrak{p}R_{\mathfrak{q}}) = n$. $\square$

Proposition 6.3.4. *A Cohen-Macaulay ring is catenary.*

Proof. Let $\mathfrak{p} \subset \mathfrak{q}$ be two primes of a Cohen-Macaulay ring R. The ring $R_{\mathfrak{q}}$ is Cohen-Macaulay by assumption. Applying Proposition 6.2.2 (ii) with $A = M = R_{\mathfrak{q}}$, for the prime $\mathfrak{p}R_{\mathfrak{q}} \in \operatorname{Supp}(R_{\mathfrak{q}})$, we obtain precisely the condition appearing in Lemma 6.3.3. $\square$

Proposition 6.3.5. *Any finitely generated algebra over a Cohen-Macaulay ring is catenary.*

Proof. Let S a be finitely generated algebra over a Cohen-Macaulay ring R. Then S is a quotient of the ring $R[t_1, \cdots, t_n]$ for some n. The latter ring is Cohen-Macaulay by Proposition 6.2.7, hence catenary by Proposition 6.3.4. It follows that S is catenary by Lemma 6.3.2. $\square$

Example 6.3.6. Any finitely generated k-algebra (k a field), or any finitely generated $\mathbb{Z}$-algebra, is catenary.

CHAPTER 7

Normal rings

In this chapters section R is a (noetherian commutative unital) ring.

1. Reduced rings

LEMMA 7.1.1. *Let A be a reduced local ring such that* $\operatorname{depth} A = 0$. *Then A is a field.*

PROOF. The maximal ideal $\mathfrak{m}$ is an associated prime of A (Lemma 5.2.4), hence $\mathfrak{m} = \operatorname{Ann}(u)$ for some $u \in A - 0$. If A is not a field, then $\mathfrak{m} \neq 0$, hence u is a zerodivisor in A. In particular u is not invertible, and so belongs to $\mathfrak{m}$. But then $u^2 = 0$. □

LEMMA 7.1.2. *Let N be an R-submodule of M. If $N_{\mathfrak{p}} = 0$ for every $\mathfrak{p} \in \operatorname{Ass}(M)$, then $N = 0$.*

PROOF. Let $\mathfrak{p} \in \operatorname{Ass}(N)$. Then $\mathfrak{p} \in \operatorname{Ass}(M)$ by Proposition 1.2.5, hence by assumption $N_{\mathfrak{p}} = 0$, so that $\mathfrak{p} \notin \operatorname{Supp}(N)$, a contradiction with Corollary 1.3.2. Hence $\operatorname{Ass}(N) = \varnothing$, and $N = 0$ by Corollary 1.2.3. □

PROPOSITION 7.1.3. *The following conditions are equivalent:*

(i) The ring R is reduced.
(ii) For every $\mathfrak{p} \in \operatorname{Ass}(R)$, the ring $R_{\mathfrak{p}}$ is a field.
(iii) For every prime $\mathfrak{p}$, the ring $R_{\mathfrak{p}}$ is reduced or has depth ≥ 1.

PROOF. (i) $\Rightarrow$ (ii): We apply Lemma 7.1.1.
(ii) $\Rightarrow$ (iii): A field is reduced.
(iii) $\Rightarrow$ (i): The set N of nilpotent elements of R is an ideal of R. We apply Lemma 7.1.2 to the submodule $N \subset M = R$. □

PROPOSITION 7.1.4. *A reduced ring has no embedded prime.*

PROOF. Let R be a reduced ring. If $\mathfrak{p} \subsetneq \mathfrak{q}$ are elements of $\operatorname{Ass}(R)$, then $\dim R_{\mathfrak{q}} > 0$ and $R_{\mathfrak{q}}$ is a field by Lemma 7.1.1, a contradiction. □

EXAMPLE 7.1.5. Let R be a reduced ring of dimension ≤ 1. Then the ring R is Cohen-Macaulay. To see this, we may assume that R is local. If $\operatorname{depth} R = 0$, then $\dim R = 0$ by Lemma 7.1.1. If $\operatorname{depth} R > 0$, then $\operatorname{depth} R \geq 1 = \dim R$.

2. Locally integral rings

LEMMA 7.2.1. *Let R be a reduced ring with exactly one minimal prime $\mathfrak{p}$. Then R is an integral domain.*

PROOF. We have $\operatorname{Ass}(R) = \{\mathfrak{p}\}$ by Proposition 7.1.4, hence $R - \mathfrak{p}$ consists of nonzerodivisors (Lemma 1.2.9), and therefore the localisation morphism $R \to R_{\mathfrak{p}}$ is injective. Since $R_{\mathfrak{p}}$ is a field by Lemma 7.1.1, its subring R is an integral domain. □

Remark 7.2.2. Let M be a finitely generated R-module. We say that M is *reduced* if for every $\mathfrak{p} \in \mathrm{Ass}(M)$ the $R_\mathfrak{p}$-module $M_\mathfrak{p}$ is simple (i.e. $\mathrm{length}_{R_\mathfrak{p}} M_\mathfrak{p} = 1$). We say that M is *integral* if it is reduced and has exactly one associated (or equivalently, minimal) prime.

Then a ring is reduced, resp. an integral domain, if and only if it is reduced, resp. integral, as a module over itself.

Lemma 7.2.3. *Let $f\colon M \to N$ be a morphism of finitely generated R-modules.*

(i) If $f_\mathfrak{p}\colon M_\mathfrak{p} \to N_\mathfrak{p}$ is injective for every $\mathfrak{p}$ such that $\mathrm{depth}_{R_\mathfrak{p}} M_\mathfrak{p} = 0$, *then f is injective.*

(ii) If $f_\mathfrak{p}\colon M_\mathfrak{p} \to N_\mathfrak{p}$ is bijective for every $\mathfrak{p}$ such that $\mathrm{depth}_{R_\mathfrak{p}} N_\mathfrak{p} = 0$ *or* $\mathrm{depth}_{R_\mathfrak{p}} M_\mathfrak{p} \leq 1$, *then f is bijective.*

Proof. (i) : Apply Lemma 7.1.2 to the submodule $\ker f \subset M$.

(ii) : We know by (i) that f is injective. Let $Q = \mathrm{coker}\, f$, and $\mathfrak{p} \in \mathrm{Ass}(Q)$. Then we have an exact sequence of $R_\mathfrak{p}$-modules (Proposition 4.5.4)

$$\mathrm{Hom}(\kappa(\mathfrak{p}), N_\mathfrak{p}) \to \mathrm{Hom}(\kappa(\mathfrak{p}), Q_\mathfrak{p}) \to \mathrm{Ext}^1(\kappa(\mathfrak{p}), M_\mathfrak{p}).$$

Since $Q_\mathfrak{p} \neq 0$, the morphism $f_\mathfrak{p}$ is not surjective, hence by our assumptions, the modules on the left and right of the sequence above vanish, hence so does the module in the middle. Thus $\mathfrak{p}R_\mathfrak{p} \notin \mathrm{Ass}_{R_\mathfrak{p}}(Q_\mathfrak{p})$, hence $\mathfrak{p} \notin \mathrm{Ass}(Q)$ by Proposition 1.2.10. Thus $\mathrm{Ass}(Q) = \varnothing$, and $Q = 0$ by Corollary 1.2.3. □

Definition 7.2.4. Let R be a ring, and S a subset of $\mathrm{Spec}(R)$. A subset of S is *closed* if its is of the form $S \cap \mathrm{Supp}(M)$, where M is a finitely generated R-module. We say that S is *connected* if it cannot be written as the disjoint union of two non-empty closed subsets.

Remark 7.2.5. One can check that this defines a topology on $\mathrm{Spec}(R)$, the *Zariski topology*. We will not use this remark.

