A Primer of Commutative Algebra

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May 30, 2009, v2.10

Abstract

These notes prove the basic theorems in commutative algebra required for algebraic geometry and algebraic groups. They assume only a knowledge of the algebra usually taught in advanced undergraduate or first-year graduate courses.

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Notations and Conventions

Our convention is that rings have identity elements and homomorphisms of rings respect the identity elements. A unit of a ring is an element admitting an inverse. The units of a ring \( A \) form a group, which we denote \( \mathbb{A}^\times \). Throughout “ring” means “commutative ring”.

\(^1\)An element \( e \) of a ring \( A \) is an identity element if \( ea = a = ae \) for all elements \( a \) of the ring. It is usually denoted \( 1_A \) or just \( 1 \). Some authors call this a unit element, but then an element can be a unit without being a unit element. Worse, a unit need not be the unit.

\(^2\)This notation differs from that of Bourbaki, who writes \( A^\times \) for the multiplicative monoid \( A \setminus \{0\} \) and \( A^\times \) for the group of units. We shall rarely need the former, and \( \times \) is overused.
Following Bourbaki, we let \( \mathbb{N} = \{0, 1, 2, \ldots\} \). For a field \( k, k^a \) denotes an algebraic closure of \( k \).

- \( X \subset Y \) if \( X \) is a subset of \( Y \) (not necessarily proper).
- \( \bar{X} \equiv Y \) if \( X \) is defined to be \( Y \), or equals \( Y \) by definition.
- \( X \approx Y \) if \( X \) is isomorphic to \( Y \).
- \( X \simeq Y \) if \( X \) and \( Y \) are canonically isomorphic (or there is a given or unique isomorphism).

**Acknowledgements**

I thank the following for providing corrections and comments for earlier versions of these notes: Andrew McLennan, Shu Otsuka.

## 1 Rings and algebras

Let \( A \) be a ring. A **subring** of \( A \) is a subset that contains \( 1_A \) and is closed under addition, multiplication, and the formation of negatives. An **\( A \)-algebra** is a ring \( B \) together with a homomorphism \( i_B: A \to B \). A **homomorphism** of \( A \)-algebras \( B \to C \) is a homomorphism of rings \( \varphi: B \to C \) such that \( \varphi(i_B(a)) = i_C(a) \) for all \( a \in A \).

Elements \( x_1, \ldots, x_n \) of an \( A \)-algebra \( B \) are said to **generate** \( B \) if every element of \( B \) can be expressed as a polynomial in the \( x_i \) with coefficients in \( i_B(A) \), i.e., if the homomorphism of \( A \)-algebras \( A[X_1, \ldots, X_n] \to B \) acting as \( i_B \) on \( A \) and sending \( X_i \) to \( x_i \) is surjective. We then write \( B = (i_B A)[x_1, \ldots, x_n] \).

A ring homomorphism \( A \to B \) is of **finite type**, and \( B \) is a **finitely generated** \( A \)-algebra, if \( B \) is generated by a finite set of elements as an \( A \)-algebra.

A ring homomorphism \( A \to B \) is **finite**, and \( B \) is a **finite** \( A \)-algebra, if \( B \) is finitely generated as an \( A \)-module. If \( A \to B \) and \( B \to C \) are finite ring homomorphisms, then so also is their composite \( A \to C \).

Let \( k \) be a field, and let \( A \) be a \( k \)-algebra. When \( 1_A \neq 0 \), the map \( k \to A \) is injective, and we can identify \( k \) with its image, i.e., we can regard \( k \) as a subring of \( A \). When \( 1_A = 0 \), the ring \( A \) is the zero ring \( \{0\} \).

Let \( A[X] \) be the ring of polynomials in the symbol \( X \) with coefficients in \( A \). If \( A \) is an integral domain, then \( \deg(g) = \deg(f) + \deg(g) \), and so \( A[X] \) is also an integral domain; moreover, \( A[X]^\times = A^\times \).

Let \( A \) be an algebra over a field \( k \). If \( A \) is an integral domain and finite as a \( k \)-algebra, then it is a field because, for each nonzero \( a \in A \), the \( k \)-linear map \( x \mapsto ax: A \to A \) is injective, and hence is surjective, which shows that \( a \) has an inverse. If \( A \) is an integral domain and each element of \( A \) is algebraic over \( k \), then for each \( a \in A \), \( k[a] \) is an integral domain finite over \( k \), and hence contains an inverse of \( a \); again \( A \) is a field.

