

# Commutative Algebra

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These notes, taken by Markus Himmel, will at times differ significantly from what was lectured. In particular, all errors are almost certainly my own.

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## CHAPTER 0

# Introduction

REMARK 0.0. Commutative algebra is the study of commutative rings developed from

- (1) algebraic geometry and
- (2) algebraic number theory

In (1) focus is on  $k[X_1, \dots, X_n]$ , the polynomial ring over the field  $k$ . In (2) focus is on  $\mathbb{Z}$ , the ring of rational integers. Modern development of (1) by Grothendieck encompasses much of (2).

Going back further, Hilbert wrote a series of papers on polynomial invariant theory, 1888-1893.

EXAMPLE 0.1. Denote by  $\Sigma_n$  the symmetric group on  $\{1, \dots, n\}$ .  $\Sigma_n$  acts on  $k[X_1, \dots, X_n]$  by permuting variables: given  $\sigma \in \Sigma_n$ ,  $f \in k[X_1, \dots, X_n]$ , we set

$$(\sigma f)(X_1, \dots, X_n) := f(X_{\sigma^{-1}(1)}, \dots, X_{\sigma^{-1}(n)}).$$

The action of  $\Sigma_n$  is via ring automorphisms so it makes sense to define the *ring of invariants*

$$S := \{f \in k[X_1, \dots, X_n] \mid \forall \sigma \in \Sigma_n: \sigma f = f\}.$$

$S$  is a ring, called the *ring of symmetric polynomials*. Consider the following elementary symmetric functions:

$$\begin{aligned} e_1(X_1, \dots, X_n) &= X_1 + \dots + X_n, \\ e_2(X_1, \dots, X_n) &= \sum_{i < j} X_i X_j, \\ &\vdots \\ e_n(X_1, \dots, X_n) &= X_1 \cdots X_n. \end{aligned}$$

It turns out that  $S$  is generated as a ring by these  $e_i$  and the canonical map  $k[Y_1, \dots, Y_n] \rightarrow S$  given by  $Y_i \mapsto e_i$  is an isomorphism of rings.

Hilbert showed that  $S$  is finitely generated for many other groups. Among the way he proved a few very deep results.

- the basis theorem,
- the Nullstellensatz,
- the polynomial nature of the Hilbert function (and beginnings of dimension theory),
- the syzygy theorem (and beginnings of the homological theory of polynomial rings).

REMARK 0.2. Emmy Noether (1921) extracted the key property that made the basis theorem work: we call a ring *noetherian* if every ideal is finitely generated. There are many properties that are equivalent to this.

THEOREM 0.3. Hilbert's basis theorem states that if  $R$  is a commutative Noetherian ring, then so is  $R[X]$ .

COROLLARY 0.4. In particular, if  $k$  is a field, then  $k[X_1, \dots, X_n]$  is noetherian.

Noether developed a theory of ideals for noetherian rings, for example the existence of a primary decomposition which generalises the factorisation into primes known from number theory.

### Links between commutative algebra and algebraic geometry

REMARK. Recall the fundamental theorem of algebra: a polynomial  $f \in \mathbb{C}[X]$  is determined up to scalar multiples by its zeros up to multiplicity.

Given  $f \in \mathbb{C}[X_1, \dots, X_n]$  we have a polynomial function  $\mathbb{C}^n \rightarrow \mathbb{C}$  given by  $(a_1, \dots, a_n) \mapsto f(a_1, \dots, a_n)$ .

Different polynomials yield different functions, so  $\mathbb{C}[X_1, \dots, X_n]$  can be viewed as the ring of polynomial functions on complex affine  $n$ -space.

Given  $I \subseteq \mathbb{C}[X_1, \dots, X_n]$ , define the set of common zeros

$$Z(I) = \{(a_1, \dots, a_n) \in \mathbb{C}^n \mid \forall f \in I: f(a_1, \dots, a_n) = 0\},$$

called an (affine) algebraic set, which is a subset of  $\mathbb{C}^n$ .

REMARK. (1) One can replace  $I$  by the ideal generated by  $I$  and get the same algebraic set. Replacing an ideal by a generating set of the ideal leaves the algebraic set unchanged. Hilbert's basis theorem asserts that any algebraic set is the set of common zeros of a finite set of polynomials.

(2)

$$\bigcap_j Z(I_j) = Z\left(\bigcup_j I_j\right),$$

$$\bigcup_{j=1}^n Z(I_j) = Z\left(\prod_{j=1}^n I_j\right)$$

for ideals  $I_j$ . Define a topology of  $\mathbb{C}^n$  with closed sets being the algebraic sets. This is the Zariski topology; it is coarser than the normal topology on  $\mathbb{C}^n$ .

(3) For  $S \subseteq \mathbb{C}^n$  define

$$I(S) := \{f \in \mathbb{C}[X_1, \dots, X_n] \mid \forall (a_1, \dots, a_n) \in S: f(a_1, \dots, a_n) = 0\}.$$

This is an ideal of  $\mathbb{C}[X_1, \dots, X_n]$  and it is radical, i.e., if  $f^r \in I(S)$  for some  $r \geq 1$ , then  $f \in I(S)$ .

The Nullstellensatz is a family of results asserting that the correspondence

$$I \mapsto Z(I)$$

$$I(S) \leftarrow S$$

gives a bijection between the radical ideals of  $\mathbb{C}[X_1, \dots, X_n]$  and the algebraic subsets of  $\mathbb{C}^n$ . In particular, the maximal ideals of  $\mathbb{C}[X_1, \dots, X_n]$  correspond to points in  $\mathbb{C}^n$ .

### Dimension

REMARK. A large section of the course treats dimension of rings:

- the maximal length of chains of prime ideals;
- in geometric context in terms of growth rates (uses Hilbert function);
- the transcendence degree of the field of fractions (of an integral domain).

Over commutative rings these all give the same answer. A fourth way uses homological algebra and gives the same answer at least for nice noetherian rings.

Most of the theory dates between 1920 and 1950.

Rings of dimension 0 are called artinian rings. In dimension 1, special things happen which are important in number theory; this is crucial in the study of algebraic curves.





## CHAPTER 1

### Noetherian Rings

REMARK. Throughout the lecture,  $R$  is a commutative unital ring.

LEMMA 1.1. Let  $M$  be a (left)  $R$ -module. The following are equivalent.

- (i) all submodules of  $M$  (including  $M$  itself) are finitely generated,
- (ii) the ascending chain condition (ACC) holds: there are no strictly increasing infinite chains of submodules.
- (iii) maximum condition in submodules holds: any nonempty set  $\mathcal{S}$  of submodules of  $M$  has a maximal element  $L$ , i.e., if  $L' \in \mathcal{S}$  and  $L \subseteq L'$ , then  $L = L'$ .

PROOF. If all submodules of  $M$  are finitely generated and  $N_1 \subseteq N_2 \subseteq \dots$  is an increasing chain of submodules of  $M$ , define  $N := \bigcup_{i=1}^{\infty} N_i$ . This is a submodule of  $M$ , so it is finitely generated with generators  $m_1, \dots, m_k$ . Each  $m_i$  lies in some  $N_{n_i}$ . If  $n$  is the maximum of all  $n_i$ , we have  $N_n = N$  and the chain is stationary.

If the ACC holds and  $\mathcal{S}$  is nonempty, let  $M_0 := \{0\}$ . Proceed inductively. If  $M_i$  is maximal, we are done. Otherwise, there is some  $M_{i+1}$  such that  $M_i \subsetneq M_{i+1}$ . By the ACC, this process must terminate after a finite number of steps.

If the maximum condition holds and  $N$  is any submodule of  $M$ , define  $\mathcal{S}$  to be the collection of finitely generated submodules of  $N$ .  $\mathcal{S}$  is nonempty as it contains the zero module. Let  $L$  be a maximal member of  $\mathcal{S}$ . Let  $x \in N$ . Then  $L + Rx$  is finitely generated and  $L \subseteq L + Rx$ , hence,  $x \in L$  and therefore  $N = L$ .  $\square$

DEFINITION 1.2. An  $R$ -module is called noetherian if all of its submodules are finitely generated.

LEMMA 1.3. Let  $N$  be a submodule of  $M$ . Then  $M$  is noetherian if and only if  $N$  and  $M/N$  are noetherian.

PROOF. If  $M$  is noetherian, then in particular all submodules of  $N$  are finitely generated. Furthermore, all submodules of  $M/N$  are of the form  $Q/N$ , where  $Q$  is submodule of  $M$  containing  $N$ .  $Q$  is finitely generated, say by  $x_1, \dots, x_r$ . Then  $Q/N$  is generated by  $x_1 + N, \dots, x_r + N$ .

Conversely, if both  $N$  and  $M/N$  are noetherian, and  $L_1 \subseteq L_2 \subseteq \dots$  is an increasing chain of submodules of  $M$ , define  $Q_i := L_i + N$  and  $N_i := L_i \cap N$ . Then  $Q_i/N$  and  $N_i$  are chains of submodules of  $M/N$  and  $N$ , respectively, so they terminate and we find  $r$  such that  $\forall i \geq r: Q_i/N = Q_r/N$  and  $s$  such that  $\forall i \geq s: N_i = N_s$ . Define  $k := \max\{r, s\}$ .

We will show that  $\forall i \geq k: L_i = L_k$ . Indeed, let  $\ell \in L_i$ . Then  $\ell + N \in Q_i/N = Q_k/N = (L_k + N)/N$ , so there are  $\tilde{\ell} \in N, \ell' \in L_k, \hat{\ell} \in N$  such that  $\ell - \tilde{\ell} = \ell' + \hat{\ell}$ . Rearranging, we find that  $\ell - \ell' = \tilde{\ell} + \hat{\ell} \in N$ , and since  $L_k \subseteq L_i$  we conclude that  $\ell - \ell' \in N \cap L_i = N \cap L_k$ . Therefore,  $\ell = (\ell - \ell') + \ell' \in L_k$  and we are done.  $\square$

ALTERNATIVE PROOF. It suffices to show that if

$$0 \longrightarrow A \xrightarrow{f} B \xrightarrow{g} C \longrightarrow 0$$

is a short exact sequence of  $R$ -modules, then  $B$  is noetherian if and only if both  $A$  and  $C$  are noetherian.

If  $B$  is noetherian and  $N$  is a submodule of  $C$ , then  $g^{-1}(N)$  is a submodule of  $B$ , thus finitely generated, say by  $b_1, \dots, b_n$ . If  $c \in N$ , then

$$c = f\left(\sum_{i=1}^n r_i b_i\right) = \sum_{i=1}^n r_i f(b_i),$$

so  $N$  is finitely generated. If  $N$  is a submodule of  $A$ , then it is isomorphic to a submodule of  $B$ , which is finitely generated, hence  $N$  is also finitely generated.

Assume that  $A$  and  $C$  are finitely generated and  $N$  is a submodule of  $B$ . Then  $g(N)$  is finitely generated, say by  $c_1, \dots, c_n$ . Additionally,  $f^{-1}(N)$  is finitely generated, say by  $a_1, \dots, a_m$ . Pick preimages  $b_1, \dots, b_n$  such that  $g(b_i) = c_i$ . Now let  $x \in N$ . Then  $g(x) = \sum_{i=1}^n r_i c_i$  and therefore  $x - \sum_{i=1}^n r_i b_i \in \ker g = \operatorname{im} f$ . Thus

$$x - \sum_{i=1}^n r_i b_i = f\left(\sum_{i=1}^m r'_i a_i\right).$$

Rearranging gives

$$x = \sum_{i=1}^m r'_i f(a_i) + \sum_{i=1}^n r_i b_i$$

and we conclude that  $N = \langle b_1, \dots, b_n, f(a_1), \dots, f(a_m) \rangle$  as required.  $\square$

LEMMA 1.4. Let  $M, N, M_1, \dots$  be  $R$ -modules.

- (i)  $M \oplus N$  is noetherian if and only if both  $M$  and  $N$  are.
- (ii)  $M_1 \oplus \dots \oplus M_n$  is noetherian if and only if all  $M_i$  are.
- (iii) If  $M$  is noetherian then every homomorphic image is noetherian.
- (iv) If  $M$  can be represented as the sum  $M_1 + \dots + M_n$ , then  $M$  is noetherian if and only if each  $M_i$  is.

PROOF.

- (i) Apply the previous lemma to the split exact sequence

$$0 \longrightarrow N \xrightarrow{\iota} M \oplus N \xrightarrow{\pi} M \longrightarrow 0.$$

- (ii) Induction.
- (iii) If  $\theta: M \rightarrow N$ , apply the previous lemma to the short exact sequence

$$0 \longrightarrow \ker \theta \longrightarrow M \xrightarrow{\theta} \operatorname{im} \theta \longrightarrow 0.$$

- (iv) If  $M$  is noetherian, then so is  $M_i$  as a submodule of  $M$ . If all  $M_i$  are noetherian, then so is  $M_1 \oplus \dots \oplus M_n$ , and since the map

$$\begin{aligned} M_1 \oplus \dots \oplus M_n &\rightarrow M_1 + \dots + M_n, \\ (m_1, \dots, m_n) &\mapsto m_1 + \dots + m_n \end{aligned}$$

is surjective,  $M_1 + \dots + M_n$  is noetherian.  $\square$

DEFINITION 1.5. A ring  $R$  is called noetherian if it is noetherian as a module over itself.

LEMMA 1.6. If  $R$  is a noetherian ring and  $M$  is a finitely generated  $R$ -module. Then  $M$  is noetherian.

PROOF. Assume  $M$  is generated by  $m_1, \dots, m_n$ . Then  $R^n \cong R^{\oplus n}$  is noetherian and the map  $R^n \rightarrow M$  given by  $e_i \mapsto m_i$  is surjective, so  $M$  is noetherian.  $\square$

THEOREM 1.7. If  $R$  is a noetherian ring, then  $R[X]$  is also noetherian.

PROOF. We will show that every ideal (i.e., submodule) of  $R[X]$  is finitely generated. Let  $I$  be an ideal and let  $I_n := \{f \in I \mid \deg f \leq n\}$ .  $0 \in I_n$  and  $I_0 \subseteq I_1 \subseteq \dots$  form an ascending chain.

Define  $R_n$  to be the set of coefficients of  $X^n$  appearing in elements of  $I_n$ .

If  $a, b \in R_n$ , then  $a + b \in R_n$  and  $ra \in R_n$  for any  $r \in R$ . Therefore,  $R_n$  is an ideal of  $R$ .

Furthermore, if  $a \in R_n$ , then  $a \in R_{n+1}$  by multiplying the corresponding polynomial by  $X$ .

Since  $R$  is noetherian, the chain  $R_0 \subseteq R_1 \subseteq \dots$  terminates, so we have  $N$  such that  $\forall n \geq N: R_n = R_N$ . Each of  $R_0, \dots, R_N$  is a finitely generated ideal of  $R$ , say  $R_j$  is generated by  $a_{j1}, \dots, a_{jk_j}$ . There are polynomials  $f_{j1}, \dots, f_{jk_j}$  such that  $\deg f_{ji} = j$  and leading coefficient of  $f_{ji}$  is  $a_{ji}$ .

We will show that the finite set  $\{f_{jk} \mid 0 \leq j \leq N, 1 \leq k \leq k_j\}$  generates  $I$ .

We will use induction on  $\deg f$ , where  $f \in I$ . If  $\deg f = 0$ , then  $f = a$  for some  $a \in R$ . By definition of  $R_0$ ,  $a \in R_0$ , and  $a$  is in the ideal generated by the  $f_{0i}$ .