Lemma 7.2.6. *If there are ideals $J_0, J_1 \neq R$ such that the diagonal ring morphism $f\colon R \to R/J_0 \times R/J_1$ is bijective, then* $\mathrm{Spec}(R)$ *is not connected.*

Proof. We have $J_0 \cap J_1 = \ker f = \{0\}$. It follows that every prime contains the product ideal J_0J_1, hence one of the ideals J_i for $i \in \{0, 1\}$. This proves that $\mathrm{Supp}(R/J_0) \cup \mathrm{Supp}(R/J_1) = \mathrm{Spec}(R)$. Using the surjectivity of f, we find $x \in R$ such that $x - 1 \in J_0$ and $x \in J_1$. Thus $1 \in J_0 + J_1$, so that no prime contains both J_0 and J_1. Therefore $\mathrm{Supp}(R/J_0) \cap \mathrm{Supp}(R/J_1) = \varnothing$. □

Remark 7.2.7. The converse of Lemma 7.2.6 is true and can be deduced from the proof of Theorem 7.2.9.

Lemma 7.2.8. *The spectrum of a local ring is connected.*

Proof. Since the maximal ideal contains every prime, it is an element of every non-empty closed subset of the spectrum. Thus the latter cannot decompose as a disjoint union of non-empty closed subsets. □

Theorem 7.2.9 (Hartshorne). *Let $(A, \mathfrak{m})$ be a local ring of depth ≥ 2. Then* $\mathrm{Spec}(A) - \{\mathfrak{m}\}$ *is connected.*

Proof. Assume that $\operatorname{Spec}(A) - \{\mathfrak{m}\}$ is not connected. Then we can find two subsets F_0 and F_1 closed in $\operatorname{Spec}(A)$, such that $F_0 \cap F_1 \subset \{\mathfrak{m}\}$ and $\operatorname{Spec}(A) - \{\mathfrak{m}\} \subset F_1 \cup F_0$. The set $\operatorname{Ass}(A)$ does not contain $\mathfrak{m}$ by assumption, hence decomposes as the disjoint union of $\operatorname{Ass}(A) \cap F_0$ and $\operatorname{Ass}(A) \cap F_1$. By Proposition 1.2.7, we can find for each $i \in \{0, 1\}$ an ideal J_i such that

$$\operatorname{Ass}_A(A/J_i) = \operatorname{Ass}(A) \cap F_i \text{ and } \operatorname{Ass}_A(J_i) = \operatorname{Ass}(A) \cap F_{1-i}.$$

The subset F_i contains $\operatorname{Ass}_A(A/J_i)$ and $\operatorname{Ass}_A(J_{1-i})$. Since it is closed, it contains $\operatorname{Supp}_A(A/J_i)$ and $\operatorname{Supp}_A(J_{1-i})$. In particular $J_{1-i} \neq A$ (as $F_i \neq \operatorname{Spec}(A)$).

Consider the diagonal ring morphism $f \colon A \to A/J_0 \times A/J_1 = N$. Let $\mathfrak{p} \in \operatorname{Spec}(A)$ be such that $\mathfrak{p} \neq \mathfrak{m}$. Then there is $i \in \{0, 1\}$ such that $\mathfrak{p} \notin F_i$. Thus $\mathfrak{p} \notin \operatorname{Supp}(A/J_i)$ and $\mathfrak{p} \notin \operatorname{Supp}(J_{1-i})$, and we deduce that the morphism $f_{\mathfrak{p}}$ is bijective. In particular, this is so when $\operatorname{depth}_{A_{\mathfrak{p}}} N_{\mathfrak{p}} = 0$ (because $\operatorname{Ass}(N) \subset \operatorname{Ass}(A)$ by Proposition 1.2.5, and $\mathfrak{m} \notin \operatorname{Ass}(A)$ by assumption), or when $\operatorname{depth} A_{\mathfrak{p}} \leq 1$ (by assumption). It follows from Lemma 7.2.3 (ii) that f is bijective, hence $\operatorname{Spec}(A)$ is not connected by Lemma 7.2.6. This contradicts Lemma 7.2.8. □

Definition 7.2.10. A ring R is *locally integral* if the ring $R_{\mathfrak{p}}$ is an integral domain for every $\mathfrak{p} \in \operatorname{Spec}(R)$.

Proposition 7.2.11. *The following conditions are equivalent:*

(i) The ring R is locally integral.

(ii) For every $\mathfrak{p} \in \operatorname{Spec}(R)$, the ring $R_{\mathfrak{p}}$ is an integral domain or has depth ≥ 2.

Proof. (i) $\Rightarrow$ (ii) : Clear.

(ii) $\Rightarrow$ (i): We assume that R is local, and show that R is an integral domain. We know that R is reduced by Proposition 7.1.3, so it will suffice to prove that R has a unique minimal prime by Lemma 7.2.1. Assuming the contrary, the set of minimal primes decomposes as the disjoint union of two non-empty subsets M_0 and M_1. For $i \in \{0, 1\}$, let $Q_i = R/J_i$ be a quotient of R such that $\operatorname{Ass}_R(Q_i) = M_i$ (Proposition 1.2.7). If $\mathfrak{q} \in \operatorname{Spec}(R)$, then $\mathfrak{q}$ contains a minimal prime, and therefore an element of $\operatorname{Ass}_R(Q_i)$ for some $i \in \{0, 1\}$. It follows that $\mathfrak{q} \in \operatorname{Supp}_R(Q_i)$. Thus we have $\operatorname{Spec}(R) = \operatorname{Supp}_R(Q_0) \cup \operatorname{Supp}_R(Q_1)$. The set $\operatorname{Supp}_R(Q_0) \cap \operatorname{Supp}_R(Q_1)$ is non-empty (see Lemma 7.2.8; namely it contains the maximal ideal); let $\mathfrak{p}$ be a minimal element of this set (i.e. a prime minimal over $J_0 + J_1$), and write $X_i = \operatorname{Supp}_{R_{\mathfrak{p}}}((Q_i)_{\mathfrak{p}})$ for $i \in \{0, 1\}$. If we view $\operatorname{Spec}(R_{\mathfrak{p}})$ as a subset of $\operatorname{Spec}(R)$, then $X_i = \operatorname{Supp}_R(Q_i) \cap \operatorname{Spec}(R_{\mathfrak{p}})$, hence

$$\operatorname{Spec}(R_{\mathfrak{p}}) = X_0 \cup X_1 \text{ and } X_0 \cap X_1 = \{\mathfrak{p}R_{\mathfrak{p}}\}.$$

Since $\mathfrak{p} \in \operatorname{Supp}(Q_0) \cap \operatorname{Supp}(Q_1)$, it is not a minimal prime of R, hence $X_i - \{\mathfrak{p}R_{\mathfrak{p}}\}$ contains M_i, and in particular is not empty. This gives a decomposition of the set $\operatorname{Spec}(R_{\mathfrak{p}}) - \{\mathfrak{p}R_{\mathfrak{p}}\}$ as the disjoint union of two non-empty closed subsets. By Theorem 7.2.9 we have $\operatorname{depth} R_{\mathfrak{p}} \leq 1$, hence by assumption the ring $R_{\mathfrak{p}}$ is an integral domain. In particular $\mathfrak{p}$ contains exactly one minimal prime of R. But for each $i \in \{0, 1\}$, we have $\mathfrak{p} \in \operatorname{Supp}_R(Q_i)$, hence $\mathfrak{p}$ contains an element of M_i, a contradiction. □

3. Normal rings

Definition 7.3.1. A ring is an *integrally closed domain* if it is an integral domain, and coincides with its integral closure in its fraction field. We say that a ring R is *normal* if the ring $R_{\mathfrak{p}}$ is an integrally closed domain for every $\mathfrak{p} \in \operatorname{Spec}(R)$.

Lemma 7.3.2. *Let A be a local integrally closed domain such that* $\operatorname{depth} A = 1$. *Then A is a discrete valuation ring.*

Proof. Let $\mathfrak{m}$ be the maximal ideal of A. Since $\mathfrak{m} \notin \operatorname{Ass}(A)$, we can find a nonzerodivisor $x \in \mathfrak{m}$. Then $\operatorname{depth}_A A/xA = 0$ by Proposition 5.2.2, hence $\mathfrak{m} \in \operatorname{Ass}_A(A/xA)$. Therefore there is an element $a \in A$ such that $a \notin xA$ and $a\mathfrak{m} \subset xA$. We let K be the fraction field of A and $t = ax^{-1} \in K$, and consider the A-submodule T of K generated by t. Then $\mathfrak{m}T \subset A$ is an ideal of A.