Assume next that  $0 < \deg f \leq N$  and that the claim is true for smaller degrees. Let  $a$  be the leading coefficient of  $f$ .  $a \in R_n$ , so we may write

$$a = \sum_j r_{nj} a_{nj}.$$

Then

$$f - \sum_j r_{nj} f_{nj}$$

is in  $I$  and of smaller degree, so is expressible as a linear combination of the  $f_{ij}$ , so  $f$  is expressible as a linear combination as well.

Finally, assume that  $\deg f > N$  and that the claim is true for smaller degrees. If  $a$  is the leading coefficient of  $f$ , then  $a \in R_n = R_N$ , so we may write

$$a = \sum_j r_{Nj} a_{Nj}.$$

Then

$$f - X^{n-N} \sum_j r_{Nj} f_{Nj}$$

is in  $I$  and of smaller degree, so is expressible as a linear combination of the  $f_{ij}$ , so  $f$  is expressible as a linear combination as well.  $\square$

REMARK. In practice one uses Gröbner bases for ideals, which are special generating sets that admit efficient algorithms.

EXAMPLE. • Fields are noetherian.

- PIDs are noetherian.
- Let  $p$  be a prime number.  $\{\frac{m}{n} \mid m, n \in \mathbb{Z}, p \nmid n\}$  is an example of a localization of  $\mathbb{Z}$  (at  $p$ ). All localizations of noetherian rings are noetherian.
- $k[X_1, X_2, \dots]$  is not noetherian, as there is an infinite chain  $(X_1) \subsetneq (X_1, X_2) \subsetneq \dots$ .
- $k[X_1, \dots, X_n]$  is noetherian, by Hilbert's basis theorem and induction.
- $\mathbb{Z}[X_1, \dots, X_n]$  is noetherian: every finitely generated commutative ring is noetherian, since if  $R$  is generated by  $r_1, \dots, r_n$ , we have a surjective map  $\mathbb{Z}[X_1, \dots, X_n] \rightarrow R$  given by  $X_i \mapsto r_i$ .
- Group algebras of free abelian groups of finite rank: if  $A$  is an abelian group, the group algebra of  $A$  is the free  $\mathbb{Z}$ -module with basis  $A$ . It is an  $A$ -algebra with the multiplication defined as the  $\mathbb{Z}$ -bilinear continuation of  $(a, b) \mapsto ab$ . If  $A$  is generated by  $g_1, \dots, g_n$ , then  $\mathbb{Z}A$  is generated as a ring by  $g_1, g_1^{-1}, \dots, g_n, g_n^{-1}$ .

- The ring of formal power series  $k[[X]]$  is noetherian if  $k$  is noetherian, see below.

Here are some non-commutative rings which are left and right noetherian:

- The enveloping algebra of a finite dimensional Lie algebra.
- The Iwasawa algebras of compact  $p$ -adic groups.

**THEOREM 1.8.** If  $R$  is a noetherian ring, then the ring  $R[[X]]$  of formal power series over  $R$  is noetherian.

**PROOF 1.** Adapt the proof of Hilbert's basis theorem, but use trailing coefficients rather than leading coefficients. See the first exercise sheet.  $\square$

**THEOREM 1.9 (Cohen's theorem).** If every prime ideal in a ring  $R$  is finitely generated, then  $R$  is noetherian.

**PROOF.** Assume that  $R$  is not noetherian. Let  $\mathcal{S}$  be the collection of non-finitely generated ideals of  $R$ .  $\mathcal{S}$  is nonempty by assumption and partially ordered by inclusion. Furthermore, every chain of ideals in  $\mathcal{S}$  has an upper bound (indeed, the union of an increasing chain of ideals in  $\mathcal{S}$  is an ideal and not finitely generated, since otherwise all generators would lie in some member of the chain, which would then be finitely generated), so by Zorn's lemma there is a maximal member  $I \in \mathcal{S}$ .  $I$  has the property that it is not finitely generated, but every ideal  $J$  such that  $I \subsetneq J$  is finitely generated.

We will now show that  $I$  is a prime ideal. Suppose  $a$  and  $b$  are such that  $ab \in I$ ,  $a \notin I$ ,  $b \notin I$ . Since  $I$  is maximally non-finitely-generated,  $I + Ra$  is finitely generated, say by  $i_1 + r_1a, \dots, i_n + r_na$ . Define

$$J := \{s \in R \mid sa \in I\}.$$

$J$  is an ideal, and it satisfies  $I \subsetneq I + Ra \subseteq J$  (here we use that  $ab \in I$ ). Again by maximality of  $I$ ,  $J$  is finitely generated. Therefore, if we can show that  $I = Ri_1 + \dots + Ri_n + Ja$ , then  $I$  is finitely generated, a contradiction.

The inclusion " $\supseteq$ " follows by definition of  $J$ , so let  $t \in I \subseteq I + Ra$ , so

$$t = u_1(i_1 + r_1a) + \dots + u_n(i_n + r_na)$$

for suitable  $u_i \in R$ . We may rewrite this as

$$t = u_1i_1 + \dots + u_ni_n + (u_1r_1 + \dots + u_nr_n)a.$$

Since the whole right hand side is in  $I$  and everything but the last summand is also in  $I$ , the last summand is in  $I$ , so  $u_1r_1 + \dots + u_nr_n \in J$  by definition of  $J$ , so indeed  $t \in Ri_1 + \dots + Ri_n + Ja$  and we are done.  $\square$

**LEMMA 1.10.** Let  $p$  be a prime ideal of  $R[[X]]$  and  $\theta: R[[X]] \rightarrow R$  given by  $X \mapsto 0$ . The  $p$  is a finitely generated ideal of  $R[[X]]$  if and only if  $\theta(p)$  is a finitely generated ideal of  $R$ .

**PROOF.** We already know that images of finitely generated ideals are finitely generated.

Conversely, suppose that  $\theta(p) = Ra_1 + \dots + Ra_n$ .

If  $X \in p$ , then  $p$  is generated by  $a_1, \dots, a_n, X$ : given any  $f \in p$ , we can find  $g$  such that  $f - Xg \in R$  and so indeed  $a_i \in p$  (!) and  $f \in Ra_1 + \dots + Ra_n + X$ .

On the other hand, if  $X \notin p$ , let  $f_1, \dots, f_n \in p$  have constant terms  $a_1, \dots, a_n$  (these exist by definition of  $\theta$ ). We will show that  $p$  is generated by  $f_1, \dots, f_n$ . Let  $g_0 \in p$  and let  $b = \sum_{i=1}^n b_i a_i$  be the constant term of  $g$ , so there is  $g_1$  such that  $g_0 - \sum_{i=1}^n r_{0,i} f_i = g_1 X$ . We have  $g_1 X \in p$ , but since  $p$  is prime and  $X \notin p$ , we have  $g_1 \in p$ . Continuing inductively, we find  $r_{j,i} \in R$  and  $g_{j+1} \in p$  such that  $g_j - \sum_{i=1}^n r_{j,i} f_i = g_{j+1} X$ .

Define  $h_j := \sum_{i=0}^{\infty} r_{i,j} X^i$ . We can calculate

$$\begin{aligned}
 \sum_{i=1}^n h_i f_i &= \sum_{i=1}^n \left( \sum_{j=0}^{\infty} r_{j,i} X^j \right) f_i \\
 &= \sum_{i=1}^n \sum_{j=0}^{\infty} r_{j,i} f_i X^j \\
 &= \sum_{j=0}^{\infty} \sum_{i=1}^n r_{j,i} f_i X^j \\
 &= \sum_{j=0}^{\infty} X^j \sum_{i=1}^n r_{j,i} f_i \\
 &= \sum_{j=0}^{\infty} X^j (g_j - g_{j+1} X) \\
 &= g_0,
 \end{aligned}$$

so  $g_0$  is in the span of  $f_1, \dots, f_n$  as required.  $\square$

LEMMA 1.11. The set  $N(R)$  of all nilpotent elements of  $R$  is an ideal and  $R/N(R)$  has no nonzero nilpotent elements.

PROOF. If  $x \in N(R)$ , then there is  $m \in \mathbb{N}$  such that  $x^m = 0$ , which implies  $(rx)^m = 0$ , so  $rx \in N(R)$ . If  $x, y \in N(R)$ , there are  $n, m \in \mathbb{N}$ ,  $x^n = y^m = 0$ . Then  $(x+y)^{m+n-1}$  is a linear combination of terms  $\lambda x^s y^t$  with  $s+t = m+n-1$ . In particular,  $s \geq n \vee t \leq m$ , and so  $(x+y)^{m+n-1} = 0$  and  $x+y \in N(R)$ .

Furthermore, if  $s \in R/N(R)$ , then  $s = x + N(R)$ . If  $s$  is nilpotent, i.e.,  $s^n = 0$ , then  $0 = s^n = (x + N(R))^n = x^n + N(R)$ , i.e.,  $x^n \in N(R)$ . That means that for some  $m$  we have  $x^{nm} = 0$ , so  $x \in N(R)$ , so  $s = 0$ .  $\square$

DEFINITION 1.12. The ideal  $N(R)$  is called the nilradical of  $R$ .

THEOREM 1.13. The nilradical  $N(R)$  is the intersection of all prime ideals of  $R$ .

PROOF. Define  $I := \bigcap_{p \text{ prime}} p$ .

If  $x \in N(R)$ , i.e.,  $x^n = 0$ , and  $p$  is prime, then  $x^n = 0 \in p$ , so  $x \in p$ . Hence,  $N(R) \subseteq I$ .

To show that  $I \subseteq N(R)$ , we will show that  $x \notin N(R)$  implies  $x \notin I$ . Indeed, if  $x \notin N(R)$ , define  $\mathcal{S}$  to be the collection of all ideals  $J$  that are disjoint from the set  $\{x^n \mid n > 0\}$ . We have  $(0) \in \mathcal{S}$ , so  $\mathcal{S}$  is nonempty, and as usual, upper bounds of chains exist, so Zorn's lemma gives us a maximal member  $J_1$  of  $\mathcal{S}$ . We have  $x \notin J_1$ , so if we can show that  $J_1$  is prime, we are done.

Suppose  $yz \in J_1$ ,  $y, z \notin J_1$ . Then  $J_1 + Ry$  and  $J_1 + Rz$  are strictly larger than  $J_1$ , so we find  $n, m$  such that  $x^n \in J_1 + Ry$ ,  $x^m \in J_1 + Rz$ . This implies  $x^{n+m} \in J_1 + Ryz$  (write  $x^n = j_1 + r_1 y$ ,  $x^m = j_2 + r_2 z$ ), but then  $x^{n+m} \in J_1 + Ryz = J_1$ , which is a contradiction because  $J_1 \in \mathcal{S}$ .  $\square$

DEFINITION 1.14. The radical  $\sqrt{I}$  of an ideal  $I$  is defined as

$$\sqrt{I} := \{r \in R \mid \exists n \in \mathbb{N}: r^n \in I\}$$

We call an ideal radical if  $I = \sqrt{I}$ .

REMARK. It is unsubstantial whether 0 is allowed as an exponent or not: if  $r^0 = 1 \in I$ , then  $I = R$ , so  $r^1 \in I$ .

We have an equality  $\sqrt{I} + I = N(R/I)$  of ideals of  $R/I$ .

$\sqrt{I}$  is the intersection of all prime ideals that contain  $I$ :  $\sqrt{I}/I$  is the intersection of all prime ideals of  $R/I$ , then use the correspondence between prime ideals of  $R/I$  and prime ideals of  $R$  that contain  $I$ .

DEFINITION 1.15. The Jacobson radical  $J(R)$  of  $R$  is the intersection of all maximal ideals of  $R$ .

REMARK. We have  $N(R) \subseteq J(R)$ .

THEOREM 1.16 (Nakayama's lemma). If  $M$  is a finitely generated  $R$ -module such that  $J(R)M = M$ , then  $M = 0$ .

PROOF. Suppose that  $M \neq 0$ . Define  $\mathcal{S}$  to be the collection of proper submodules of  $M$ . Then  $(0) \in \mathcal{S}$ , and if we have an ascending chain of proper submodules, then the union is also a proper submodule (otherwise all generators would already lie in one of the proper submodules). So by Zorn, there is a maximal proper submodule  $M_1$ .

The quotient  $M/M_1$  is a simple module, as we can pullback any submodule of  $M/M_1$  to a submodule of  $M$  lying between  $M_1$  and  $M$ . If  $0 \neq m \in M/M_1$ , the submodule generated by  $m$  is all of  $M/M_1$ .

The homomorphism  $R \rightarrow M/M_1$  of  $R$ -modules given by  $r \mapsto rm + M_1$  is surjective. If  $I$  is the kernel of this map, then there is an isomorphism of  $R$ -modules  $M/M_1 \cong R/I$ , but since the former is a simple  $R$ -module, so is the latter. Now if  $J$  is an ideal of  $R/I$ , then it is also an  $R$ -submodule of  $R/I$ , which shows that  $R/I$  has only two ideals, so it is a field. This means that  $I$  is a maximal ideal.

Let  $n \in M$ . Since  $m$  generates  $M/M_1$ , we can write  $n = rm + m'$  for some  $r \in R$ ,  $m' \in M_1$ . If  $i \in I$ , then  $in = rim + im' \in M'$ , since  $im \in M'$  by definition of  $I$ . This means that  $IM \subseteq M_1$ .

Since  $I$  is maximal, we have  $J(R) \subseteq I$ , and so

$$J(R)M \subseteq IM \subseteq M_1 \subsetneq M,$$

contrary to our assumption.  $\square$

REMARK. In a commutative ring,  $N(R) \leq J(R)$ . They are in general not equal, take for example  $R_p = \{\frac{m}{n} \in \mathbb{Q} \mid p \nmid n\}$  for some prime  $p$ . This has a unique maximal ideal  $p = \{\frac{m}{n} \in \mathbb{Q} \mid p \mid n, p \nmid m\}$ , but it is an integral domain, so  $N(R) = (0)$  while  $J(R) = p$ .

On the other hand, for  $R = k[X_1, \dots, X_n]/I$ , where  $k$  is algebraically closed and  $I$  is any ideal, then we do indeed have  $N(R) = J(R)$ . This is Hilbert's Nullstellensatz.

EXAMPLE. A commutative ring is called artinian if it does not contain an infinite, strictly decreasing chain of ideals (equivalently, if every nonempty set of ideals has a minimal member). An  $R$ -module is called artinian if it satisfies that analogous property for submodules.

Examples of artinian rings:  $\mathbb{Z}/p\mathbb{Z}$ ,  $k[X]/(f)$ , where  $k$  is a field and  $f \neq 0$ .  $k[X]$  is not artinian: we have the chain  $(X) \supseteq (X^2) \supseteq \dots$ .

Recall that an ideal  $I$  is prime if and only iff  $R/I$  is an integral domain if and only if  $I_1, I_2 \subseteq I$  implies that  $I_1 \subseteq I \vee I_2 \subseteq I$ .

We will now show that if  $R$  is artinian, then prime ideals are maximal, which in particular means that  $N(R) = J(R)$ . Indeed, let  $p$  be a prime ideal and  $x \in R$  such that  $x \notin p$ . By the descending chain condition,  $(x) \supseteq (x^2) \supseteq \dots$  becomes stationary, so there is a number  $n$  and some  $y \in R$  such that  $x^n = yx^{n+1}$ . Rearranging, we have  $x^n(1 - xy) = 0 \in p$ . Since  $p$  is prime and  $x \notin p$ ,  $x^n \notin p$ , so we must have  $1 - xy \in p$ , so  $x + p$  has the inverse  $y + p$  in  $R/p$ . Since  $x$  was arbitrary,  $R/p$  is a field, so  $p$  is maximal.