Assume that $\mathfrak{m}T \subset \mathfrak{m}$. Then we see by induction that for all $n \in \mathbb{N}$, the element $u_n = t^n x$ belongs to $\mathfrak{m}$. Since A is noetherian, for n large enough the element u_n is an A-linear combination of the elements u_i for $i < n$. This gives a unital polynomial p with coefficients in A such that $p(t)x = 0$ in K. Since x is invertible in K, it follows that $p(t) = 0$, showing that t is integral over A. Since A is integrally closed in K, we have $t \in A$, contradicting the choice of a.

So $\mathfrak{m}T = A$, and there is $u \in \mathfrak{m}$ such that $ut = 1$. Then

$$\mathfrak{m} = (ut)\mathfrak{m} = u(t\mathfrak{m}) \subset u(\mathfrak{m}T) = uA.$$

So $\mathfrak{m} = uA$. Moreover u is a nonzerodivisor in A, since $ua = x$ is one. This proves that A is a discrete valuation ring. □

Example 7.3.3. Let R be a normal ring of dimension ≤ 2. Then R is Cohen-Macaulay. Indeed we may assume that R is local, and is an integrally closed domain. If $\operatorname{depth} R = 0$, then $\dim R = 0$ by Lemma 7.1.1. If $\operatorname{depth} R = 1$, then $\dim R = 1$ by Lemma 7.3.2. Otherwise $\operatorname{depth} R \geq 2 = \dim R$, so that in any case R is Cohen-Macaulay

Theorem 7.3.4 (Serre). *The following conditions are equivalent:*

(i) The ring R is normal.

(ii) Let $\mathfrak{p} \in \operatorname{Spec}(R)$. If $\operatorname{depth} R_\mathfrak{p} = 0$*, then the ring $R_\mathfrak{p}$ is a field. If* $\operatorname{depth} R_\mathfrak{p} = 1$*, then the ring $R_\mathfrak{p}$ is a discrete valuation ring.*

(iii) For every $\mathfrak{p} \in \operatorname{Spec}(R)$, the ring $R_\mathfrak{p}$ is an integrally closed domain or has depth ≥ 2.

Proof. (i) $\Rightarrow$ (ii): This follows from Lemma 7.1.1 and Lemma 7.3.2.

(ii) $\Rightarrow$ (iii): Fields and discrete valuation rings are integrally closed domains.

(iii) $\Rightarrow$ (i): We may assume that the ring R is local, and prove that it is an integrally closed domain. The ring R is an integral domain by Proposition 7.2.11. Let R' be the integral closure of R in its function field, and $\mathfrak{p} \in \operatorname{Spec}(R)$. If $\operatorname{depth} R_\mathfrak{p} \leq 1$, then the morphism $R_\mathfrak{p} \to R'_\mathfrak{p}$ is bijective because $R_\mathfrak{p}$ is integrally closed (integral closure commutes with localisation). On the hand R' is an integral domain containing R, hence $\operatorname{Ass}_R(R') = \{0\}$. Thus if $\operatorname{depth}_{R_\mathfrak{p}} R'_\mathfrak{p} = 0$, then $\mathfrak{p} = 0 \in \operatorname{Ass}(R)$, hence $\operatorname{depth} R_\mathfrak{p} \leq 1$, so that we are in the case considered above. It follows from Lemma 7.2.3 that $R = R'$, hence R is an integrally closed domain. □

Definition 7.3.5. Let n be an integer n. We consider the following conditions on a ring R.

(Rn) : For every prime $\mathfrak{p}$ of height $\leq n$, the local ring $R_\mathfrak{p}$ is regular.

(Sn) : For every prime $\mathfrak{p}$, we have $\operatorname{depth} R_\mathfrak{p} \geq \min(\operatorname{height} \mathfrak{p}, n)$.

We have proved

Proposition 7.3.6. *Let R be a ring. Then:*

(i) R reduced $\iff$ R satisfies (R0) and (S1).

(ii) *R normal* $\Longleftrightarrow$ *R satisfies* ($R1$) *and* ($S2$).

If R is a Cohen-Macaulay ring, then for every $\mathfrak{p}$, we have $\operatorname{height}\mathfrak{p} = \operatorname{depth} R_{\mathfrak{p}}$, so that R satisfies the condition (Sn) for every n. Thus we obtain:

Proposition 7.3.7. *A Cohen-Macaulay ring R is*

(i) *reduced if and only if the ring $R_{\mathfrak{p}}$ is so for every minimal prime $\mathfrak{p}$,*
(ii) *locally integral if and only if the ring $R_{\mathfrak{p}}$ is so for every prime $\mathfrak{p}$ of height ≤ 1,*
(iii) *normal if and only if the ring $R_{\mathfrak{p}}$ is so for every prime $\mathfrak{p}$ of height ≤ 1.*

CHAPTER 8

Projective dimension

In this chapter $(A, \mathfrak{m}, k)$ is a local commutative noetherian ring.

1. Projective dimension over a local ring

PROPOSITION 8.1.1. *Let M be a finitely generated A-module. The following conditions are equivalent:*

(i) M *is free.*
(ii) M *is projective.*
(iii) M *is flat.*
(iv) $\mathrm{Tor}_1(M, k) = 0$.
(v) $\mathrm{Ext}^1(M, k) = 0$

PROOF. We have (i) ⇒(ii) ⇒(iii) ⇒ (iv) and (ii) ⇒ (v).

Let $m_1, \cdots, m_n$ be elements of M giving modulo $\mathfrak{m}M$ a k-basis of $M/\mathfrak{m}M$. This gives a morphism $\varphi\colon A^n \to M$, which is surjective by Nakayama's Lemma 1.1.6. Let Q be its kernel. We have an exact sequence

$$\mathrm{Tor}_1(M, k) \to Q \otimes_A k \to A^n \otimes_A k \xrightarrow{\varphi \otimes_A k} M \otimes_A k \to 0.$$

If $\mathrm{Tor}_1(M, k) = 0$, since $\varphi \otimes_A k$ is injective, we obtain $Q \otimes_A k = 0$, hence $Q = 0$ by Nakayama's Lemma 1.1.6. This proves (iv) ⇒ (i).

We also have an exact sequence

$$0 \to \mathrm{Hom}_A(M, k) \xrightarrow{\varphi^*} \mathrm{Hom}_A(A^n, k) \to \mathrm{Hom}_A(Q, k) \to \mathrm{Ext}^1_A(M, k).$$

The morphism φ^* decomposes as a sequence of isomorphisms

$$\mathrm{Hom}_A(M, k) \to \mathrm{Hom}_k(M \otimes_A k, k) \xrightarrow{(\varphi \otimes_A k)^*} \mathrm{Hom}_k(A^n \otimes_A k, k) \to \mathrm{Hom}_A(A^n, k)$$

hence is an isomorphism. Thus if $\mathrm{Ext}^1_A(M, k) = 0$, then $0 = \mathrm{Hom}_A(Q, k) = \mathrm{Hom}_k(Q \otimes_A k, k)$, hence $Q \otimes_A k = 0$, and finally $Q = 0$ by Nakayama's Lemma 1.1.6. This proves (v) ⇒ (i). □

DEFINITION 8.1.2. Let R be a commutative unital ring. The *projective dimension* of an R-module M, denoted $\mathrm{projdim}_R M \in \mathbb{N} \cup \{-\infty, \infty\}$, is defined as the infimum of the lengths n of the finite projective resolutions $0 \to L_n \to \cdots \to L_0 \to M \to 0$ of M if $M \neq 0$, and as $-\infty$ if $M = 0$.

Since the functors Ext and Tor may be computed using any projective resolution of M, we see that

$$\mathrm{Tor}_n(M, -) = \mathrm{Ext}^n(M, -) = 0 \quad \text{when} \quad n > \mathrm{projdim}_R M.$$

PROPOSITION 8.1.3. *Let M be a finitely generated A-module and n an integer. The following conditions are equivalent:*

(i) $\operatorname{projdim} M \leq n$.
(ii) $\operatorname{Tor}_{n+1}(M,k) = 0$.
(iii) $\operatorname{Ext}^{n+1}(M,k) = 0$.
(iv) *Let* $0 \to L_n \to \cdots \to L_0 \to M \to 0$ *be an exact sequence with and* L_i *projective for* $i = 0, \cdots, n-1$. *Then* L_n *is projective.*

PROOF. It is clear that (ii) $\Leftarrow$ (i) $\Rightarrow$ (iii) and that (iv) $\Rightarrow$ (i).

Let us now prove (iv) using (ii) or (iii). Let $Z_i = \operatorname{im}(L_i \to L_{i-1})$ for $i = 1, \cdots, n-1$, and let $Z_0 = M$ and $Z_n = L_n$. We have exact sequences, for $i = 0, \cdots, n-1$,

$$0 \to Z_{i+1} \to L_i \to Z_i \to 0,$$

giving exact sequences (Proposition 4.5.3)

$$\operatorname{Ext}^j(L_i,k) \to \operatorname{Ext}^j(Z_{i+1},k) \to \operatorname{Ext}^{j+1}(Z_i,k) \to \operatorname{Ext}^{j+1}(L_i,k)$$

and (Proposition 4.3.3)

$$\operatorname{Tor}_{j+1}(L_i,k) \to \operatorname{Tor}_{j+1}(Z_i,k) \to \operatorname{Tor}_j(Z_{i+1},k) \to \operatorname{Tor}_j(L_i,k).$$

Since for $j > 0$ the four extreme modules vanish, we obtain

$$\operatorname{Ext}^j(Z_{i+1},k) \simeq \operatorname{Ext}^{j+1}(Z_i,k) \text{ and } \operatorname{Tor}_{j+1}(Z_i,k) \simeq \operatorname{Tor}_j(Z_{i+1},k),$$

and we conclude that

$$\operatorname{Ext}^1(L_n,k) \simeq \operatorname{Ext}^{n+1}(M,k) \text{ and } \operatorname{Tor}_1(L_n,k) \simeq \operatorname{Tor}_{n+1}(M,k),$$

so that L_n is free by Proposition 8.1.1 under the assumption (ii) or (iii). □

COROLLARY 8.1.4. *Let M, M' be two finitely generated A-modules. Then*

$$\operatorname{projdim}(M \oplus M') = \max(\operatorname{projdim} M, \operatorname{projdim} M').$$

We will use the following technical lemma in the next proof.

LEMMA 8.1.5. *Let R be a commutative ring. Consider an exact sequence of R-modules*

$$M_1 \xrightarrow{f_1} M_2 \xrightarrow{f_2} M_3 \xrightarrow{f_3} M_4,$$

and let $x \in R$ be a nonzerodivisor in M_4. Then the sequence of R/xR-modules

$$M_1/xM_1 \to M_2/xM_2 \to M_3/xM_3$$

is exact.

PROOF. The sequence is clearly a complex. Let $m_2 \in M_2$ and assume that $f_2(m_2) = xm_3$ for some $m_3 \in M_3$. We have $xf_3(m_3) = f_3 \circ f_2(m_2) = 0$. Since x is a nonzerodivisor in M_4, it follows that $f_3(m_3) = 0$, hence $m_3 = f_2(m_2')$ for some $m_2' \in M_2$. Therefore $m_2 - xm_2' = f_1(m_1)$ with $m_1 \in M_1$. This proves the statement. □

PROPOSITION 8.1.6. *Let M be a finitely generated A-module, and $x \in \mathfrak{m}$ be a nonzerodivisor in M and in A. We have, for every n, isomorphisms of A-modules*

$$\operatorname{Tor}_n^{A/xA}(M/xM,k) \simeq \operatorname{Tor}_n^A(M,k) \quad \textit{and} \quad \operatorname{Ext}^n_{A/xA}(M/xM,k) \simeq \operatorname{Ext}^n_A(M,k).$$

In particular

$$\operatorname{projdim}_{A/xA} M/xM = \operatorname{projdim}_A M.$$

PROOF. Let $L \to M$ be a (possibly infinite) free resolution of the A-module M (Proposition 4.2.6). The A/xA-modules $L_n/xL_n = L_n \otimes_A (A/xA)$ are free, and fit into the complex of A/xA-modules $L/xL = L \otimes_A (A/xA)$. For every n, the element x is a nonzerodivisor in L_n and in M, hence $L/xL \to M/xM$ is a free resolution the A/xA-module M/xM by Lemma 8.1.5. Since $x \in \mathfrak{m}$, the morphisms of complexes of A-modules

$$L \otimes_A k \to (L/xL) \otimes_{A/xA} k \quad \text{and} \quad \operatorname{Hom}_{A/xA}(L/xL, k) \to \operatorname{Hom}_A(L, k)$$

are bijective in each degree, hence are quasi-isomorphisms. □

2. The Auslander-Buchsbaum formula

We will use the following

LEMMA 8.2.1. *Consider an exact sequence of finitely generated A-modules*

$$0 \to M' \to M \to M'' \to 0.$$

If $\operatorname{projdim} M < \operatorname{projdim} M''$, *then* $\operatorname{projdim} M' = \operatorname{projdim} M'' - 1$.

PROOF. Let $n \geq \operatorname{projdim} M''$. Using the exact sequence (Proposition 4.3.3)

$$\operatorname{Tor}_{n+1}(M, k) \to \operatorname{Tor}_{n+1}(M'', k) \to \operatorname{Tor}_n(M', k) \to \operatorname{Tor}_n(M, k)$$

we see that $\operatorname{Tor}_n(M', k) \simeq \operatorname{Tor}_{n+1}(M'', k)$. Taking $n = \operatorname{projdim} M''$, we obtain $\operatorname{Tor}_n(M', k) = 0$, hence $\operatorname{projdim} M' \leq \operatorname{projdim} M'' - 1$ in view of Proposition 8.1.3. Taking $n = \operatorname{projdim} M'' - 1$, we obtain $\operatorname{Tor}_n(M', k) \neq 0$, hence $\operatorname{projdim} M' \geq \operatorname{projdim} M'' - 1$. □

THEOREM 8.2.2 (Auslander-Buchsbaum). *Let M be a finitely generated A-module of finite projective dimension. Then*

$$\operatorname{projdim} M + \operatorname{depth} M = \operatorname{depth} A.$$

PROOF. We argue by induction on $\operatorname{projdim} M$.

If $\operatorname{projdim} M = 0$, then M is free by Proposition 8.1.1 (and nonzero), and $\operatorname{depth} M = \operatorname{depth} A$ by Lemma 5.2.10.