**THEOREM 1.17** (Artin-Tate lemma). Let  $R \subseteq S \subseteq T$  be commutative rings. Suppose that  $R$  is noetherian,  $T$  is finitely generated as an  $R$ -algebra and  $T$  is a finitely generated  $S$ -module. Then  $S$  is a finitely generated  $R$ -algebra.

**PROOF.** Suppose  $T$  is generated as an  $R$ -algebra by  $t_1 = 1, \dots, t_n \in T$ . By assumption, we have  $x_1 = 1, \dots, x_m \in T$  such that  $T = Sx_1 + \dots + Sx_m$ . Therefore, if  $1 \leq i \leq n$ , we may write

$$(1) \quad t_i = \sum_{j=1}^m s_{ij}x_j$$

for some  $s_{ij} \in S$ . Furthermore,  $1 \leq i, j \leq m$ , we find  $s_{ijk} \in S$  satisfying

$$(2) \quad x_i x_j = \sum_{k=1}^m s_{ijk} x_k.$$

Define  $S_0$  as the  $R$ -subalgebra of  $S$  generated by the  $s_{ij}$  and the  $s_{ijk}$ . We have  $R \subseteq S_0 \subseteq S$ . If  $t \in T$ , we may write  $t$  as a polynomial in the  $t_i$ . Since  $t_1 = 1$ , we may assume that this polynomial does not have a constant term. Substituting (1) and then repeatedly substituting (2), we find that  $T$  is finitely generated by the  $x_i$  as a  $S_0$  module.

Next, we note that  $S_0$  is a noetherian ring. Since  $S_0$  is finitely generated as an  $R$ -algebra, we have a surjective homomorphism of rings  $\varphi: R[X_1, \dots, X_k] \rightarrow S_0$ . Then  $S_0$  is isomorphic to a quotient of  $R[X_1, \dots, X_k]$ , which is noetherian by the Basissatz. Quotients of noetherian rings are noetherian rings: indeed,  $R[X_1, \dots, X_n]/\ker \varphi$  is a noetherian  $R[X_1, \dots, X_n]$ -module, which implies that it is a  $R[X_1, \dots, X_n]/\ker \varphi$ -module.

As a finitely generated module over a noetherian ring, we find that  $T$  is a noetherian  $S_0$ -module. Since  $S$  is an  $S_0$ -submodule of  $T$ , we find that  $S$  is finitely generated as a  $S_0$ -module.

This allows us to write every element of  $S$  as a polynomial in the generators of  $S$  as an  $S_0$ -module and the  $s_{ij}$  and  $s_{ijk}$ , so  $S$  is a finitely generated  $R$ -algebra.  $\square$

**LEMMA 1.18** (Zariski's lemma). If  $k$  is a field, and  $R$  is a finitely generated  $k$ -algebra which is a field, then  $R$  is a finite-dimensional  $k$ -vector space (i.e., a finite algebraic extension of  $k$ ).

**PROOF.** Denote the generators of  $R$  as a  $k$ -algebra by  $x_1, \dots, x_n \in R$ . Suppose that  $R$  is not a finite algebraic extension of  $k$ . Then we may reorder the  $x_i$  such that there is an  $1 \leq m \leq n$  such that  $x_1, \dots, x_m$  is a transcendence basis, i.e.,  $x_1, \dots, x_m$  are all transcendental, but  $k(x_1, \dots, x_m) \subseteq R$  is finite algebraic.

Therefore we have  $k \subseteq k(x_1, \dots, x_m) \subseteq R$ , and Artin-Tate tells us that  $k(x_1, \dots, x_m)$  is a finitely generated  $k$ -algebra, say with generators  $q_1, \dots, q_k$ , where  $q_i = f_i/g_i$  for some  $f_i, g_i \in k[x_1, \dots, x_n]$  and  $g_i \neq 0$ . This means that we can write every element  $q \in k(x_1, \dots, x_m)$  as

$$q = \frac{f}{q_1^{e_1} \cdots q_k^{e_k}}.$$

However, since  $k[x_1, \dots, x_n]$  is a UFD, we can see that

$$\frac{1}{q_1 \cdots q_k + 1}$$

is not of this form, a contradiction.  $\square$

**THEOREM 1.19** (Hilbert's Nullstellensatz (weak version)). Let  $k$  be a field,  $T$  a finitely generated  $k$ -algebra, and  $m$  a maximal ideal of  $T$ . Then  $T/m$  is a finite

algebraic extension of  $k$ . In particular, if  $k$  is algebraically closed, and  $T$  is the polynomial algebra, then maximal ideals  $m$  are of the form  $(X_1 - a_1, \dots, X_n - a_n)$ .

PROOF. Let  $m$  be a maximal ideal of  $T$ . Define  $R := T/m$ . This is a field. By Zariski's lemma,  $k \subseteq T/m$  is a finite algebraic extension. If  $k$  is algebraically closed and  $T = k[X_1, \dots, X_n]$ , then this means that the map natural map  $\Phi: k \rightarrow k[X_1, \dots, X_n] \rightarrow k[X_1, \dots, X_n]/m$  is an isomorphism. Let  $a_i := \Phi^{-1}(X_i)$ . Then we have that  $I := (X_1 - a_1, \dots, X_n - a_n) \subseteq \ker \Phi = m$ .

On the other hand the natural map  $k \rightarrow k[X_1, \dots, X_n]/I$  is injective, because the kernel is not trivial and  $k$  is a field, and it is surjective, because every polynomial in the quotient by  $I$  "reduces" to an element of  $k$ , so  $I$  is maximal, so  $I = m$  since  $m \supseteq I$  is a proper ideal.  $\square$

THEOREM 1.20. Let  $k$  be an algebraically closed field, and  $R$  a finitely generated  $k$ -algebra. Then  $N(R) = J(R)$ . Thus if  $I$  is a radical ideal of  $k[X_1, \dots, X_n]$  and  $R = k[X_1, \dots, X_n]/I$  then the intersection of the maximal ideals of  $R$  is 0.

Furthermore, any radical ideal is the intersection of the maximal ideals containing it.

### Minimal and associated primes

LEMMA 1.21. If  $R$  is a noetherian ring, then any ideal  $I$  contains a power of its radical  $\sqrt{I}$ .

For  $I = (0)$ , this means that  $N(R)$  is nilpotent.

PROOF. Since  $R$  is noetherian,  $\sqrt{I}$  is finitely generated, say by  $x_1, \dots, x_n$ . Then we find natural numbers  $m_i$  such that  $x_i^{m_i} \in I$ . If we define  $m := 1 + \sum_{i=1}^n (m_i - 1)$ , then the binomial theorem tells us that elements of the form  $x_1^{r_1} \cdots x_n^{r_n}$  with  $\sum_{i=1}^n r_i = m$  generate the ideal  $\sqrt{I}^m$ . By our choice of  $m$ , for some  $i$  we must have  $r_i \geq m_i$ , so every generator lies in  $I$ , so  $\sqrt{I}^m \subseteq I$ .  $\square$

LEMMA 1.22. If  $R$  is noetherian, then every radical ideal of  $I$  is the intersection of finitely many primes.

PROOF. Let  $\mathcal{S}$  be the set of radical ideals that are not the intersection of finitely many prime ideals. Suppose that  $\mathcal{S}$  is nonempty. Since  $R$  is noetherian,  $\mathcal{S}$  has a maximal member  $I$ . We will show that  $I$  is prime (a contradiction, since  $I$  is not the intersection of finitely many prime ideals).

Indeed, if  $I$  is not prime, then there are ideals  $J'_1, J'_2 \not\subseteq I$  such that  $J'_1 J'_2 \subseteq I$  (indeed we can find principal ideals that work). Defining  $J_1 := J'_1 + I$ ,  $J_2 := J'_2 + I$ , we find that  $I \subsetneq J_i$ , but  $J_1 J_2 \subseteq I$ . Since  $I$  was maximal, we can write

$$\sqrt{J_1} = Q_1 \cap \cdots \cap Q_n, \quad \sqrt{J_2} = Q'_1 \cap \cdots \cap Q'_m,$$

where all  $Q_i, Q'_i$  are prime.

Now define

$$J := \sqrt{J_1} \cap \sqrt{J_2} = Q_1 \cap \cdots \cap Q_n \cap Q'_1 \cap \cdots \cap Q'_m.$$

From the preceding lemma, we obtain  $n_1$  and  $n_2$  such that  $J^{n_1} \subseteq J_1^{n_1} \subseteq J_1$  and  $J^{n_2} \subseteq J_2^{n_2} \subseteq J_2$ . Then we have  $J^{n_1+n_2} \subseteq J_1 J_2 \subseteq I$ . Since  $I \in \mathcal{S}$ ,  $I$  is a radical ideal, which means that  $J \subseteq I$ .

On the other hand,  $I \subseteq J_i \subseteq \sqrt{J_i}$ , so  $I \subseteq J$ .

This means that  $I = J$  is the intersection of finitely many prime ideals, which is a contradiction to  $I \in \mathcal{S}$ .  $\square$

REMARK. If we have written  $\sqrt{I} = p_1 \cap \cdots \cap p_m$  with  $p_i$  prime (as we have just seen is always possible), then we can remove any  $p_i$  from the list if it is a superset



of one of the others. Therefore, we may assume that  $p_i \not\subseteq p_j$  for all pairs  $i \neq j$ . Now if  $p$  is another prime ideal and  $\sqrt{I} \subseteq p$ , then  $p_1 \cdots p_m \subseteq \bigcap p_i = \sqrt{I} \subseteq p$ , some since  $p$  is prime, one of the  $p_i$  must be fully contained in  $p$ .

**DEFINITION 1.23.** The minimal primes  $p$  over an ideal  $I$  of a noetherian ring are those prime ideals such that if  $p'$  is a prime ideal and  $I \subseteq p' \subseteq p$ , then  $p = p'$ .

If  $I$  is radical and we choose  $p_i$  as in the previous remark, then  $p_i$  is a minimal prime: indeed, if  $p'$  is prime such that  $I \subseteq p' \subseteq p_i$ , then by the remark some  $p_j$  satisfies  $p_j \subseteq p' \subseteq p_i$ , but due to the way we chose the  $p_i$  this means that  $i = j$  and  $p' = p_i$ .

**LEMMA 1.24.** Let  $I$  be an ideal of a noetherian ring. Then  $\sqrt{I}$  is the intersection of the minimal primes over  $I$ . Furthermore, there is a finite product of minimal primes over  $I$  that is contained in  $I$ .

**PROOF.** If  $p$  is a prime over  $I$ , then  $\sqrt{I} \subseteq p$  as  $p$  is prime. This implies that the minimal primes over  $I$  are exactly the minimal primes over  $\sqrt{I}$ , so the intersection of the minimal primes over  $I$  is the intersection of the minimal primes over  $\sqrt{I}$ , which is  $\sqrt{I}$  itself.

By a previous remark, we can find minimal primes  $p_1, \dots, p_n$  such that  $p_1 \cdots p_n \subseteq \sqrt{I}$ . Since there is some  $m$  such that  $\sqrt{I}^m \subseteq I$ , we have that  $p_1^m \cdots p_n^m \subseteq I$  as required.  $\square$

**EXAMPLE.** Recall that the Nullstellensatz gives a bijection between radical ideals  $\mathbb{C}[X_1, \dots, X_n]$  and algebraic subsets of  $\mathbb{C}^n$ .

If  $I$  is a radical ideal of  $\mathbb{C}[X_1, \dots, X_n]$ , then  $(a_1, \dots, a_n)$  is a common zero of all  $f \in I$  if and only if  $I \subseteq (X_1 - a_1, \dots, X_n - a_n)$ <sup>1</sup>. Consider the ideal

$$J := \bigcap_{(a_1, \dots, a_n) \in V(I)} (X_1 - a_1, \dots, X_n - a_n),$$

This is a radical ideal (TODO: why?). The bijection in the Nullstellensatz tells us that  $I = J$ . Therefore, we may write any radical ideal as the intersection of maximal ideals it is contained in, which are all of the form  $(X_1 - a_1, \dots, X_n - a_n)$  (as we already know).

Furthermore, Hilbert's Nullstellensatz tells us that if  $J \subseteq \mathbb{C}[X_1, \dots, X_n]$  is an ideal, then  $N(\mathbb{C}[X_1, \dots, X_n]/J) = J(\mathbb{C}[X_1, \dots, X_n]/J)$ .

**DEFINITION 1.25.** Let  $R$  be a noetherian ring and let  $M$  be a finitely generated  $R$ -module. We call a prime ideal  $p$  an associated prime of  $M$  if it is the annihilator of an element of  $M$ , i.e., there is  $m \in M$  such that  $p = \text{ann}(m) = \{r \in R \mid rm = 0\}$ .

We further define

$$\text{Ass}(M) := \{p \mid p \text{ prime}, \exists m \in M : p = \text{ann}(m)\}.$$

**EXAMPLE.** If  $p$  is a prime ideal of  $R$ , then  $\text{Ass}(R/p) = \{p\}$ . Indeed, if  $r \in R$ , then there are two cases. If  $r \in p$ , then  $\text{ann}(r+p) = \text{ann}(0) = R$ , which is not prime. Otherwise, if  $r \notin p$ , then if  $0+p = (s+p)(r+p)$ , we have  $rs \in p$ , and since  $p$  is prime and  $r \notin p$ , we have  $s \in p$ . Conversely,  $p$  is trivially contained in the annihilator, and we conclude that  $\text{ann}(r) = p$ .

**DEFINITION 1.26.** If  $M$  is an  $R$ -module, then we call a submodule  $N$  of  $M$   $p$ -primary (or just primary) if  $\text{Ass}(M/N) = \{p\}$  for a prime ideal  $p$ . Since ideals are just submodules, the definition extends to ideals.

<sup>1</sup>Indeed, if  $\{(a_1, \dots, a_n)\} \subseteq V(I)$ , then  $I = \sqrt{I} = I(V(I)) \subseteq I(\{(a_1, \dots, a_n)\}) = (X_1 - a_1, \dots, X_n - a_n)$ . Conversely, if  $I \subseteq (X_1 - a_1, \dots, X_n - a_n)$ , then  $\{(a_1, \dots, a_n)\} \subseteq V(I)$ . To see that  $I(\{(a_1, \dots, a_n)\}) = (X_1 - a_1, \dots, X_n - a_n)$ , note that " $\supseteq$ " is clear, but the latter is maximal as we have seen before.

LEMMA 1.27. If  $\text{ann}(M) := \bigcap_{m \in M} \text{ann}(m) = p$  for some prime ideal  $p$ , then we have  $p \in \text{Ass}(M)$ .

PROOF. Suppose  $M$  is generated by  $m_1, \dots, m_k$ . Define  $I_j := \text{ann}(m_j)$ . Then

$$\prod I_j \subseteq \bigcap I_j = \bigcap \text{ann}(m_j) = \text{ann}(M) = p.$$

Since  $p$  is prime, this forces  $I_j \subseteq p$ , but  $p = \text{ann}(M) \subseteq \text{ann}(m_j) = I_j$ , so  $p = I_j$ , hence  $p \in \text{Ass}(M)$ .  $\square$

LEMMA 1.28. Let  $Q$  be maximal amongst the annihilators of nonzero elements of  $M$ . Then  $Q$  is prime, hence  $Q \in \text{Ass}(M)$ .