If $\operatorname{projdim} M = 1$, we let E be a (finite) family of elements of M whose image in $M/\mathfrak{m}M$ form a k-basis. This gives a morphism $\varphi\colon L_0 \to M$, where L_0 is the free A-module with basis E. Since $\varphi \otimes_A k$ is an isomorphism, the morphism φ is surjective by Nakayama's Lemma 1.1.6, and its kernel L_1 is contained in $\mathfrak{m}L_0$. So we have an exact sequence of A-modules

$$0 \to L_1 \xrightarrow{d} L_0 \to M \to 0$$

with $d(L_1) \subset \mathfrak{m}L_0$. By Lemma 8.2.1, we have $\operatorname{projdim} L_1 = \operatorname{projdim} M - 1 = 0$, so that the A-module L_1 is free by Proposition 8.1.1. It is also finitely generated, and we deduce that the morphism of A-modules

$$\mathfrak{m} \operatorname{Hom}_A(L_1, L_0) \to \operatorname{Hom}_A(L_1, \mathfrak{m}L_0)$$

is surjective. Thus $d = x_1 d_1 + \cdots + x_n d_n$ for some $x_j \in \mathfrak{m}$ and $d_j \in \operatorname{Hom}_A(L_1, L_0)$ for $j = 1, \cdots, n$, so that the morphism $\operatorname{Ext}^i(k, d) = x_1 \operatorname{Ext}^i(k, d_1) + \cdots + x_n \operatorname{Ext}^i(k, d_n)$ (Proposition 4.5.2 (v)) vanishes for every i (observe that $\mathfrak{m} \operatorname{Ext}^i(k, L_0) = 0$ by Proposition 4.5.2 (iv)). We obtain short exact sequences of A-modules (Proposition 4.5.4), for every i,

$$0 \to \operatorname{Ext}^i(k, L_0) \to \operatorname{Ext}^i(k, M) \to \operatorname{Ext}^{i+1}(k, L_1) \to 0.$$

Now L_0 and L_1 are free, and nonzero (because $\operatorname{projdim} M = 1$), hence $\operatorname{depth} L_1 = \operatorname{depth} L_0 = \operatorname{depth} A$ by Lemma 5.2.10. It follows that $\operatorname{depth} M = \operatorname{depth} A - 1$.

Now let us assume that $\operatorname{projdim} M \geq 2$. Choose an exact sequence of A-modules

$$0 \to N \to L \to M \to 0.$$

with L free and finitely generated (and nonzero). We have $\operatorname{projdim} N = \operatorname{projdim} M - 1$ by Lemma 8.2.1. Thus we obtain by induction

$$\operatorname{projdim} N + \operatorname{depth} N = \operatorname{depth} A.$$

In particular $\operatorname{depth} N < \operatorname{depth} A = \operatorname{depth} L$ (Lemma 5.2.10). Using the long exact sequence of A-modules

$$\operatorname{Ext}^{i-1}(k, L) \to \operatorname{Ext}^{i-1}(k, M) \to \operatorname{Ext}^{i}(k, N) \to \operatorname{Ext}^{i}(k, L),$$

we see that $\operatorname{depth} M = \operatorname{depth} N - 1$, as required. □

COROLLARY 8.2.3. *Let M be a finitely generated A-module of finite projective dimension. Then*

(i) $\operatorname{projdim} M \leq \operatorname{depth} A$, *with equality if and only if* $\mathfrak{m} \in \operatorname{Ass}(M)$.
(ii) $\operatorname{depth} M \leq \operatorname{depth} A$, *with equality if and only if M is free and nonzero.*

CHAPTER 9

Regular rings

In this chapter A is a local ring.

1. Homological dimension

DEFINITION 9.1.1. The *homological dimension* of a commutative unital noetherian ring R is the supremum of the integers $\operatorname{projdim}_R M$, where M runs over the finitely generated R-modules. It is denoted $\operatorname{dimh} R \in \mathbb{N} \cup \{\infty\}$.

REMARK 9.1.2. We can show (using Baer's criterion) that $\operatorname{dimh} R$ is the supremum $\operatorname{projdim}_R M$, where M runs over all R-modules.

PROPOSITION 9.1.3. *Let A be a local (noetherian) ring with residue field k. Then*

$$\operatorname{dimh} A = \operatorname{projdim}_A k = \sup\{n \mid \operatorname{Tor}_n^A(k,k) \neq 0\} = \inf\{n \mid \operatorname{Tor}_{n+1}^A(k,k) = 0\}.$$

PROOF. The last two equalities follow from Proposition 8.1.3. Let $m = \operatorname{projdim}_A k$, and M be a finitely generated A-module. Then $\operatorname{Tor}_{m+1}^A(k, M) = 0$, hence $\operatorname{Tor}_{m+1}^A(M,k) = 0$ by Proposition 4.3.5, and thus $\operatorname{projdim}_A M \leq m$ by Proposition 8.1.3. Therefore $\operatorname{dimh} A \leq m$; the other inequality is immediate. □

COROLLARY 9.1.4. *If the homological dimension of a local (noetherian) ring is finite, it is equal to its depth.*

PROOF. Let A be the local ring, k its residue field. We have $\operatorname{depth}_A k = 0$. We apply the Auslander-Buchsbaum Theorem 8.2.2 to the A-module k, and obtain that $\operatorname{projdim}_A k = \operatorname{depth} A$. □

2. Regular rings

THEOREM 9.2.1 (Serre). *A local ring is regular if and only if it has finite homological dimension.*

PROOF. Let $(A, \mathfrak{m}, k)$ be a local ring. Assume that A is regular. We prove by induction on $n = \dim A$ that $\operatorname{projdim}_A k = n$ (see Proposition 9.1.3). This is clear when $n = 0$, because then $A = k$ by Example 3.2.2. Assume that $n > 0$. Let $\{x_1, \cdots, x_n\}$ be a regular system of parameters for A. Then the local ring A/x_nA is regular of dimension $n-1$ (Lemma 3.2.4). Since A is an integral domain by Proposition 3.2.6, the nonzero element x_n is a nonzerodivisor in A. By Proposition 6.2.5, the ring A is Cohen-Macaulay, hence by Proposition 6.1.7 the tuple $(x_1, \cdots, x_n)$ is an A-regular sequence. Thus x_n is a nonzerodivisor in $K = A/\{x_1, \cdots, x_{n-1}\}A$. By Proposition 8.1.6, it follows that $\operatorname{projdim}_A K = \operatorname{projdim}_{A/x_nA} k$. By induction we have $\operatorname{dimh} A/x_nA = n-1$, hence $\operatorname{projdim}_A K = n-1$. We have an exact sequence of A-modules

$$0 \to K \xrightarrow{x_n} K \to k \to 0.$$

This gives a long exact sequence (Proposition 4.3.3)

$$\operatorname{Tor}_i^A(K,k) \to \operatorname{Tor}_i^A(K,k) \to \operatorname{Tor}_i^A(k,k) \to \operatorname{Tor}_{i-1}^A(K,k) \to \operatorname{Tor}_{i-1}^A(K,k).$$

By Proposition 4.3.2 (vi), the morphism $\operatorname{Tor}_i^A(K,k) \to \operatorname{Tor}_i^A(K,k)$ is multiplication by x_n. Since $x_n \in \mathfrak{m}$ acts trivially on k, this morphism vanishes by Proposition 4.3.2 (vi). We obtain short exact sequences, for every i,

$$0 \to \operatorname{Tor}_i^A(K,k) \to \operatorname{Tor}_i^A(k,k) \to \operatorname{Tor}_{i-1}^A(K,k) \to 0.$$

Taking $i = n+1$, since $\operatorname{Tor}_n^A(K,k) = \operatorname{Tor}_{n+1}^A(K,k) = 0$, we see that $\operatorname{Tor}_{n+1}^A(k,k) = 0$, thus $\operatorname{projdim}_A k \leq n$ by Proposition 8.1.3. Taking $i = n$, we have $\operatorname{Tor}_{n-1}^A(K,k) \neq 0$ by Proposition 8.1.3, so that $\operatorname{Tor}_n^A(k,k) \neq 0$ and thus $\operatorname{projdim}_A k \geq n$.

For the converse, we proceed by induction on $n = \operatorname{dimh} A$. Assume that $n = 0$. Then $\operatorname{projdim}_A k = 0$, so that the A-module k is free, and (being nonzero) contains a copy of A. Thus $\mathfrak{m} = \operatorname{Ann}_A(k) = 0$, hence A is a field, hence a regular local ring (Example 3.2.2). Now we assume that $\infty > n > 0$. We have $\operatorname{depth} A = n$ by Corollary 9.1.4, and thus $\mathfrak{m} \notin \operatorname{Ass}(A)$ (Lemma 5.2.4). We have $\mathfrak{m}^2 \neq \mathfrak{m}$ by Nakayama's Lemma 1.1.6 (otherwise $\mathfrak{m} = 0$ and A is a field, a contradiction with the fact that $n > 0$). By prime avoidance (Proposition 2.4.5), we can find an element $x \in \mathfrak{m}$ which is not in $\mathfrak{m}^2$, nor in any of the finitely many associated primes of A (Corollary 1.3.6). By Lemma 1.2.9, the element x is a nonzerodivisor in A. Let $B = A/xA$, and $\mathfrak{n} = \mathfrak{m}/xA$ its maximal ideal. Consider the complex of B-modules

$$0 \to k \xrightarrow{u} \mathfrak{m}/x\mathfrak{m} \xrightarrow{v} \mathfrak{n} \to 0,$$

where u is induced by the map $A \to \mathfrak{m}, r \mapsto xr$, and v is the natural quotient $\mathfrak{m}/x\mathfrak{m} \to \mathfrak{m}/xA = \mathfrak{n}$. We claim that the sequence is exact. Indeed v is surjective and we have $\ker v = xA/x\mathfrak{m} = \operatorname{im} u$. If $a \in A$ is such that $a \mod \mathfrak{m} \in \ker u$, then $xa = xm$ for some $m \in \mathfrak{m}$. Thus $x(a-m) = 0$, and since x is a nonzerodivisor in A, we have $a = m \in \mathfrak{m}$, proving that u is injective.

The natural morphism of k-vector spaces $\mathfrak{m}/\mathfrak{m}^2 \to \operatorname{Hom}_k(\operatorname{Hom}_k(\mathfrak{m}/\mathfrak{m}^2, k), k)$ is injective (in fact bijective). Therefore since $x \neq 0 \mod \mathfrak{m}^2$, we may find a linear form $\varphi \colon \mathfrak{m}/\mathfrak{m}^2 \to k$ such that $\varphi(x) \neq 0 \in k$. Replacing φ with $(1/\varphi(x)) \cdot \varphi$, we may assume that $\varphi(x) = 1$. Composing φ with the surjection $\mathfrak{m}/x\mathfrak{m} \to \mathfrak{m}/\mathfrak{m}^2$, we obtain a morphism of B-modules $\psi \colon \mathfrak{m}/x\mathfrak{m} \to k$ sending $x \mod x\mathfrak{m}$ to 1. This gives a splitting of the exact sequence above (we have $\psi \circ u = \mathrm{id}_k$), so that we have a decomposition as B-modules

$$\mathfrak{m}/x\mathfrak{m} = k \oplus \mathfrak{n}.$$

It follows from Corollary 8.1.4 that

$$\operatorname{projdim}_B k \leq \operatorname{projdim}_B \mathfrak{m}/x\mathfrak{m}.$$

From Proposition 8.1.6, we know that

$$\operatorname{projdim}_B \mathfrak{m}/x\mathfrak{m} = \operatorname{projdim}_A \mathfrak{m}.$$

Since this quantity is smaller than $\operatorname{dimh} A = n$, we have $\operatorname{projdim}_B k < \infty$, so that B has finite homological dimension (Proposition 9.1.3). We have $\operatorname{depth} B = n-1$ by Proposition 5.2.2, hence $\operatorname{dimh} B = n-1$ by Corollary 9.1.4. By the induction hypothesis, the local ring B is regular. Therefore A is a regular local ring by Lemma 3.2.5. $\square$

Corollary 9.2.2. *Let A be a regular local ring, and $\mathfrak{p}$ a prime of A. Then $A_{\mathfrak{p}}$ is a regular local ring.*

Proof. Let $n = \operatorname{projdim}_A A/\mathfrak{p}$. Then we may find an exact sequence of A-modules $0 \to L_n \to \cdots \to L_0 \to A/\mathfrak{p} \to 0$ with L_i free and finitely generated for $i = 0, \cdots, n-1$ (Lemma 4.2.1). By Proposition 8.1.3, the module L_n is projective. Since L_n is finitely generated, it is free by Proposition 8.1.1. Localising the finite resolution $0 \to L_n \to \cdots \to L_0 \to A/\mathfrak{p} \to 0$ at $\mathfrak{p}$, we obtain a finite resolution of the $A_{\mathfrak{p}}$-module $(A/\mathfrak{p})_{\mathfrak{p}} = \kappa(\mathfrak{p})$ by free, hence projective, $A_{\mathfrak{p}}$-modules. Thus $\operatorname{projdim}_{A_{\mathfrak{p}}} \kappa(\mathfrak{p}) < \infty$, hence $\operatorname{dimh} A_{\mathfrak{p}} < \infty$ by Proposition 9.1.3, and finally $A_{\mathfrak{p}}$ is regular by Theorem 9.2.1. $\square$

Corollary 9.2.3. *A regular local ring is an integrally closed domain.*

Proof. Let A be a regular local ring, and $\mathfrak{p}$ a prime of A. The ring $A_{\mathfrak{p}}$ is a regular local ring by Corollary 9.2.2. If $\operatorname{depth} A_{\mathfrak{p}} = 0$, since $A_{\mathfrak{p}}$ is a reduced local ring, it is a field by Lemma 7.1.1. If $\operatorname{depth} A_{\mathfrak{p}} = 1$, then $A_{\mathfrak{p}}$ is a regular local ring of dimension one, that is, a discrete valuation ring by Example 3.2.3. It follows that A is normal by Theorem 7.3.4, and being local, is an integrally closed domain. $\square$

Definition 9.2.4. A ring R is called *regular* if $R_{\mathfrak{p}}$ is a regular local ring for every prime $\mathfrak{p}$. By Corollary 9.2.2, it is equivalent to require that $R_{\mathfrak{m}}$ be a regular local ring for every maximal ideal $\mathfrak{m}$.

CHAPTER 10

Factorial rings

In this chapter R is a commutative unital noetherian ring.

1. Locally free modules

LEMMA 10.1.1. *An ideal of R is a free R-module of rank one if and only if it is generated by a nonzerodivisor in R.*

PROOF. If $I = iR$ with i a nonzerodivisor in R, then the surjective morphism $R \to I$, $r \mapsto ri$ must be injective, because so is the composite $R \to I \subset R$.

Conversely, if I is free and generated by i, we have an isomorphism $R \to I$, $r \mapsto ri$. The composite $R \to I \subset R$ is injective and coincides with multiplication by i in R, proving that i is a nonzerodivisor in R. $\square$

DEFINITION 10.1.2. An R-module M is *locally free* if the $R_{\mathfrak{p}}$-module $M_{\mathfrak{p}}$ is free for every $\mathfrak{p} \in \operatorname{Spec}(R)$. We say that the R-module M is *locally free of rank n* if the $R_{\mathfrak{p}}$-module $M_{\mathfrak{p}}$ is free of rank n for every $\mathfrak{p} \in \operatorname{Spec}(R)$.

LEMMA 10.1.3. *Let M, N be R-module with M finitely generated, and let S be a multiplicatively closed subset of R. Then the morphism of $S^{-1}R$-modules*

$$S^{-1}\operatorname{Hom}_R(M,N) \to \operatorname{Hom}_{S^{-1}R}(S^{-1}M, S^{-1}N)$$

is bijective

PROOF. Since M is finitely generated and R is noetherian we may find finitely generated free modules F_0, F_1 fitting into an exact sequence

$$F_1 \to F_0 \to M \to 0.$$

We deduce a commutative diagram with exact rows

$$\begin{tikzcd}
0 \arrow[r] & S^{-1}\operatorname{Hom}_R(M,N) \arrow[r] \arrow[d] & S^{-1}\operatorname{Hom}_R(F_0,N) \arrow[r] \arrow[d] & S^{-1}\operatorname{Hom}_R(F_1,N) \arrow[d] \\
0 \arrow[r] & \operatorname{Hom}_{S^{-1}R}(S^{-1}M, S^{-1}N) \arrow[r] & \operatorname{Hom}_{S^{-1}R}(S^{-1}F_0, S^{-1}N) \arrow[r] & \operatorname{Hom}_{S^{-1}R}(S^{-1}F_1, S^{-1}N)
\end{tikzcd}$$