PROOF. Let  $Q \in \text{ann}(m)$  and  $r_1 \cdot r_2 \in Q$ , but  $r_2 \notin Q$ . We will show that  $r_1 \in Q$ . Since  $r_1 r_2 \in Q$  we have  $r_1 r_2 m = 0$ . This means that  $r_1 \in \text{ann}(r_2 m)$ . Since,  $r_2 \notin Q$ , we have that  $r_2 m \neq 0$ .

We have  $Q = \text{ann}(m) \subseteq \text{ann}(r_2 m)$ , and since  $r_2 m$  is nonzero as we have just seen, by maximality of  $Q$ , we have  $Q = \text{ann}(r_2 m)$ . Hence,  $r_1 \in \text{ann}(r_2 m) = Q$  as required.  $\square$

LEMMA 1.29. Let  $M$  be a nonzero finitely generated module over a noetherian ring  $R$ . Then there is a chain

$$0 \subsetneq M_1 \subsetneq M_2 \subsetneq \dots \subsetneq M_t = M$$

of submodules with  $M_i/M_{i-1} \cong R/p_i$  for some prime ideal  $p_i$ .

PROOF. By the previous lemma we find  $0 \neq m_1 \in M$  such that  $\text{ann}(m_1)$  is a prime ideal. Set  $M_1 = Rm_1$ . Then the kernel of the map  $R \rightarrow M_1$  given by  $r \mapsto rm_1$  is precisely  $\text{ann}(m_1)$ , so  $M_1 \cong R/p_1$  (as  $R$ -modules).

Similarly, if  $M_i$  is a proper submodule of  $M$ , then we find  $m_{i+1} + M_i \in M/M_i$  such that  $\text{ann}(m_{i+1} + M_i)$  is a prime ideal. Set  $M_{i+1} := M_i + Rm_{i+1}$ . Then the map  $R \rightarrow M_{i+1}/M_i$  given by  $r \mapsto rm_{i+1} + M_i$  is surjective and has kernel  $\text{ann}(m_{i+1} + M_i)$ . Furthermore,  $m_{i+1} \notin M_i$ , since otherwise the annihilator of  $m_{i+1} + M_i$  would be all of  $R$ . Therefore,  $M_i$  is a proper submodule of  $M_{i+1}$ .

By the ascending chain condition, this process terminates.  $\square$

LEMMA 1.30. If  $N$  is a submodule of a finitely generated module  $M$  over a noetherian ring  $R$ , then  $\text{Ass}(M) \subseteq \text{Ass}(N) \cup \text{Ass}(M/N)$ .

PROOF. Let  $\text{ann}(m) \in \text{Ass}(M)$  for some  $m \in M$ . Define  $M_1 := Rm \cong R/\text{ann}(m)$ .

Let  $rm \in M_1$ . It is trivial that  $\text{ann}(m) \subseteq \text{ann}(rm)$ . Conversely, if  $s \in \text{ann}(rm)$ , then  $sr m = 0$ , but  $\text{ann}(m)$  is prime and  $rm \neq 0$ , so we must have  $s \in \text{ann}(m)$ . Hence  $\text{ann}(rm) = \text{ann}(m)$ .

Now if  $M_1 \cap N \neq 0$ , then by what we just saw there is  $rm \in M_1 \cap N$  with  $\text{ann}(rm) = \text{ann}(m)$ , so  $\text{ann}(m) \in \text{Ass}(N)$ .

On the other hand, if  $M_1 \cap N = 0$ , then  $r \in \text{ann}(m + N)$  iff  $r \cdot m \in N$  iff  $r \cdot m = 0$ , so  $\text{ann}(m) = \text{ann}(m + N) \in \text{Ass}(M/N)$ .  $\square$

LEMMA 1.31. If  $R$  is a noetherian ring and  $M$  is finitely generated, then  $\text{Ass}(M)$  is finite.

PROOF. Take a chain

$$M_0 = 0 \subsetneq M_1 \subsetneq M_2 \subsetneq \dots \subsetneq M_t = M.$$

such that  $M_{i+1}/M_i \cong R/p_i$  for  $i \geq 0$ .

We will show inductively that  $M_{i+1} = 0$  for  $i \geq 0$ . Indeed, if  $i = 0$ , then  $M_i \cong R/p_0$ , and we have previously calculated that  $\text{Ass}(R/p_0) = \{p_0\}$ .

If  $i > 0$ , then  $M_i$  is a submodule of  $M_{i+1}$ . By the previous lemma, we have  $\text{Ass}(M_{i+1}) \subseteq \text{Ass}(M_i) \cup \text{Ass}(M_{i+1}/M_i)$ . The former is finite by the inductive hypothesis, while the latter is a one-element set.  $\square$

PROPOSITION 1.32. Each minimal prime over an ideal  $I$  is an associated prime of  $R/I$ .

PROOF. By (1.24), we find minimal primes  $p_1, \dots, p_n$  and natural numbers  $s_1, \dots, s_n$  such that  $p_1^{s_1} \cdots p_n^{s_n} \subseteq I$ . Additionally, we may assume that  $i \neq j$  implies  $p_i \neq p_j$ .

Define

$$M := (p_2^{s_2} \cdots p_n^{s_n} + I)/I$$

and let  $J := \text{ann}(M)$ . Clearly, every element of  $p_1^{s_1}$  annihilates  $M$ , so  $p_1^{s_1} \subseteq J$ . Furthermore, we have

$$Jp_2^{s_2} \cdots p_n^{s_n} \subseteq I \subseteq p_1,$$

but  $p_1$  is prime and we cannot have  $p_i^{s_i} \subseteq p_1$  for  $i \neq 1$  as the  $p_i$  are minimal primes, so we must have  $J \subseteq p_1$ . In particular,  $J \neq R$ , so  $M \neq 0$ .

Invoke (1.29) to obtain a chain

$$0 \subsetneq M_1 \subsetneq M_2 \subsetneq \cdots \subsetneq M_t = M$$

of submodules with  $M_i/M_{i-1} \cong R/q_i$  for some prime ideal  $q_i$ .

Since  $p_1^{s_1}$  annihilates  $M$ , in particular it annihilates  $M_j/M_{j-1}$  for every  $j$ . So we have  $p_1^{s_1} \subseteq \text{ann}(M_j/M_{j-1}) = \text{ann}(R/q_j) = q_j$  for every  $j$ . Since  $q_j$  is prime, we conclude  $p_1 \subseteq q_j$  for every  $j$ .

On the other hand,  $\prod q_j \subseteq J$ : by induction on  $j$  assume that  $\prod_{k=1}^j q_k$  annihilates  $M_j$ . If  $x \in M_{j+1}$  and  $r \in \prod_{k=1}^j q_k$ , and  $s \in q_{j+1}$  then  $rx \in M_j$ , since  $q_{j+1}$  annihilates  $M_{j+1}/M_j$ . By the inductive hypothesis,  $rsx = 0$ , so  $\prod_{k=1}^{j+1} q_k$  annihilates  $M_{j+1}$ .

Hence  $\prod q_j \subseteq J \subseteq p_1$ , so there is some  $j$  such that  $q_j \subseteq p_1$ , but we have seen that  $p_1 \subseteq q_j$ , so there is  $j$  such that  $q_j = p_1$ . Let  $j$  be the least such  $j$ . In particular,  $\prod_{k < j} q_k \subsetneq p_1$ .

We will now show that  $p_1 \in \text{Ass}(M)$ . For this, take  $x \in M_j \setminus M_{j-1}$ . If  $j = 1$ , then  $\text{ann}(x) = p_1$  (since  $M_1 \cong R/p_1$ ), but  $x \in M \subseteq R/I$ , so  $p_1 \in \text{Ass}(R/I)$ .

On the other hand, if  $j > 1$ , choose some  $r \in (\prod_{k < j} q_k) \setminus p_1$  (this is indeed nonempty, since otherwise one of the  $q_k$  would be contained in  $p_1$ ). Note that if  $s \in p_1 = q_j$ , then  $r(sx) = 0$  (this is just the induction we did earlier). So we have  $s(rx) = 0$ , which means that we have  $p_1 \subseteq \text{ann}(rx)$ .

Note that  $\text{ann}(rx + M_{j-1}) = p_1$  since  $rx + M_{j-1} \neq 0$ , but  $M_j/M_{j-1} \cong R/q_j = R/p_1$ . Since  $r \notin p_1$ , we conclude that  $rx \notin M_{j-1}$ . Now if  $s \in \text{ann}(rx)$ , then certainly  $s \in \text{ann}(rx + M_{j-1}) = p_1$ , so  $\text{ann}(rx) \subseteq p_1$ .

Putting the last two paragraphs together, we have  $\text{ann}(rx) = p_1$ , so  $p_1 \in \text{Ass}(M) \subseteq \text{Ass}(R/I)$ .

By changing the order of the  $p_i$ , we see that  $p_j \in \text{Ass}(R/I)$  for every  $j$ , completing the proof.  $\square$

EXAMPLE 1.33. The converse of the previous theorem fails in general. For example, take  $R = k[X, Y]$ ,  $p = (X, Y) > q = (X)$  and  $I = pq = (X^2, XY)$ .

We have  $\sqrt{I} = q$ . Since this is a prime, (1.24) tells us that  $q$  is the only minimal prime over  $q$ . It is possible to show that  $\text{Ass}(R/I) = \{p, q\}$ . In particular,  $I$  is not primary, but we can write

$$I = (X^2, XY, Y^2) \cap (X),$$

where  $(X^2, XY, Y^2) = (X, Y)^2$  is  $p$ -primary and  $(X)$  is  $q$ -primary. This is an example of a primary decomposition.

DEFINITION 1.34. If  $R$  is a noetherian ring,  $M$  is a finitely generated  $R$ -module and  $N \subseteq M$  is a submodule, then a primary decomposition of  $N$  consists of submodules  $N_1, \dots, N_s$  of  $M$  containing  $N$  such that  $N_i$  is  $p_i$ -primary, where the  $p_i$  are pairwise distinct, such that  $N = \bigcup_{i=1}^n N_i$  (in particular, this means that there is an embedding  $M/N \rightarrow \bigoplus M/N_i$ ).

REMARK. This primary decomposition exists (which we will not show) and is not necessarily unique. However, Atiyah-Macdonald Chapter 4 contains two uniqueness theorems for finitely generated modules over noetherian rings:

- (1) the  $p_i$  occurring in a primary decomposition are unique and are precisely  $\text{Ass}(M/N)$ ;
- (2) the  $N_j$  belonging to  $p_j$  which are minimal elements of the set  $\{p_i\}$  are unique. The  $N_j$  belonging to the rest of the  $p_j$  (which are called embedded), are not necessarily unique.

In the previous example,  $q$  is minimal and  $p$  is embedded, Hence, the ideal  $(X)$  is unique and the decomposition shows that  $\text{Ass}(R/I) = \{p, q\}$ , which is rather tricky to prove from first principles.

## CHAPTER 2

### Localisation

REMARK. As always, all rings  $R$  are commutative with unity.

Let  $S$  be a multiplicatively closed subset of  $R$  (i.e.,  $S$  is closed under multiplication and  $1 \in S$ ). We define a relation  $\equiv$  on  $R \times S$  by saying that  $(r_1, s_1) \equiv (r_2, s_2) \iff \exists x \in S: (r_1 s_2 - r_2 s_1)x = 0$ . Reflexivity and symmetry are immediate, for transitivity, assume that

$$(r_1 s_2 - r_2 s_1)x = 0 = (r_2 s_3 - r_3 s_2)y.$$

Multiplying the left hand side with  $s_3 y$  and the right hand side with  $s_1 x$  and the subtracting the two yields the desired identity

$$(r_1 s_3 - r_3 s_1)s_2 xy = 0,$$

since  $s_2 xy \in S$ .

This shows that  $\equiv$  is an equivalence relation, and we will denote equivalence classes of  $(r_1, s_1)$  by  $\frac{r_1}{s_1}$  and the quotient by  $S^{-1}R$ . We make  $S^{-1}R$  into a ring by setting

$$\begin{aligned} \frac{r_1}{s_1} + \frac{r_2}{s_2} &:= \frac{r_1 s_2 + r_2 s_1}{s_1 s_2}, \\ \frac{r_1}{s_1} \cdot \frac{r_2}{s_2} &:= \frac{r_1 r_2}{s_1 s_2}. \end{aligned}$$

Furthermore, we have a ring homomorphism  $R \rightarrow S^{-1}R$  given by  $r \mapsto \frac{r}{1}$ .

LEMMA 2.1. Let  $\varphi: R \rightarrow T$  be a ring homomorphism with  $\varphi(s)$  a unit in  $T$  for all  $s \in S$ . Then there is a unique homomorphism of rings  $\alpha: S^{-1}R \rightarrow T$  such that  $\varphi = \alpha \circ \theta$ , i.e., the diagram

$$\begin{array}{ccc} R & \xrightarrow{\theta} & S^{-1}R \\ & \searrow \varphi & \downarrow \exists! \alpha \\ & & T \end{array}$$

is commutative.

PROOF. We will first show uniqueness. Suppose we have  $\alpha: S^{-1}R \rightarrow T$  satisfying  $\alpha \circ \theta = \varphi$ .

Then we have

$$\forall r \in R: \alpha\left(\frac{r}{1}\right) = \alpha(\theta(r)) = \varphi(r),$$

$$\forall s \in S: \alpha\left(\left(\frac{s}{1}\right)^{-1}\right) = \alpha\left(\frac{s}{1}\right)^{-1} = \alpha(\theta(s))^{-1} = \varphi(s)^{-1}.$$

Thus,  $\alpha\left(\frac{r}{s}\right) = \alpha\left(\frac{r}{1}\right)\alpha\left(\frac{1}{s}\right) = \varphi(r)\varphi(s)^{-1}$  is uniquely determined by  $\varphi$ .

For existence, we define  $\alpha\left(\frac{r}{s}\right) := \varphi(r)\varphi(s)^{-1}$ . We need to show that this is well-defined. If  $\frac{r_1}{s_1} = \frac{r_2}{s_2}$ , then we find  $x \in S$  such that  $(r_1 s_2 - r_2 s_1)x = 0$ . Applying  $\varphi$ , we find  $(\varphi(r_1)\varphi(s_2) - \varphi(r_2)\varphi(s_1))\varphi(x) = 0$ . Since  $\varphi(x)$  is a unit, we can cancel it and since the  $\varphi(s_i)$  are units, we can rewrite this two the required relation  $\varphi(r_1)\varphi(s_1)^{-1} = \varphi(r_2)\varphi(s_2)^{-1}$ .

It is also possible to check that  $\alpha$  is indeed a homomorphism of rings.  $\square$

- EXAMPLE. (1) If  $R$  is an integral domain and  $S = R \setminus \{0\}$ , then  $S^{-1}R$  is just the field of fractions of  $R$ .
- (2) We have that  $S^{-1}R$  is the zero ring if and only if  $0 \in S$ .
- (3) If  $I$  is an ideal of  $R$ , then  $S = 1 + I$  is multiplicatively closed.
- (4) Let  $p$  be a prime ideal. Then  $S = R \setminus p$  is multiplicatively closed (indeed, if  $x, y \in S$ , then if  $xy \in R \setminus S = p$ , then  $x \in p = R \setminus S$  or  $y \in p = R \setminus S$ , which is not possible). We write  $R_p$  for  $S^{-1}R$ , and the process of passing from  $R$  to  $R_p$  is called localisation at  $p$ . The elements  $\frac{r}{s}$  with  $r \in p$  form an ideal of  $R_p$ . This is a unique maximal ideal in  $R_p$ : if  $\frac{r}{s}$  satisfies  $r \notin p$ , then  $r \in S$ , so  $\frac{r}{s}$  has an inverse in  $R_p$  and is not part of any maximal ideal.

DEFINITION 2.2. A ring with a unique maximal ideal is called local.

REMARK. Some authors require a local ring to also be noetherian. We do not.

- EXAMPLE. (1) Let  $R = \mathbb{Z}$ , and  $p$  prime number. Then  $(p)$  is a prime ideal, and we have  $R_{(p)} = \{\frac{m}{n} \mid p \nmid n\} \subseteq \mathbb{Q}$ .  
The maximal ideal is given by  $\{\frac{m}{n} \mid p \mid m, p \nmid n\}$ .
- (2) Let  $R = k[X_1, \dots, X_n]$ ,  $p = (X_1 - \alpha_1, \dots, X_n - \alpha_n)$ . Then we can interpret  $R_p$  as a subring of  $k(X_1, \dots, X_n)$  consisting of those rational functions that are defined at  $(\alpha_1, \dots, \alpha_n) \in k^n$ , and the unique maximal ideal consists of those rational functions which are zero at  $(\alpha_1, \dots, \alpha_n)$ .

### 1. Localization of modules

DEFINITION. Given a left  $R$ -module  $M$ , define a relation  $\equiv$  on  $M \times S$ , where  $S$  is a multiplicatively closed subset  $S \subseteq R$  by

$$(m_1, s_1) \equiv (m_2, s_2) \iff \exists x \in S: x(m_1 s_2 - m_2 s_1) = 0.$$

This is again an equivalence relation with  $\frac{m}{s}$  denoting the equivalence class of  $(m, s)$ . The quotient is denoted by  $S^{-1}M$ .  $S^{-1}M$  has the structure of an  $S^{-1}R$ -module via

$$\begin{aligned} \frac{m_1}{s_1} + \frac{m_2}{s_2} &:= \frac{s_2 m_1 + s_1 m_2}{s_1 s_2} \\ \frac{r_1}{s_1} \frac{m_2}{s_2} &= \frac{r_1 m_2}{s_1 s_2}. \end{aligned}$$

Again, we write  $M_p$  in the case  $S = R \setminus p$  for a prime ideal  $p$ .

If  $\theta: M_1 \rightarrow M_2$  is an  $R$ -linear map, then an  $S^{-1}R$ -linear map  $S^{-1}\theta: S^{-1}M_1 \rightarrow S^{-1}M_2$  is given by  $\frac{m_1}{s} \mapsto \frac{\theta(m_1)}{s}$ . This is functorial in the sense that if  $\varphi: M_2 \rightarrow M_3$  is another  $R$ -linear map then  $S^{-1}(\varphi \circ \theta) = S^{-1}\varphi \circ S^{-1}\theta$ .

LEMMA 2.3. If

$$M_1 \xrightarrow{\theta} M \xrightarrow{\varphi} M_2$$

is exact at  $M$ , then

$$S^{-1}M_1 \xrightarrow{S^{-1}\theta} S^{-1}M \xrightarrow{S^{-1}\varphi} S^{-1}M_2$$

is exact at  $S^{-1}M$ .

PROOF. By functoriality, we have

$$(S^{-1}\varphi) \circ (S^{-1}\theta) = S^{-1}(\varphi \circ \theta) = S^{-1}0 = 0,$$

hence  $\text{im}(S^{-1}\theta) \subseteq \ker(S^{-1}\varphi)$ .

Now suppose  $\frac{m}{s} \in \ker(S^{-1}\varphi) \subseteq S^{-1}M$ . This means that  $\frac{\varphi(m)}{s} = 0$  in  $S^{-1}M_2$ . By definition of localization, this means that there is  $t \in S$  such that  $t\varphi(m) = 0$  in

$M_2$ . By linearity,  $0 = t\varphi(m) = \varphi(tm)$ , hence  $tm \in \ker \varphi = \text{im } \theta$ , so we find  $m_1 \in M_1$  such that  $\theta(m_1) = tm$ . Then we can calculate in  $S^{-1}M$  that

$$\frac{m}{s} = \frac{tm}{ts} = \frac{\theta(m_1)}{ts} = (S^{-1}\theta)\left(\frac{m_1}{ts}\right),$$

hence  $\frac{m}{s} \in \text{im } S^{-1}\theta$ , and we conclude that  $\ker S^{-1}\varphi = \text{im } S^{-1}\theta$  as claimed.  $\square$

REMARK. If  $N \subseteq M$  is a submodule, then  $S^{-1}N \subseteq S^{-1}M$  is a submodule in the natural way. In particular, if  $I \subseteq R$  is an ideal, then  $S^{-1}I$  is an ideal of  $S^{-1}R$ .

LEMMA 2.4. Let  $N \subseteq M$  be a submodule. Then  $S^{-1}(M/N) \cong S^{-1}M/S^{-1}N$ .

PROOF. Applying the previous lemma to the short exact sequence

$$0 \longrightarrow N \xrightarrow{\iota} M \xrightarrow{\varepsilon} M/N \longrightarrow 0$$

yields exactness of

$$0 \longrightarrow S^{-1}N \xrightarrow{S^{-1}\iota} S^{-1}M \xrightarrow{S^{-1}\varepsilon} S^{-1}(M/N) \longrightarrow 0.$$

Since  $S^{-1}\iota$  is just the inclusion  $S^{-1}N \subseteq S^{-1}M$ , we find that  $S^{-1}(M/N) \cong S^{-1}M/S^{-1}N$ .  $\square$

LEMMA 2.5. (i) Every ideal in  $S^{-1}R$  is of the form  $S^{-1}I$  for some ideal  $I$  of  $R$ .

(ii) The prime ideals of  $S^{-1}R$  are in one-to-one correspondence with the prime ideals of  $R$  that do not meet  $S$ .

PROOF. For the first part, let  $J$  be an ideal of  $S^{-1}R$  and define  $I := \{r \in R \mid \frac{r}{1} \in J\}$ . This is clearly an ideal. Now if  $\frac{r}{s} \in J$ , then  $\frac{r}{1} = \frac{s}{1} \frac{r}{s} \in J$ , hence  $r \in I$ , so  $\frac{r}{s} \in S^{-1}I$  and  $J \subseteq S^{-1}I$ .

Conversely, if  $\frac{r}{s} \in S^{-1}I$ , i.e.,  $r \in I$  and  $s \in S$ , then  $\frac{r}{1} \in J$ , so  $\frac{r}{s} = \frac{1}{s} \frac{r}{1} \in J$ .

Hence,  $S^{-1}I = J$ , completing the first part.

Let  $q$  be a prime ideal of  $S^{-1}R$  and set  $p := \{r \in R \mid \frac{r}{1} \in q\}$ . By the previous part,  $p$  is an ideal and  $q = S^{-1}p$ .

The ideal  $p$  is prime, since if  $xy \in p$ , then  $\frac{xy}{1} = \frac{x}{1} \frac{y}{1} \in q$ , so either  $\frac{x}{1}$  or  $\frac{y}{1}$  is in  $q$ , hence,  $x \in p$  or  $y \in p$ .

Furthermore, we have  $p \cap S = \emptyset$ , since if  $r \in S \cap p$ , then  $\frac{r}{1} \in q$  by definition of  $p$  and  $\frac{1}{r}$  is valid element of  $S^{-1}R$ , so  $1 = \frac{1}{r} \frac{r}{1} \in q$  since  $q$  is an ideal, but  $q$  is prime, so  $1 \notin q$ , a contradiction.

Conversely, let  $p$  be a prime ideal of  $R$  that does not meet  $S$ . If  $\frac{r}{s}, \frac{x}{y} \in S^{-1}R$  such that  $\frac{rx}{sy} \in S^{-1}p$ , then by definition of localisation we have  $zrx \in p$  for some  $z \in S$ . Since  $z \in S$ , we have  $z \notin p$ , so since  $p$  is prime, we must have  $rx \in p$ . Again since  $p$  is prime, we find that  $r \in p$  or  $x \in p$ , so  $\frac{r}{s} \in S^{-1}p$  or  $\frac{x}{y} \in S^{-1}p$ , so  $S^{-1}p$  is prime.

Hence, the mappings  $p \mapsto S^{-1}p$  and  $q \mapsto \{r \in R \mid \frac{r}{1} \in q\}$  are inverse bijections (one half is given by the first part of the proof, the other half is obvious) that preserve primality in both directions.  $\square$

LEMMA 2.6. If  $R$  is noetherian, then  $S^{-1}R$  is noetherian.

PROOF. Using the previous lemma, a chain  $J_1 \subseteq J_2 \subseteq \dots$  in  $S^{-1}R$  lifts to a chain  $I_1 \subseteq I_2 \subseteq \dots$  in  $R$  such that  $J_i = S^{-1}I_i$  for each  $i$ . Since  $R$  is noetherian, the chain  $\{I_i\}$  terminates, so the chain  $\{J_i\} = \{S^{-1}I_i\}$  must terminate as well.  $\square$

DEFINITION 2.7. A property  $P$  of a ring  $R$  or  $R$ -module  $M$  is called local if  $R$  or  $M$  has the property  $P$  if and only if  $R_p$  (resp.  $M_p$ ) has property  $P$  for each prime ideal  $p$  of  $R$ .

LEMMA 2.8. The following are equivalent for an  $R$ -module  $M$ .

- (i)  $M = 0$ ,
- (ii) for all prime ideals  $p$ , we have  $M_p = 0$ ,
- (iii) for all maximal ideals  $q$ , we have  $M_q = 0$ .

PROOF. It is obvious that (i) implies (ii) and (ii) implies (iii), so it will suffice to show that (iii) implies (i). Indeed, suppose that  $M_q = 0$  for every maximal ideal  $q$ , but  $M \neq 0$ .

Let  $0 \neq m \in M$ . The annihilator  $\{r \in R \mid rm = 0\}$  of  $m$  is a proper ideal of  $R$ , hence it is contained in a maximal ideal  $q$  of  $R$ . Since  $M_q$  is trivial, we have  $\frac{m}{1} = 0$  in  $M_q$ , so there is some  $s \in R \setminus q$  such that  $sm = 0$  in  $R$ . But since  $s \notin q$ , we have  $s \notin \text{ann}(m)$ , i.e.,  $sm \neq 0$ , a contradiction.  $\square$

LEMMA 2.9. Let  $\varphi: M \rightarrow N$  be a homomorphism of  $R$ -modules. The following are equivalent.

- (i)  $\varphi$  is injective,
- (ii)  $\varphi_p: M_p \rightarrow N_p$  is injective for all primes  $p$  of  $R$ ,
- (iii)  $\varphi_q: M_q \rightarrow N_q$  is injective for all maximal ideals  $q$  of  $R$ .

PROOF. (i) implies (ii) by exactness of localization. It is obvious that (ii) implies (iii).

Now assume that  $\varphi_q$  is injective for all maximal ideals  $q$ . The sequence

$$0 \longrightarrow \ker \varphi \xrightarrow{\iota} M \xrightarrow{\varphi} N$$

is exact. Hence

$$0 \longrightarrow (\ker \varphi)_q \xrightarrow{\iota_q} M_q \xrightarrow{\varphi_q} N_q$$

is exact for every maximal ideal  $q$ . By exactness,  $(\ker \varphi)_q$  is isomorphic to  $\ker \varphi_q$ , which is trivial by assumption. Hence  $(\ker \varphi)_q$  is trivial for every maximal ideal  $q$ , so by the previous result, we have  $\ker \varphi = 0$  as required.  $\square$

LEMMA 2.10. Let  $p$  be a prime ideal of  $R$  and  $S$  a multiplicatively closed subset of  $R$  such that  $S \cap p = \emptyset$ . By (2.5),  $S^{-1}p$  is a prime ideal of  $S^{-1}R$ . Then  $(S^{-1}R)_{S^{-1}p} \cong R_p$ . In particular, if  $q$  is a prime ideal of  $R$  with  $p \subseteq q$ , then  $(R_q)_{p_q} \cong R_p$ , by taking  $S = R \setminus q$ .

PROOF. On the second exercise sheet.  $\square$

## 2. A proof of the Nullstellensatz

REMARK. Let  $k$  be a field and  $R$  a  $k$ -algebra which is also an integral domain. If  $R$  is a finite-dimensional  $k$ -vector space, then  $R$  is a field: indeed, if  $0 \neq r \in R$ , then multiplication by  $r$  is a  $k$ -linear map. Since  $R$  is an integral domain, this map is injective, and since  $R$  is finite-dimensional, every injective map is surjective. Hence we find an inverse of  $r$ .

THEOREM. Let  $k$  be an algebraically closed field, and  $R$  a finitely generated  $k$ -algebra. Then  $N(R) = J(R)$ . Thus if  $I$  is a radical ideal of  $k[X_1, \dots, X_n]$  and  $R = k[X_1, \dots, X_n]/I$  then the intersection of the maximal ideals of  $R$  is 0.

Furthermore, any radical ideal is the intersection of the maximal ideals containing it.

PROOF. Let  $p$  be any prime ideal of  $R$  and let  $s \in R \setminus p$ . The set  $S := \{1, s, s^2, \dots\}$  is multiplicative, so we get a localization  $S^{-1}R$  and a map  $\theta: R \rightarrow S^{-1}R$ .  $R$  is a finitely generated  $k$ -algebra and  $S^{-1}R$  generated as a  $k$ -algebra by  $\theta(R)$  and  $1/s$ . Hence  $S^{-1}R$  is a finitely generated  $k$ -algebra. Let  $q$  be a maximal



ideal of  $S^{-1}R$  containing  $S^{-1}p$ . By the weak Nullstellensatz,  $S^{-1}R/q$  is a finite field extension of  $k$ .

The ideal  $p_1 := \theta^{-1}(q)$  is a prime ideal containing  $p$ , and by the correspondence of prime ideals we know that  $p_1$  does not meet  $S$ . Hence  $\theta$  induces an injective  $k$ -vector space homomorphism  $R/p_1 \rightarrow S^{-1}R/q$ . Since  $S^{-1}R/q$  is finite-dimensional, this implies that  $R/p_1$  is also finite-dimensional.

By the remark, this implies that  $R/p_1$  (which is an integral domain since  $p_1$  is prime) is a field, hence  $p_1$  is a maximal ideal. Hence, for any  $s \notin p$ , we find a maximal ideal containing  $p$  but not containing  $s$ , i.e.,

$$R \setminus p \subseteq \bigcup \{\text{complements of maximal ideals containing } p\}.$$

By elementary set theory, this means that

$$\bigcap \{\text{maximal ideals containing } p\} \subseteq p.$$

Since the converse inclusion is trivial, we have that  $p$  is the intersection of maximal ideals containing  $p$ . Hence the intersection of all primes is the same as the intersection of all maximals, which is what we wanted to show.  $\square$



## CHAPTER 3

### Tensor products

DEFINITION 3.1. If  $L, M, N$  are  $R$ -modules, then a function  $\varphi: M \times N \rightarrow L$  is called  $R$ -bilinear if

$$\begin{aligned}\varphi(r_1 m_1 + r_2 m_2, n) &= r_1 \varphi(m_1, n) + r_2 \varphi(m_2, n), \\ \varphi(m, r_1 n_1 + r_2 n_2) &= r_1 \varphi(m, n_1) + r_2 \varphi(m, n_2).\end{aligned}$$

REMARK. The idea is to reduce the study of bilinear maps to the of linear (i.e.,  $R$ -module) maps.