A diagram chase shows that it suffices to prove that the two rightmost vertical arrows are isomorphisms. We thus reduced to assuming that M is free, in which case the statement is clear (to give a morphism from a free module consists exactly in specifying the image of a basis). $\square$

PROPOSITION 10.1.4. *If P is a finitely generated and locally free R-module, then P is projective.*

PROOF. Let $M \to N$ be a surjective morphism of R-modules. To prove that the morphism of R-modules $\mathrm{Hom}_R(P, M) \to \mathrm{Hom}_R(P, N)$ is surjective, it will suffice to prove that the morphism of $R_{\mathfrak{p}}$-modules $(\mathrm{Hom}_R(P, M))_{\mathfrak{p}} \to (\mathrm{Hom}_R(P, N))_{\mathfrak{p}}$ is surjective for every $\mathfrak{p} \in \mathrm{Spec}(R)$. By Lemma 10.1.3, the latter morphism may be identified with $\mathrm{Hom}_{R_{\mathfrak{p}}}(P_{\mathfrak{p}}, M_{\mathfrak{p}}) \to \mathrm{Hom}_{R_{\mathfrak{p}}}(P_{\mathfrak{p}}, N_{\mathfrak{p}})$, which is surjective because the $R_{\mathfrak{p}}$-module $P_{\mathfrak{p}}$ is projective (being free). $\square$

DEFINITION 10.1.5. A finitely generated R-module M is *stably free* if there is a finitely generated free R-module F such that $M \oplus F$ is a free R-module.

LEMMA 10.1.6. *A finitely generated projective R-module admitting a finite resolution by finitely generated free modules is stably free.*

PROOF. We prove the statement by induction on the length n of the resolution. Let M be the module, and $0 \to F_n \to \cdots \to F_0 \to M \to 0$ its resolution. Let $N = \ker(F_0 \to M)$. Then the exact sequence

$$0 \to N \to F_0 \to M \to 0$$

splits because M is projective. Since $N \oplus M \simeq F_0$ is free, it follows that N is projective. The R-module N is also finitely generated (being a quotient of F_0). We have a finite resolution $0 \to F_n \to \cdots \to F_1 \to N \to 0$ of N by finitely generated free modules of length $n-1$, hence by induction there is a finitely generated free R-module F such that $G = N \oplus F$ is free. Then $M \oplus G = M \oplus N \oplus F \simeq F_0 \oplus F$ is free, and M is stably free. $\square$

2. The exterior algebra

DEFINITION 10.2.1. Let M be an R-module. For every integer $n \geq 0$, we define an R-module $\Lambda^n_R M = \Lambda^n M$ as the quotient of $M^{\otimes n} = M \otimes_R \cdots \otimes_R M$ by the submodule generated by the elements $m_1 \otimes \cdots \otimes m_n$ with $m_i = m_j$ for some $i \neq j$.

The morphism $M^{\otimes m} \otimes_R M^{\otimes n} \to M^{\otimes m+n}$ induces a surjective morphism $\Lambda^m M \otimes_R \Lambda^n M \to \Lambda^{m+n} M$ that we denote by $x \otimes y \mapsto x \wedge y$. This operation turns $\Lambda_R M = \Lambda M = \bigoplus_{n \geq 0} \Lambda^n R$ into an R-algebra equipped with a morphism of R-modules $M \to \Lambda M$, satisfying the following universal property. If B is an R-algebra, then any morphism of R-modules $f\colon M \to B$ such that $f(m)^2 = 0$ for any $m \in M$ extends uniquely to a morphism of R-algebras $\Lambda M \to B$.

REMARK 10.2.2. We have $\Lambda^0 M \simeq R$, and $\Lambda^1 M \simeq M$.

The following results may be proved using the universal property of the exterior algebra.

PROPOSITION 10.2.3. *(i) If $R \to S$ is a ring morphism and M an R-module, then $(\Lambda^n_R M) \otimes_R S \simeq \Lambda^n_S(M \otimes_R S)$.*

(ii) Let M, N be two R-modules. Then we have an isomorphism of graded R-algebras $\Lambda(M \oplus N) \simeq \Lambda M \otimes \Lambda N$.

LEMMA 10.2.4. *Let M be a finitely generated, locally free R-module of rank one. Then $\Lambda^i M = 0$ for $i > 1$.*

PROOF. It will be enough to prove that the $R_{\mathfrak{p}}$-module $(\Lambda^i M)_{\mathfrak{p}} = \Lambda^i(M_{\mathfrak{p}})$ (Proposition 10.2.3 (i)) vanishes for every $\mathfrak{p} \in \mathrm{Spec}(R)$. Thus we may assume that M is free, generated by an element m. If $x, y \in M$, and $z \in \Lambda^{i-2} M$, then x and y are scalar multiples of m, hence $x \wedge y \wedge z$ is a scalar multiple of $m \wedge m \wedge z = 0 \wedge z = 0$. $\square$

We denote by $R^m = R \oplus \cdots \oplus R$ the free R-module of rank m (with a given basis).

Lemma 10.2.5. *Let L be a finitely generated, locally free R-module of rank one. Then*

$$\Lambda^n(L \oplus R^{n-1}) \simeq L.$$

Proof. By Proposition 10.2.3 (ii), we have

$$\Lambda^n(L \oplus R^{n-1}) \simeq \bigoplus_{i_1+\ldots+i_n=n} \Lambda^{i_1} L \otimes \Lambda^{i_2} R \otimes \cdots \otimes \Lambda^{i_n} R.$$

In view of Remark 10.2.2 and Lemma 10.2.4, there is only one nonzero summand in the right hand side, namely L, when $i_1 = \cdots = i_n = 1$. □

Proposition 10.2.6. *Let L be a finitely generated, locally free R-module of rank one. If L is stably free, then L is free of rank one.*

Proof. We may assume that $R \neq 0$. There are integers m and n such that $L \oplus R^m \simeq R^n$. Choosing $\mathfrak{p} \in \operatorname{Spec}(R)$ and applying $- \otimes_R \kappa(\mathfrak{p})$ to that isomorphism, we see that $m = n - 1$ (isomorphic $\kappa(\mathfrak{p})$-vector spaces have the same dimension). Then using Lemma 10.2.5 twice (for the modules L and R), we obtain isomorphisms of R-modules

$$R \simeq \Lambda^n R^n \simeq \Lambda^n(L \oplus R^{n-1}) \simeq L.$$ □

3. Factorial rings

Definition 10.3.1. An element $x \in R$ is called *irreducible* if it is not a unit, and whenever $x = ab$ then a or b is a unit.

Lemma 10.3.2. *Any nonzero element of an integral domain decomposes as the product of finitely many irreducible elements.*

Proof. Assume that $x \in R$ does not decompose that way. We construct by induction an infinite chain of principal ideals $x_n R \subsetneq x_{n+1} R \subsetneq \cdots$, with x_n admitting no decomposition as above. This will contradict the noetherianity of R. We let $x_0 = x$. Now assume that x_n is constructed. Since x_n is not irreducible, it can be factored as ab with a, b non-units and nonzero. Then one element $x_{n+1} \in \{a, b\}$ does not decompose as a product of irreducible elements (otherwise x would). We have $x_n R \subset x_{n+1} R$. In case of equality, we have $x_{n+1} = x_n c$ for some $c \in R$. Then $abc \in \{a, b\}$, which implies (since R is an integral domain) $1 \in \{bc, ac\}$, and therefore one of the elements b or a is a unit, a contradiction. □

Definition 10.3.3. A ring is a *factorial* if it is an integral domain and every ideal generated by an irreducible element is prime.

Lemma 10.3.4. *An integral domain is factorial if and only if every height one prime is principal.*

Proof. Let R be a factorial ring, and let $\mathfrak{p}$ be a prime of height one of R. Let $x \in \mathfrak{p} - \{0\}$. By Lemma 10.3.2, we may decompose x as $p_1 \cdots p_n$ with p_i irreducible elements (possibly not pairwise distinct). Then there is an index i such that $p_i \in \mathfrak{p}$. We have $0 \subsetneq p_i R \subset \mathfrak{p}$, and the ideal $p_i R$ is prime because R is factorial. Since height $\mathfrak{p} = 1$, it follows that $p_i R = \mathfrak{p}$.