If  $\varphi: M \times N \rightarrow T$  is bilinear and  $\theta: T \rightarrow L$  is linear, then  $\theta \circ \varphi$  is bilinear. Composition with  $\varphi$  gives a well defined function  $\varphi^*$  from  $R$ -linear maps  $T \rightarrow L$  to bilinear maps  $M \times N \rightarrow L$ .

$$\begin{array}{ccc} M \times N & \xrightarrow{\varphi} & T \\ & \searrow \varphi^*(\theta) & \downarrow \theta \\ & & L \end{array}$$

We say that  $\varphi$  is universal if  $\varphi^*$  is a bijection for every  $L$ . If this happens that study of bilinear maps  $M \times N \rightarrow L$  is reduced to the study if linear maps  $T \rightarrow L$ .

- LEMMA 3.2. (i) Given  $R$ -modules  $M, N$ , there is an  $R$ -module  $T$  and a universal map  $\varphi: M \times N \rightarrow T$ .  
(ii) Given two universal maps  $\varphi_1: M \times N \rightarrow T_1$ ,  $\varphi_2: M \times N \rightarrow T_2$ , there is a unique isomorphism  $\beta: T_1 \rightarrow T_2$  such that  $\varphi_2 = \beta \circ \varphi_1$ .

PROOF. Let  $F$  be the free  $R$ -module on the generators  $e_{(m,n)}$  indexed by pairs  $(m, n) \in M \times N$ . Let  $X$  be the  $R$ -submodule generated by all elements of the forms

$$e_{(r_1 m_1 + r_2 m_2, n)} - r_1 e_{(m_1, n)} - r_2 e_{(m_2, n)}, \quad e_{(m, r_1 n_1 + r_2 n_2)} - r_1 e_{(m, n_1)} - r_2 e_{(m, n_2)}.$$

Define  $T := F/X$  and write  $m \otimes n$  for the image of the basis element  $e_{(m,n)}$  in  $T$ .  $T$  is generated by elements of the form  $m \otimes n$ , and we have the relations

$$\begin{aligned}(r_1 m_1 + r_2 m_2) \otimes n &= r_1 (m_1 \otimes n) + r_2 (m_2 \otimes n) \\ m \otimes (r_1 n_1 + r_2 n_2) &= r_1 (m \otimes n_1) + r_2 (m \otimes n_2).\end{aligned}$$

Define  $\varphi: M \times N \rightarrow T$  via  $(m, n) \mapsto m \otimes n$  and note that  $\varphi$  is bilinear. Any map  $\alpha: M \times N \rightarrow L$  extends to a map of  $R$ -modules  $\bar{\alpha}: F \rightarrow L$  by sending  $e_{(m,n)} \mapsto \alpha(m, n)$ . If  $\alpha$  is bilinear then  $\bar{\alpha}$  vanishes on the generators of  $X$ , hence it induces a map of  $R$ -modules  $\alpha': T \rightarrow L$  such that  $\alpha'(m \otimes n) = \alpha(m, n)$ , and  $\alpha'$  is uniquely determined by these relations. Hence  $\varphi$  is universal.

The proof of uniqueness is just the usual dance with universal properties.  $\square$

DEFINITION 3.3. The module  $T$  is usually denoted  $M \otimes_R N$  and is called the tensor product of  $M$  and  $N$  over  $R$ .

REMARK.  $\bullet$  We often drop the subscript  $R$  if it is clear what ring we are using.

- Not all elements of  $M \otimes_R N$  are of the form  $m \otimes n$ . A general element is of the form  $\sum_{i=1}^r m_i \otimes n_i$ .
- If  $R = k$  is a field and  $k^s, k^t$  are finite-dimensional vector spaces over  $k$ , then the map  $M \times N \rightarrow k^{st}$  given by numbering basis elements of  $k^{st}$  by pairs  $(i, j)$ ,  $1 \leq i \leq s, 1 \leq j \leq t$  and sending  $(a_i, b_j) \mapsto e_{(i,j)}$  is universal, hence  $M \otimes N \cong k^{st}$ .
- It is possible to define tensor products over non-commutative rings, where  $M$  is a right  $R$ -module and  $N$  is a left  $R$ -module. In this situation,  $M \otimes N$  is only an abelian group, not necessarily an  $R$ -module. The construction is analogous, but you take the free abelian group instead of the free  $R$ -module and use the relations

$$\begin{aligned} e_{(m_1+m_2, n)} &= e_{(m_1, n)} + e_{(m_2, n)} \\ e_{(m, n_1+n_2)} &= e_{(m, n_1)} + e_{(m, n_2)} \\ e_{(mr, n)} &= e_{(m, rn)}. \end{aligned}$$

If  $M$  is an  $(R, S)$ -bimodule and  $N$  is an  $(S, T)$ -bimodule, then  $M \otimes N$  becomes a  $(R, T)$ -bimodule.

- On the exercise sheet we will see that  $\mathbb{Z}/r\mathbb{Z} \otimes_{\mathbb{Z}} \mathbb{Z}/s\mathbb{Z} \cong \mathbb{Z}/\gcd(r, s)\mathbb{Z}$ .
- one can construct a universal trilinear map  $L \times M \times N \rightarrow T$ , unique up to isomorphism, denoted by  $L \otimes M \otimes N$ .

LEMMA 3.4. The following maps exist and are isomorphisms.

(i)

$$\begin{aligned} M \otimes N &\rightarrow N \otimes M \\ m \otimes n &\mapsto n \otimes m, \end{aligned}$$

(ii)

$$\begin{aligned} (M \otimes N) \otimes L &\rightarrow M \otimes (N \otimes L) \rightarrow M \otimes N \otimes L \\ (m \otimes n) \otimes \ell &\mapsto m \otimes (n \otimes \ell) \mapsto m \otimes n \otimes \ell, \end{aligned}$$

(iii)

$$\begin{aligned} (M \oplus N) \otimes L &\rightarrow (M \otimes L) \oplus (N \otimes L) \\ (m, n) \otimes \ell &\mapsto (m \otimes \ell, n \otimes \ell), \end{aligned}$$

(iv)

$$\begin{aligned} R \otimes_R M &\rightarrow M \\ r \otimes m &\mapsto rm. \end{aligned}$$

PROOF. (i) The map  $M \times N \rightarrow N \otimes M$  given by  $(m, n) \mapsto n \otimes m$  is bilinear, hence it induces the map  $M \otimes N \rightarrow N \otimes M$  given by  $m \otimes n \mapsto n \otimes m$ . Swapping the roles of  $M$  and  $N$  yields an inverse.

(ii) Exercise (appears on the second example sheet).

(iii) We have a bilinear map

$$\begin{aligned} (M \oplus N) \times L &\rightarrow (M \otimes L) \oplus (N \otimes L) \\ ((m, n), \ell) &\mapsto (m \otimes \ell, n \otimes \ell). \end{aligned}$$

This map induces a linear map

$$\begin{aligned} (M \oplus N) \otimes L &\rightarrow (M \otimes L) \oplus (N \otimes L) \\ (m, n) \otimes \ell &\mapsto (m \otimes \ell, n \otimes \ell), \end{aligned}$$

and we will find an inverse. Indeed, the maps

$$\begin{aligned} M \times L &\rightarrow (M \oplus N) \otimes L & N \times L &\rightarrow (M \oplus N) \otimes L \\ (m, \ell) &\mapsto (m, 0) \otimes \ell & (n, \ell) &\mapsto (0, n) \otimes \ell \end{aligned}$$

are bilinear, and by the universal property of the tensor product and the universal property of the direct sum we obtain a linear map

$$\begin{aligned} \Psi: (M \otimes L) \oplus (N \otimes L) &\rightarrow (M \oplus N) \otimes L \\ (m \otimes \ell_1, n \otimes \ell_2) &\mapsto (m, 0) \otimes \ell_1 + (0, n) \otimes \ell_2. \end{aligned}$$

We trivially calculate that this is the required inverse.

(iv) Another exercise, cf. Proposition 2.14 in Atiyah-Macdonald.

□

EXAMPLE. We have a natural bijection

$$\operatorname{Hom}(M \otimes N, L) \cong \operatorname{Hom}(M, \operatorname{Hom}(N, L))$$

Indeed, if  $\varphi: M \times N \rightarrow L$  is a bilinear map, we get  $\theta: M \rightarrow \operatorname{Hom}(N, L)$  as  $m \mapsto (n \mapsto \varphi(m, n))$ . Conversely, if  $\theta: M \rightarrow \operatorname{Hom}(N, L)$  is linear, then we obtain a bilinear map  $M \times N \rightarrow L$  by setting  $(m, n) \mapsto \theta(m)(n)$ .



# Exercises

## Example Sheet 1

### Exercise 1.

LEMMA. Let  $R$  and  $S$  be (commutative unital) rings. Denote by  $\mathcal{I}_R$  the set of ideals of  $R$ . Then there is a bijective correspondence

$$\begin{aligned}\mathcal{I}_{R \times S} &\leftrightarrow \mathcal{I}_R \times \mathcal{I}_S, \\ I &\mapsto (\pi_1(I), \pi_2(I)), \\ I_1 \times I_2 &\leftrightarrow (I_1, I_2).\end{aligned}$$

PROOF. We need to show the following.

- (i) If  $I$  is an ideal of  $R \times S$ , then  $\pi_1(I)$  is an ideal of  $R$  and  $\pi_2(I)$  is an ideal of  $S$ ,
- (ii) if  $I_1$  is an ideal of  $R$ ,  $I_2$  is an ideal of  $S$ , then  $I_1 \times I_2$  is an ideal of  $R \times S$ ,
- (iii) if  $I$  is an ideal of  $R \times S$ , then  $I = \pi_1(I) \times \pi_2(I)$  and
- (iv) if  $I_1$  is an ideal of  $R$ ,  $I_2$  is an ideal of  $S$ , then  $I_1 = \pi_1(I_1 \times I_2)$  and  $I_2 = \pi_2(I_1 \times I_2)$ .

Indeed (i) follows from surjectivity of the projection and (ii) and (iv) are obvious. It remains to show (iii).

If  $(r, s) \in I$ , then  $r = \pi_1((r, s)) \in \pi_1(I)$  and  $s = \pi_2((r, s)) \in \pi_2(I)$ , so  $(r, s) \in \pi_1(I) \times \pi_2(I)$ .

Conversely, if  $(r, s) \in \pi_1(I) \times \pi_2(I)$ , then there are  $r', s'$  such that  $(r, s') \in I$  and  $(r', s) \in I$ . We conclude that  $(r, s) = (r, s') \cdot (1, 0) + (r', s) \cdot (0, 1) \in I$ .  $\square$

EXERCISE. The direct product of finitely many noetherian rings is noetherian.

SOLUTION. Since the terminal object in the category of rings is the zero ring, which is noetherian, by induction it suffices to show that if  $R$  and  $S$  are noetherian, then  $R \times S$  is noetherian.

Let  $I$  be an ideal of  $R \times S$ . We have to show that  $I$  is finitely generated. By the Lemma,  $I = I_1 \times I_2$  for an ideal  $I_1$  of  $R$  and an ideal  $I_2$  of  $S$ . Since  $R$  and  $S$  are noetherian,  $I_1$  is finitely generated, say by  $r_1, \dots, r_n$  and so is  $I_2$ , say by  $s_1, \dots, s_m$ . Then if  $(r, s) \in I_1 \times I_2$ , we have

$$(r, s) = \left( \sum_{i=1}^n \lambda_i r_i, \sum_{i=1}^m \lambda'_i s_i \right) = \sum_{i=1}^n (\lambda_i, 0)(r_i, 0) + \sum_{i=1}^m (0, \lambda'_i)(0, s_i),$$

so  $I_1 \times I_2$  is finitely generated by  $(r_1, 0), \dots, (r_n, 0), (0, s_1), \dots, (0, s_m)$ .  $\square$

### Exercise 3.

EXERCISE. The set of prime ideals in a non-zero rings possesses a minimal member with respect to inclusion.

SOLUTION. Denote the set of prime ideals of  $A$  by  $\mathcal{S}$ . Since  $A$  is nonzero,  $(0)$  is a proper ideal, which is contained in a maximal ideal, hence  $\mathcal{S}$  is nonempty.

The set  $\mathcal{S}$  is partially ordered using the relation “ $\supseteq$ ”. Let  $\mathcal{S}' \subseteq \mathcal{S}$  denote a totally ordered subset of  $\mathcal{S}$ . We will show that  $\mathcal{S}'$  admits an upper bound. Indeed, define  $S := \bigcap_{P \in \mathcal{S}'} P$ .  $S$  is obviously an ideal, and we will show that it is prime. Assume that  $x, y \in A$  such that  $xy \in S$ . Since every  $P \in \mathcal{S}'$  is prime, we may write  $\mathcal{S}' = \mathcal{S}_x \cup \mathcal{S}_y$ , where  $\mathcal{S}_x := \{P \in \mathcal{S}' \mid x \in P\}$  and  $\mathcal{S}_y := \{P \in \mathcal{S}' \mid y \in P\}$ . We claim that it is true that

$$(\star) \quad (\forall P \in \mathcal{S}' \exists P' \in \mathcal{S}_x: P' \subseteq P) \vee (\forall P \in \mathcal{S}' \exists P' \in \mathcal{S}_y: P' \subseteq P).$$

Indeed, the negation of this statement is

$$(\exists P \in \mathcal{S}' \forall P' \in \mathcal{S}_x: P' \not\subseteq P) \wedge (\exists Q \in \mathcal{S}' \forall Q' \in \mathcal{S}_y: Q' \not\subseteq Q),$$

but then  $P \cap Q$ , which is either  $P$  or  $Q$ , since  $\mathcal{S}'$  is totally ordered, is part of neither  $\mathcal{S}_x$  nor  $\mathcal{S}_y$ , which is a contradiction.

Therefore, without loss of generality, we may assume that the left hand side of  $(\star)$  is true (the case where the right hand side is true works exactly the same). Since  $P' \in \mathcal{S}_x$  and  $P' \subseteq P$  implies  $P \in \mathcal{S}_x$ , we have that  $\mathcal{S}' = \mathcal{S}_x$ , so  $x \in S$ , and  $S$  is indeed a prime ideal, and therefore every chain in  $\mathcal{S}$  admits an upper bound.

Applying Zorn's lemma gives a maximal element of  $\mathcal{S}$ , which is precisely a minimal prime ideal of  $A$ .  $\square$

### Exercise 7.

EXERCISE. Let  $M$  be a noetherian  $A$ -module and  $\theta$  be an endomorphism.

- (i) If  $\theta$  is surjective, then it is an isomorphism.
- (ii) If  $M$  is artinian and  $\theta$  is injective, then it is an isomorphism.

[Hint: in (i) consider the submodules  $\ker \theta^n$ ; in (ii), consider the quotient modules  $\text{coker } \theta^n$ .]