Conversely, assume that every height one prime of R is principal. Let $x \in R$ be an irreducible element. Let $\mathfrak{p}$ be a minimal prime over xR. Then by Krull's Theorem 2.3.2, the prime $\mathfrak{p}$ has height one, hence by assumption $\mathfrak{p} = pR$ for some $p \in R$. We have $xR \subset pR$, hence $x = pq$ for some $q \in R$. Since p is not a unit (otherwise $\mathfrak{p} = R$) and x is irreducible, the element q has to be a unit. Therefore $xR = pR$, proving that xR is prime. □

PROPOSITION 10.3.5. *A factorial ring is normal.*

PROOF. Let R be a factorial ring, and $\mathfrak{p} \in \operatorname{Spec}(R)$. If $\operatorname{depth} R_{\mathfrak{p}} = 0$, the reduced ring $R_{\mathfrak{p}}$ must be a field by Lemma 7.1.1. If $\operatorname{depth} R_{\mathfrak{p}} = 1$, then $\operatorname{height} \mathfrak{p} = \dim R_{\mathfrak{p}} \geq 1$, hence we can find a prime $\mathfrak{q}$ of height one such that $\mathfrak{q} \subset \mathfrak{p}$. Since R is factorial, there is $x \in R$ such that $\mathfrak{q} = xR$. The image of x in $\mathfrak{p}R_{\mathfrak{p}}$ is a nonzero element of the integral domain $R_{\mathfrak{p}}$, and is thus a nonzerodivisor in $R_{\mathfrak{p}}$. Therefore $\operatorname{depth} R_{\mathfrak{p}}/xR_{\mathfrak{p}} = \operatorname{depth} R_{\mathfrak{p}} - 1 = 0$ by Proposition 5.2.2. Since the ideal $xR \subset R$ is prime and contained in $\mathfrak{p}$, the ideal $xR_{\mathfrak{p}} \subset R_{\mathfrak{p}}$ is prime. Thus the ring $R_{\mathfrak{p}}/xR_{\mathfrak{p}}$ is an integral domain, and being of depth zero, it is a field by Lemma 7.1.1. Thus $R_{\mathfrak{p}}$ is an integral domain whose maximal ideal $xR_{\mathfrak{p}} = \mathfrak{p}R_{\mathfrak{p}}$ is principal, hence a discrete valuation ring. We conclude using Serre's criterion Theorem 7.3.4. □

REMARK 10.3.6. A factorial ring is also called a Unique Factorisation Domain (UFD). One may prove that a ring is factorial if and only if the decomposition of every element into a product of irreducible elements is unique (up to order and multiplication by units). Then using this characterisation, the classical proof that $\mathbb{Z}$ is an integrally closed domain can be used to give another proof of Proposition 10.3.5.

LEMMA 10.3.7 (Nagata). *Let R be an integral domain, and $x \in R - \{0\}$ be such that xR is a prime ideal of R. If $R[x^{-1}]$ is factorial, then so is R.*

PROOF. By Lemma 10.3.4, it will suffice to take a prime $\mathfrak{p}$ of height one in R, and prove that the ideal $\mathfrak{p}$ is principal. This is true if $\mathfrak{p} = xR$. Otherwise, since $\mathfrak{p}$ has height one, we must have $x \notin \mathfrak{p}$, and therefore $x^n \notin \mathfrak{p}$ for every n. It follows that $\mathfrak{p}R[x^{-1}]$ is a prime of height one in $R[x^{-1}]$. By assumption, we can find $y \in \mathfrak{p}R[x^{-1}]$ such that $\mathfrak{p}R[x^{-1}] = yR[x^{-1}]$. Multiplying with a power of x, we may assume that $y \in \mathfrak{p}$. Let E be the set of elements $y \in \mathfrak{p}$ such that $\mathfrak{p}R[x^{-1}] = yR[x^{-1}]$. We have just seen that $E \neq \varnothing$. Now the set of ideals $\{yR | y \in E\}$ of R admits a maximal element yR with $y \in E$ since R is noetherian.

We claim that $y \notin xR$. Indeed if $y = ax$ with $a \in R$, then $a \in E$ and $yR \subset aR$. By maximality $yR = aR$, hence we can find $b \in R$ such that $a = by$. Thus $y = bxy$, hence since R is an integral domain and $y \neq 0$ (because the prime $\mathfrak{p}R[x^{-1}]$ is not zero, being of height one), it follows that $bx = 1$, hence $xR = R$, a contradiction with assumption that xR is prime, proving the claim.

We now prove that $\mathfrak{p} = yR$. Since $y \in \mathfrak{p}$ by construction, it will suffice to prove that $\mathfrak{p} \subset yR$. Let $r \in \mathfrak{p}$. Since $yR[x^{-1}] = \mathfrak{p}R[x^{-1}]$, we have $x^n r = yc$ for some $c \in R$ and $n \in \mathbb{N}$. We prove that $r \in yR$ by induction on n. This is true if $n = 0$. Assume that $n > 0$. Then $yc \in xR$, and since $y \notin xR$ and xR is prime, we have $c \in xR$. Thus $x^{n-1}r = yc$, and by induction $r \in yR$. □

THEOREM 10.3.8 (Auslander-Buchsbaum). *A regular local ring is factorial.*

PROOF. Let A be a regular local ring, with maximal ideal $\mathfrak{m}$. We proceed by induction on $\dim A$. If $\dim A = 0$, then A is a field, hence is factorial. Assume that $\dim A > 0$. Then we can find $x \in \mathfrak{m} - \mathfrak{m}^2$.

Let $\mathfrak{q}$ be a prime of height one in $A[x^{-1}]$. We have $\dim A[x^{-1}] < \dim A$, since any chain of primes in $A[x^{-1}]$ gives rise to chain in $\mathrm{Spec}(A) - \{\mathfrak{m}\}$, which can always be strictly enlarged by adding $\mathfrak{m}$. Let $\mathfrak{p} \in \mathrm{Spec}(A[x^{-1}])$. Then the ring $B = (A[x^{-1}])_{\mathfrak{p}}$ coincides with the localisation of the ring A at the prime $\mathfrak{p} \cap A$, hence is a regular local ring by Corollary 9.2.2. Since $\dim B \leq \dim A[x^{-1}] < \dim A$, we know that B is factorial by induction. The ideal $\mathfrak{q}B$ of B is either the unit ideal (if $\mathfrak{q} \not\subset \mathfrak{p}$) or a prime of height one (if $\mathfrak{q} \subset \mathfrak{p}$). In any case, this ideal is principal, and by Lemma 10.1.1 it follows that $\mathfrak{q}$ is a locally free $A[x^{-1}]$-module of rank one.

There is an ideal $\mathfrak{q}'$ of A such that $\mathfrak{q} = \mathfrak{q}'A[x^{-1}]$. By Theorem 9.2.1, we can find a finite resolution by finitely generated free modules of the A-module $\mathfrak{q}'$. Tensoring with $A[x^{-1}]$, we obtain finite resolution by finitely generated free modules of the $A[x^{-1}]$-module $\mathfrak{q}' \otimes_A A[x^{-1}] = \mathfrak{q}$. Since the $A[x^{-1}]$-module $\mathfrak{q}$ is projective Proposition 10.1.4, it is stably free by Lemma 10.1.6, and thus free of rank one by Proposition 10.2.6. In other words, the ideal $\mathfrak{q}$ of $A[x^{-1}]$ is principal. It follows from Lemma 10.3.4 that the ring $A[x^{-1}]$ is factorial. The ring A/xA is regular by Lemma 3.2.4, hence an integral domain by Proposition 3.2.6. It follows xA is a prime ideal of A, and we conclude that A is factorial using Lemma 10.3.7. $\square$

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