SOLUTION. For (i), assume that  $\theta$  is not injective. Then there is some  $x \in \ker \theta \setminus \{0\}$ . Let  $n \in \mathbb{N}$ . Since  $\theta$  is surjective, so is  $\theta^n$ , so there is some  $y \in M$  such that  $\theta^n(y) = x$ . Therefore,  $y \in \ker \theta^{n+1} \setminus \ker \theta^n$  and we have an infinite strictly increasing chain

$$\ker \theta \subsetneq \ker \theta^2 \subsetneq \ker \theta^3 \subsetneq \cdots.$$

For (ii), assume that  $\theta$  is not surjective. This means that there is some  $x \notin \text{im } \theta$ . Let  $n \in \mathbb{N}$ . Then we have  $\theta^n(x) \in \text{im } \theta^n$ . Suppose that  $\theta^n(x) \in \text{im } \theta^{n+1}$ . Then there would be  $y \in M$  such that  $\theta^{n+1}(y) = \theta^n(x)$ . By injectivity of  $\theta$ , this means that  $\theta(y) = x$ , a contradiction. Therefore,  $\theta^n(x) \in \text{im } \theta^n \setminus \text{im } \theta^{n+1}$  and we have an infinite strictly decreasing chain

$$\text{im } \theta \supsetneq \text{im } \theta^2 \supsetneq \text{im } \theta^3 \supsetneq \cdots. \quad \square$$

### Exercise 8.

EXERCISE. Let  $A$  be a Noetherian ring and  $f \in A[[X]]$ . Then  $f$  is nilpotent if and only if all of its coefficients are nilpotent.

SOLUTION. First assume that  $f$  is nilpotent. Write  $f = \sum_{i=0}^{\infty} a_i X^i$  for some  $a_i \in A$ . We will argue by induction. Since  $f$  is nilpotent, there is some  $k \in \mathbb{N}$  such that  $f^k = 0$ . The constant term of  $f^k$  is  $a_0^k$ , hence  $a_0$  is nilpotent.

Next, assume that  $a_0, \dots, a_n$  are nilpotent for some  $n \in \mathbb{N}$ . Then they are also nilpotent as elements of  $A[[X]]$ . Since the set of nilpotent elements forms an ideal, we have that  $g := \sum_{i=0}^n a_i X^i$  is nilpotent, so  $f - g = \sum_{i=n+1}^{\infty} a_i X^i$  is nilpotent, i.e., there is some  $k$  such that  $(f - g)^k = 0$ . But the  $X^{k(n+1)}$ -coefficient of  $(f - g)^k$  is just  $a_{n+1}^k$ , hence  $a_{n+1}$  is nilpotent.

Next, assume that  $f = \sum_{i=0}^{\infty} a_i X^i$  and every  $a_i$  is nilpotent. Denote by  $I$  the ideal of  $A$  generated by all  $a_i$ . Then  $I \subseteq N(A)$ . Since  $N(A) = \sqrt{0}$ , by Lemma 1.21,



there is some natural number  $n$  such that  $N(A)^n \subseteq (0)$ . Since  $I^n \subseteq N(A)^n$ , this implies that  $I^n = (0)$ . Since the coefficients of  $f^n$  are elements of  $I^n$ , we conclude that  $f^n = 0$ , so  $f$  is nilpotent.  $\square$

### Exercise 9.

EXERCISE. Let  $A$  be a ring and  $M$  an  $R$ -module.

- (i)  $M[X]$  is an  $A[X]$ -module,
- (ii) If  $P$  is a prime ideal in  $A$ , then  $P[X]$  is a prime ideal in  $A[X]$ . If  $Q$  is a maximal ideal of  $A$ , is  $Q[X]$  a maximal ideal of  $A[X]$ ?
- (iii) Let  $M$  be a noetherian  $A$ -module. Then  $M[X]$  is a noetherian  $A[X]$ -module.

SOLUTION. For the second part, let  $P$  be a prime ideal in  $A$ .  $P[X]$  is obviously an ideal of  $A[X]$ . Let  $f, g \in A[X]$  such that  $fg \in P[X]$ . We can write

$$f = \sum_{i=0}^n a_i X^i, \quad g = \sum_{i=0}^m b_i X^i,$$

and also define  $a_i = 0$  for  $i > n$  and  $b_i = 0$  for  $i > m$ . Suppose that  $f \notin P[X]$  and  $g \notin P[X]$ . Then we find  $i$  and  $j$  such that  $a_i \notin P$ ,  $b_j \notin P$ . Choose  $i$  and  $j$  to be minimal among the possible  $i$  and  $j$ . Then the coefficient of  $fg$  for  $X^{i+j}$  is given by

$$\left( \sum_{k=0}^{i-1} a_k b_{i+j-k} \right) + a_i b_j + \left( \sum_{k=i+1}^{i+j} a_k b_{i+j-k} \right).$$

The coefficient is in  $P$ , and so are the sums on the left and the right, by minimality of  $i$  and  $j$ . But then  $a_i b_j \in P$ , so  $a_i \in P$  or  $b_j \in P$ , a contradiction. Hence  $f \in P[X]$  or  $g \in P[X]$ .

Let  $Q$  be a maximal ideal of  $A$ . Then  $1 \notin Q$ , hence  $1 \notin Q[X]$  and  $X \notin Q[X]$ , hence  $1 \notin (Q[X], X)$ , but  $X \in (Q[X], X)$ . We conclude that  $Q[X] \subsetneq (Q[X], X) \subsetneq A[X]$ , so  $Q[X]$  is not a maximal ideal.

The proof of the third part is almost identical to the proof of Hilbert's basis theorem. We will show that every submodule of  $M[X]$  is finitely generated. Let  $N$  be an  $A[X]$ -submodule of  $M[X]$  and define  $N_n := \{f \in N \mid \deg f \leq n\}$ . We have  $0 \in N_n$  and  $N_0 \subseteq N_1 \subseteq \dots$  form an ascending chain.

Define  $M_n$  to be the set of coefficients of  $X^n$  appearing in elements of  $N_n$ . If  $m + n \in M_n$  and  $a \in A$ , then  $m + n \in M_n$  and  $am \in M_n$ . Therefore  $M_n$  is an  $A$ -submodule of  $M$ .

Furthermore, if  $m \in M_n$ , then  $m \in M_{n+1}$  by multiplying the corresponding polynomial by  $X$ .

Since  $M$  is noetherian, the chain  $M_0 \subseteq M_1 \subseteq \dots$  terminates, so we have  $k$  such that  $\forall n \geq k: M_n = M_k$ . Each of  $M_0, \dots, M_k$  is a finitely generated submodule of  $M$ , say  $M_j$  is generated by  $m_{j1}, \dots, m_{j\ell_j}$ . There are polynomials  $f_{j1}, \dots, f_{j\ell_j} \in N$  such that  $\deg f_{ji} = j$  and the leading coefficient of  $f_{ji}$  is  $m_{ji}$ .

We will show that the finite set  $\{f_{ji} \mid 0 \leq j \leq N, 1 \leq i \leq \ell_j\}$  generated  $N$ .

We will use induction on  $\deg f$ , where  $f \in N$ . If  $\deg f = 0$ , then  $f = m$  for some  $m \in M$ . By definition of  $M_0$ ,  $m \in M_0$ , and  $m$  is in the submodule generated by the  $f_{0i}$ .

Assume next that  $0 < \deg f \leq k$  and that the claim is true for smaller degrees. Let  $m$  be the leading coefficient of  $f$ . Then  $m \in M_n$  so we may write

$$m = \sum_j a_{nj} m_{nj}.$$

Then

$$f - \sum_j a_{nj} f_{nj}$$

is in  $N$  and of smaller degree, so is expressible as a linear combination of the  $f_{ij}$ , so  $f$  is expressible as a linear combination as well.

Finally, assume that  $N < \deg f$  and that the claim is true for smaller degrees. If  $m$  is the leading coefficient of  $f$ , then  $m \in M_n = M_k$  so we may write

$$m = \sum_j a_{kj} m_{kj}.$$

Then

$$f - X^{n-k} \sum_j a_{kj} f_{kj}$$

is in  $N$  and of smaller degree, so is expressible as a linear combination of the  $f_{ij}$ , so  $f$  is expressible as a linear combination as well.  $\square$

### Exercise 10.

EXERCISE. An element  $r$  lies in the Jacobson radical of  $A$  iff  $1 - rs$  is a unit for all  $s$  in  $A$ .

SOLUTION. Let  $r \in J(A)$  and  $s \in A$ . Then  $rs \in J(A)$ , so  $rs$  is contained in every maximal ideal of  $A$ . If  $1 - rs$  were contained in a maximal ideal  $M$ , then we would have  $1 \in M$ , a contradiction. So  $1 - rs$  is not contained in any maximal ideal, so  $(1 - rs)$  is not contained in any maximal ideal, so we must have  $(1 - rs) = (1)$ , hence  $1 - rs$  is a unit.

Conversely, assume that  $1 - rs$  is a unit for every  $s$ , and let  $M$  be a maximal ideal of  $A$ . Suppose that  $r \notin M$ . Then  $A = M + Ar$ , so we find  $m \in M$  and  $s \in A$  such that  $1 = m + rs$ , but then  $m = 1 - rs$  is a unit, a contradiction. Hence  $r \in M$  and therefore  $r \in J(R)$ .  $\square$

### Exercise 11.

EXERCISE. Any field  $K$  which is finitely generated as a ring is a finite field.

SOLUTION. Suppose that  $K$  has characteristic zero. Then we can identify  $\mathbb{Q}$  with a subfield of  $K$ . Since  $K$  is finitely generated as a  $\mathbb{Z}$ -algebra (this is just a different way of saying that  $K$  is finitely generated as a ring), it is certainly finitely generated as a  $\mathbb{Q}$ -algebra. By Zariski's lemma,  $K$  is a finite-dimensional  $\mathbb{Q}$ -vector space.

Hence, all assumptions for the Artin-Tate lemma for the chain  $\mathbb{Z} \subseteq \mathbb{Q} \subseteq K$  are satisfied, so we find that  $\mathbb{Q}$  is a finitely generated  $\mathbb{Z}$ -algebra. This is of course nonsense: if we had finitely many generators, then only finitely many primes could appear as divisors of denominators in  $\mathbb{Q}$ .

Therefore,  $K$  has characteristic  $p > 0$  and is a finitely generated  $\mathbb{Z}$ -algebra, so  $K$  is also a finitely generated  $\mathbb{Z}/p\mathbb{Z}$ -algebra. Hence, by Zariski's lemma,  $K$  is a finite-dimensional  $\mathbb{Z}/p\mathbb{Z}$ -vector space, hence  $K$  is finite.  $\square$

### Exercise 12.

EXERCISE. Let  $I$  be an ideal contained in the Jacobson radical of  $A$ , and let  $M$  be an  $A$ -module and  $N$  be a finitely generated  $A$ -module. Let  $\theta: M \rightarrow N$  be a homomorphism of  $A$ -modules. If the induced map  $M/IM \rightarrow N/IN$  is surjective, then  $\theta$  is surjective.

SOLUTION. Let  $n \in N$ . By surjectivity of the induced map, we find  $m \in M$  such that  $\theta(m) + IN = n + IN$ . Hence we find  $i \in I$  and  $n_1 \in N$  such that  $\theta(m) = n + in_1$ , hence  $n + \theta(M) = i(-n_1) + \theta(M)$ . Since  $n$  was arbitrary, we conclude

$$\frac{N}{\theta(M)} \subseteq I \frac{N}{\theta(M)} \subseteq J(A) \frac{N}{\theta(M)} \subseteq \frac{N}{\theta(M)}.$$

Since  $N$  is finitely generated, so is  $N/\theta(M)$ , and by Nakayama's lemma, we must have  $N/\theta(M) = 0$ , so  $\theta$  is surjective.  $\square$

### Exercise 13.

EXERCISE. In the ring  $A$ , let  $\Sigma$  be the set of all ideals in which every element is a zero-divisor. Show that the set  $\Sigma$  has maximal elements and that every maximal element of  $\Sigma$  is a prime ideal. Hence show that the set of zero-divisors in  $A$  is a union of prime ideals.

SOLUTION. For a zero divisor  $a \in A$  denote by  $\Sigma_a$  the set of ideals containing  $a$  in which every element is a zero divisor (notice that  $\Sigma = \Sigma_0$ ). Since  $(a) \in \Sigma_a$ , we know that  $\Sigma_a$  is nonempty. Furthermore, the union of a chain of ideals in  $\Sigma_a$  is once again an element of  $\Sigma_a$ , hence  $\Sigma_a$  admits a maximal element  $I_a$  by Zorn's lemma.

Let  $x, y \in A$  such that  $xy \in I_a$ ,  $x \notin I_a$  and  $y \notin I_a$ . Then The ideals  $I_a + Ax$  and  $I_a + Ay$  contain non-zero-divisors  $u$  and  $v$ . Write  $u = i + u_1x$  and  $v = j + u_2y$  with  $i, j \in I_a$ ,  $u_1, u_2 \in A$ . Then  $uv = ij + iu_2y + ju_1x + u_1u_2xy \in I_a$ , hence  $uv$  is a zero divisor, but then  $u$  and  $v$  are also zero divisors, a contradiction.

Hence  $I_a$  is prime and if  $Z$  is the set of zero divisors, then we find that

$$Z = \bigcup_{a \in Z} I_a$$

as required.  $\square$

### Exercise 15.

LEMMA. Let  $q_1, \dots, q_n$  be pairwise distinct maximal ideals of a ring  $A$ . Then we have

$$\bigcap_{i=1}^n q_i = \prod_{i=1}^n q_i.$$

PROOF. We will proceed by induction on  $n$ . The claim is obviously true for  $n = 1$ . Suppose that

$$Q := \bigcap_{i=1}^n q_i = \prod_{i=1}^n q_i$$

and  $q_{n+1}$  is a maximal ideal distinct from the  $q_i$ . We have  $Q \not\subseteq q_{n+1}$ , because otherwise there would be some  $i \leq n$  such that  $q_i \subseteq q_{n+1}$ , since  $q_{n+1}$  is prime. But then we would have  $q_i = q_{n+1}$ , a contradiction. Hence  $Q + q_{n+1} = A$  by maximality of  $q_{n+1}$ , so we find  $u \in Q$  and  $v \in q_{n+1}$  such that  $u + v = 1$ . It is obvious that  $Qq_{n+1} \subseteq Q \cap q_{n+1}$ . Conversely, let  $x \in Q \cap q_{n+1}$ . Then  $x = x(u + v) = xu + xv \in Qq_{n+1}$ , so the claim follows.  $\square$

LEMMA. Let  $A$  be an artinian ring. Then  $A$  has finitely many maximal ideals.

PROOF. Otherwise, let  $q_1, q_2, \dots$  denote pairwise distinct maximal ideals of  $A$ . Define  $Q_n := \bigcap_{i=1}^n q_i$ . Then  $Q_n \supsetneq Q_{n+1}$ , since otherwise we would have  $Q_n \subseteq q_{n+1}$ , but by the preceding lemma and primality of  $q_{n+1}$ , this would imply that  $q_i \subseteq q_{n+1}$  for some  $i \leq n$ , hence  $q_i = q_{n+1}$ , which is not the case. Therefore, the  $Q_i$  form a strictly descending chain, which cannot exist since  $A$  is artinian.  $\square$

EXERCISE. Let  $A$  be an artinian ring. Then  $A$  is noetherian.

SOLUTION. By the second lemma,  $A$  has finitely many maximal ideals  $q_1, \dots, q_n$ . By a result from the lecture, since  $A$  is artinian, we have  $N(A) = J(A)$ , hence  $\sqrt{0} = \bigcap_{i=1}^n q_i = \prod_{i=1}^n q_i$ , where we have used the first lemma in the second step. Define  $Q_m := \prod_{i=1}^n q_i^m = \sqrt{0}^m$ . The  $Q_i$  form a decreasing chain of ideals. Since  $A$  is artinian, this chain terminates, say at  $Q_k$ . We claim that  $Q_k = 0$ . Indeed, assume that there is some  $0 \neq a \in Q_k$ . Since  $a \in \sqrt{0}$ ,  $a_\ell = 0$  for some  $\ell$ . But then...?  $\square$

**Exercise 4.**

EXERCISE. If  $A$  is a noetherian ring, then  $A[[X]]$  is a noetherian ring.

SOLUTION. Let  $I \subseteq A[[X]]$  be an ideal. For a natural number  $n$  define  $R(n)$  to be the set of trailing coefficients of elements of the form  $a_n X^n +$  higher order terms in  $I \cap (X^n)$ . As in the proof of Hilbert's basis theorem, we have  $R(0) \subseteq \dots$ . Since  $A$  is noetherian, we find  $N$  such that  $R(n) = R(N)$  for all  $n \geq N$ . For  $0 \leq i \leq N$ ,  $R(i)$  is finitely generated, say by  $r_{ij}$ ,  $0 \leq i \leq N$ ,  $1 \leq j \leq k_i$ . We find  $f_{ij} \in I$  such that  $f_{ij} = r_{ij} X^i +$  higher order terms. We claim that  $I$  is generated by the  $f_{ij}$ . Indeed, if  $f \in I$ , we can choose  $c_{ij}$  for  $1 \leq i \leq N$ ,  $1 \leq j \leq k_i$  such that  $f' := f - \sum_{i,j} c_{ij} f_{ij} \in (X^{N+1})$ .

Now let  $g_i \in A[[X]]$ ,  $1 \leq i \leq k_N$ . Write  $f' = \sum_{j=N+1}^{\infty} a_j X^j$ ,  $f_{Ni} = \sum_{j=N}^{\infty} b_{ij} X^j$ ,  $g_i = \sum_{j=0}^{\infty} c_{ij} X^j$ . For any  $k$ , the  $k$ -th coefficient of  $\sum_{i=1}^{k_N} f_{Ni} g_i$  is given by

$$\begin{aligned} \sum_{t=1}^{k_N} \sum_{i+j=k} b_{ti} c_{tj} &= \sum_{t=1}^{k_N} \sum_{i=1}^k b_{ti} c_{t(k-i)} \\ &= \left( \sum_{t=1}^{k_N} \sum_{i=N+1}^k b_{ti} c_{t(k-i)} \right) + \sum_{t=1}^{k_N} r_{Ni} c_{t(k-N)}. \end{aligned}$$

Hence, we can define the  $g_i$  inductively in such a way that the  $k$ -th coefficient of  $\sum f_{Ni} g_i$  is precisely  $a_k$ : since  $R(k) = R(N)$ , there is a choice of  $c_{t(k-N)}$  that works. Therefore,  $f' = \sum f_{Ni} g_i$ , so  $f$  is indeed in the span of the  $f_{ij}$ , hence  $I$  is finitely generated.  $\square$

LEMMA. If  $\varphi: R \rightarrow S$  is a surjective homomorphism of rings and  $R$  is noetherian, then  $S$  is noetherian.

PROOF. Any chain of ideals  $I_i$  of  $R$  can be pulled back to a chain  $\varphi^{-1}(I_i)$  of ideals in  $R$ . Since  $R$  is noetherian, this chain terminates, but since  $I_i = \varphi(\varphi^{-1}(I_i))$  by surjectivity of  $\varphi$ , the chain  $I_i$  terminates as well.  $\square$

EXERCISE. If  $A$  is a ring and  $A[X]$  or  $A[[X]]$  is noetherian, then so is  $A$ .

SOLUTION. There are surjective maps  $A[X] \rightarrow A$  and  $A[[X]] \rightarrow A$  sending a polynomial or formal power series to its constant term, hence the claim follows using the previous lemma.  $\square$

**Exercise 14.**

EXERCISE. If  $M, M', M''$  have finite length and we have a short exact sequence

$$0 \longrightarrow M' \xrightarrow{\iota} M \xrightarrow{\varphi} M'' \longrightarrow 0,$$

then  $\ell(M') - \ell(M) + \ell(M'') = 0$

SOLUTION. If

$$M' = M'_0 \supset M'_1 \supset \dots \supset M'_n = 0$$

and

$$M'' = M''_0 \supset M''_1 \supset \dots \supset M''_m = 0$$

are composition series, then

$$M = \varphi^{-1}(M''_0) \supset \cdots \supset \varphi^{-1}(M''_m) = \iota(M'_0) \supset \cdots \supset \iota(M'_n) = 0$$

is a composition series, since  $\varphi$  induces an isomorphism

$$\frac{\varphi^{-1}(M'_i)}{\varphi^{-1}(M'_{i+1})} \rightarrow \frac{M'_i}{M'_{i+1}}.$$

Hence  $\ell(M) = \ell(M') + \ell(M'')$ .  $\square$

EXERCISE. If  $V$  is a  $k$ -vector space, the following are equivalent:

- (1)  $V$  has finite dimension,
- (2)  $V$  has finite length,
- (3)  $V$  satisfies the ascending chain condition,
- (4)  $V$  satisfies the descending chain condition.

SOLUTION. If  $V$  has a finite basis  $v_1, \dots, v_n$ , then defining  $V_i := \langle v_1, \dots, v_{n-i} \rangle$  gives a composition series, hence (1) implies (2).

(2) implies (3) and (2) implies (4) by part (i) of the exercise.

If  $V$  is not finite-dimensional, then choose a basis  $B$  and let  $v_1, v_2, \dots \in B$  pairwise distinct. Then

$$\langle v_1 \rangle \subsetneq \langle v_1, v_2 \rangle \subsetneq \cdots$$

is an infinite strictly ascending chain and

$$\langle B \rangle \supsetneq \langle B \setminus \{v_1\} \rangle \supsetneq \cdots$$

is an infinite strictly descending chain. Hence (3) implies (1) and (4) implies (1).  $\square$

EXERCISE. If  $A$  is a ring in which the zero ideal is a product  $P_1 \cdots P_n$  of not necessarily distinct maximal ideals, then  $A$  is noetherian iff  $A$  is artinian

SOLUTION. Consider the chain

$$A \supseteq P_1 \supseteq P_1 P_2 \supseteq \cdots \supseteq P_1 \cdots P_n = 0.$$

The  $A$ -module  $A_i := P_1 \cdots P_i / P_1 \cdots P_{i+1}$  is an  $A/P_{i+1}$ -vector space in the obvious way. If  $A$  is noetherian or artinian, then so is  $A_i$  (since it is a quotient of a submodule of  $A$ ), and by part (iii) we obtain a composition series for  $A_i$ , using that an  $A$ -submodule is the same thing as a  $A/P_{i+1}$ -submodule.

Pulling back the composition series along the projection for every  $i$  and stitching together the results, we obtain a composition series for  $A$ . Again by part (i), we find that  $A$  is both noetherian and artinian.  $\square$

## Example Sheet 2

### Exercise 1.

EXERCISE. If  $S$  is a multiplicatively closed subset of a ring  $R$ , and  $M$  is a finitely generated  $R$ -module, then  $S^{-1}M = 0$  if and only if there is some  $s \in S$  such that  $sM = 0$ .

SOLUTION. If  $S^{-1}M = 0$ , then for all  $m \in M$  we have  $(m, 1) \sim (0, 1)$ , hence we find  $s \in S$  such that  $sm = 0$ . In particular, if  $M$  is generated by  $m_1, \dots, m_n$ , we find  $s_i$  such that  $s_i m_i = 0$ . Define  $s := \prod s_i$ , then for any  $m \in M$ , we find  $r_i \in R$  such that  $sm = s(r_1 m_1 + \cdots + r_n m_n) = 0$ , so  $sM = 0$ .

The converse direction is trivial.  $\square$

**Exercise 2.**

EXERCISE. Let  $I$  be an ideal of  $R$ , and define  $S := 1 + I$ . Then  $S^{-1}I \subseteq J(S^{-1}R)$ .

SOLUTION. Let  $i/s \in S^{-1}I$  and let  $r/t \in S^{-1}R$ . Then

$$\alpha := 1 - \frac{i}{s} \frac{r}{t} = 1 - \frac{ri}{st} = \frac{st - ri}{st}.$$

We have  $st \in 1 + I$  and  $ri \in I$ , hence  $st - ri \in 1 + I$ , so  $\alpha$  is a unit. By Exercise 10 on Example Sheet 1 we have  $i/s \in J(S^{-1}R)$ .  $\square$

**Exercise 3.**

EXERCISE. A multiplicatively closed set is saturated if and only if  $R \setminus S$  is a union of prime ideals.

SOLUTION. If  $S$  is saturated and  $x \in R \setminus S$ , let  $\Sigma$  denote the set of ideals  $I$  such that  $I \subseteq R \setminus S$  and  $x \in I$ .

If  $y \in R$ , then  $xy \in R \setminus S$ , since otherwise we would have  $x \in S$  by saturation of  $S$ . Hence  $(x) \in \Sigma$ .

The set  $\Sigma$  admits upper bounds, as the union of a chain of ideals once again is an ideal in  $\Sigma$ .

Hence we have a maximal element  $I \in \Sigma$ , which is prime, since if  $ab \in I$  and  $a \notin I$ ,  $b \notin I$ , then  $I + Ra$  and  $I + Rb$  both intersect nontrivially with  $S$ , so for  $s_1 \in S \cap I + Ra$ ,  $s_2 \in S \cap I + Rb$  we have  $s_1 s_2 \in S \cap I = \emptyset$ , a contradiction.

Hence every element of  $R \setminus S$  is contained in a prime ideal which is fully contained in  $R \setminus S$ , so  $R \setminus S$  is the union of these prime ideals.

Conversely, if  $R \setminus S$  is the union of prime ideals and  $xy \in S$ , then if  $x \notin S$ , then  $x$  was contained in one of the ideals, and by the ideal property, so would be  $xy$ , a contradiction. Hence  $x \in S$  and symmetrically  $y \in S$ .  $\square$

EXERCISE. If  $S$  is a multiplicatively closed subset of  $R$ , there is a unique smallest saturated multiplicatively closed subset  $S'$  containing  $S$ , and it is given as the complement in  $R$  of the union of the prime ideals which do not meet  $S$ .

SOLUTION. Define  $S'$  as the complement of the unions of the prime ideals which do not meet  $S$ . The set  $S'$  is multiplicatively closed (since the ideals are prime) and saturated by (i). Furthermore, by definition have  $R \setminus S' \subseteq R \setminus S$ , hence  $S \subseteq S'$ .

Let  $S''$  be a saturated multiplicatively closed subset satisfying  $S \subseteq S''$ . By (i),  $R \setminus S''$  is a union of prime ideals  $p_i$ . Let  $p_i \subseteq R \setminus S'' \subseteq R \setminus S$  be one of these prime ideals. Then  $p_i \cap S = \emptyset$ , so  $p_i \subseteq R \setminus S'$ . Hence we have  $R \setminus S'' \subseteq R \setminus S'$ , so  $S' \subseteq S''$ , completing the proof that  $S'$  is minimal.  $\square$

**Exercise 4.**

EXERCISE. Let  $S, T$  be two multiplicatively closed subsets of  $R$ , and let  $U$  be the image of  $T$  in  $S^{-1}R$ . Then  $(ST)^{-1}R$  and  $U^{-1}S^{-1}R$  are isomorphic as rings.

SOLUTION. Consider the following commutative diagram.

$$\begin{array}{ccccc} R & \xrightarrow{\alpha} & S^{-1}R & \xrightarrow{\delta} & U^{-1}S^{-1}R \\ & \searrow \beta & \downarrow \gamma & \nearrow \Phi & \uparrow \Psi \\ & & (ST)^{-1}R & & \end{array}$$

The maps  $\alpha, \beta$  and  $\delta$  are localization maps. Since  $S \subseteq ST$ ,  $\beta(s)$  is a unit for every  $s \in S$ , hence from the universal property of localization we have  $\gamma: S^{-1}R \rightarrow (ST)^{-1}R$  satisfying  $\gamma \circ \alpha = \beta$ . An element of  $U$  is of the form  $\alpha(t)$  for some  $t \in T$ .

We have  $\gamma(\alpha(t)) = \beta(t)$ , which is invertible, hence again from the universal property we have a map  $\Phi: U^{-1}S^{-1}R \rightarrow (ST)^{-1}R$  such that  $\Phi \circ \delta = \gamma$ . We know how this map is defined: if  $r \in R$ ,  $s \in S$ ,  $t \in T$ , we have

$$\Phi\left(\frac{r/s}{\alpha(t)}\right) = \gamma(r/s)\gamma(\alpha(t))^{-1} = \beta(r)\beta(s)^{-1}\beta(t)^{-1} = \frac{r}{1} \frac{1}{s} \frac{1}{t} = \frac{r}{st}.$$

Next, let  $st \in ST$ . We have

$$\delta(\alpha(st)) = \delta(\alpha(s))\delta(\alpha(t)) = \frac{s/1}{1} \frac{\alpha(t)}{1}.$$

This has the inverse

$$\frac{1/s}{1} \frac{1}{\alpha(t)},$$

so it is a unit, and the universal property yields  $\Psi: (ST)^{-1}R \rightarrow U^{-1}S^{-1}R$  satisfying  $\Psi \circ \delta = \gamma \circ \alpha$ . Again, if  $r \in R$ ,  $s \in S$  and  $t \in T$ , we have

$$\Psi\left(\frac{r}{st}\right) = \delta(\alpha(r))\delta(\alpha(st))^{-1} = \frac{r/1}{1} \frac{1/s}{1} \frac{1}{\alpha(t)} = \frac{r/s}{\alpha(t)},$$

where we have used our inverse calculation from above.

Hence,  $\Phi$  and  $\Psi$  are two-sided inverses of each other, finishing the proof.  $\square$

### Exercise 5.

EXERCISE. Let  $R$  be a ring. Suppose that for each prime ideal  $P$  the local ring  $R_P$  has no non-zero nilpotent element. Then  $R$  has no nonzero nilpotent element.

SOLUTION. Let  $x \in R$  be a nilpotent element. Consider the ideal  $\text{ann}(x) = \{r \in R \mid rx = 0\}$ . If  $\text{ann}(x) \neq R$ , then  $\text{ann}(x) \subseteq \mathfrak{m}$  for some maximal ideal  $\mathfrak{m}$ . Then  $\mathfrak{m}$  is prime. Let  $\varphi: R \rightarrow R_{\mathfrak{m}}$ . Since  $x$  is nilpotent, we find  $n$  such that  $x^n = 0$ . Then  $\varphi(x)^n = \varphi(x^n) = 0$ , hence  $\varphi(x) = 0$ . By definition of localization, this means that there is some  $s \in R \setminus \mathfrak{m}$  such that  $sx = 0$ . But then  $s \in \text{ann}(x)$ , which is a contradiction. Hence we must have  $\text{ann}(x) = R$ , in particular  $x = 1 \cdot x = 0$ .  $\square$

EXERCISE. There is a ring  $R$  such that  $R$  is not an integral domain, but for every prime ideal  $P$  of  $R$ ,  $R_P$  is an integral domain.

SOLUTION. Define  $R := \mathbb{Z}/6\mathbb{Z}$ . The prime ideals of  $R$  are (2) and (3). By writing down all elements and checking the relations between them, we can check that the localizations at both of them are fields, hence integral domains.  $\square$