## 1.1 Products and Idempotents

An element \( e \) of a ring \( A \) is **idempotent** if \( e^2 = e \). For example, 0 and 1 are both idempotents — they are called the **trivial idempotents**. Idempotents \( e_1, \ldots, e_n \) are **orthogonal** if \( e_ie_j = 0 = e_je_i \) for \( i \neq j \). Any sum of orthogonal idempotents is again idempotent. A set

\[ {\text{This is Bourbaki’s terminology. Finite homomorphisms of rings correspond to finite maps of varieties and schemes. Some other authors say “module-finite”.}} \]
\{e_1, \ldots, e_n\} of orthogonal idempotents is complete if \(e_1 + \cdots + e_n = 1\). Any set of orthogonal idempotents \(\{e_1, \ldots, e_n\}\) can be made into a complete set of orthogonal idempotents by adding the idempotent \(e = 1 - (e_1 + \cdots + e_n)\).

If \(A = A_1 \times \cdots \times A_n\) (direct product of rings), then the elements
\[
e_i = (0, \ldots, 1, \ldots, 0), \quad 1 \leq i \leq n,
\]
form a complete set of orthogonal idempotents in \(A\). Conversely, if \(\{e_1, \ldots, e_n\}\) is a complete set of orthogonal idempotents in \(A\), then \(Ae_i\) becomes a ring with the addition and multiplication induced by that of \(A\), and \(A \simeq Ae_1 \times \cdots \times Ae_n\).

## 2 Ideals

Let \(A\) be a ring. An ideal \(a\) in \(A\) is a subset such that
\[\begin{align*}
&\diamond \quad a \in A, r \in A \Rightarrow ra \in a. \\
&\diamond \quad a \in A, r \in A \Rightarrow ar \in a.
\end{align*}\]
The ideal generated by a subset \(S\) of \(A\) is the intersection of all ideals \(a\) containing \(S\) — it is easy to verify that this is in fact an ideal, and that it consists of all finite sums of the form \(\sum r_j s_j\) with \(r_j \in A, s_j \in S\). The ideal generated by the empty set is the zero ideal \(\{0\}\).

When \(S = \{s_1, s_2, \ldots\}\), we write \((s_1, s_2, \ldots)\) for the ideal it generates.

An ideal is principal if it is generated by a single element. Such an ideal \((a)\) is proper if and only if \(a\) is not a unit. Thus a ring \(A\) is a field if and only if \(1_A \neq 0\) and \(A\) contains no nonzero proper ideals.

Let \(a\) and \(b\) be ideals in \(A\). The set \(\{a + b \mid a \in a, b \in b\}\) is an ideal, denoted \(a + b\). The ideal generated by \(\{ab \mid a \in a, b \in b\}\) is denoted by \(ab\). Clearly \(ab\) consists of all finite sums \(\sum a_i b_j\) with \(a_i \in a\) and \(b_j \in b\), and if \(a = (a_1, \ldots, a_m)\) and \(b = (b_1, \ldots, b_n)\), then \(ab = (a_1 b_1, \ldots, a_i b_j, \ldots, a_m b_n)\). Note that \(ab \subseteq aA = a\) and \(ab \subseteq Ab = b\), and so \[ab \subseteq a \cap b. \quad (1)\]

The kernel of a homomorphism \(A \to B\) is an ideal in \(A\). Conversely, for any ideal \(a\) in a ring \(A\), the set of cosets of \(a\) in \(A\) forms a ring \(A/a\), and \(a \mapsto a + a\) is a homomorphism \(\varphi: A \to A/a\) whose kernel is \(a\). There is a one-to-one correspondence
\[
\{\text{ideals of } A \text{ containing } a\} \xleftarrow{\psi^{-1}(0)\mapsto b} \{\text{ideals of } A/a\}. \quad (2)
\]
For any ideal \(b\) of \(A\), \(\psi^{-1}(0)\psi(b) = a + b\).

The ideals of \(A \times B\) are all of the form \(a \times b\) with \(a\) and \(b\) ideals in \(A\) and \(B\). To see this, note that if \(c\) is an ideal in \(A \times B\) and \((a, b) \in c\), then \((a, 0) = (1, 0)(a, b) \in c\) and \((0, b) = (0, 1)(a, b) \in c\). Therefore, \(c = a \times b\) with
\[
a = \{a \mid (a, 0) \in c\}, \quad b = \{b \mid (0, b) \in c\}.
\]

An ideal \(p\) in \(A\) is prime if \(p \neq A\) and \(ab \in p \Rightarrow a \in p\) or \(b \in p\). Thus \(p\) is prime if and only if the quotient ring \(A/p\) is nonzero and has the property that
\[
ab = 0, \quad a \neq 0 \Rightarrow b = 0.
\]
\[\text{But } Ae_i \text{ is not a subring of } A \text{ if } n \neq 1 \text{ because its identity element is } e_i \neq 1_A. \text{ However, the map } a \mapsto ae_i: A \to Ae_i \text{ realizes } Ae_i \text{ as a quotient of } A.\]
i.e., \( A/p \) is an integral domain. Note that if \( p \) is prime and \( a_1 \cdots a_n \in p \), then either \( a_1 \in p \) or \( a_2 \cdots a_n \in p \); if the latter, then either \( a_2 \in p \) or \( a_3 \cdots a_n \in p \); continuing in this fashion, we find that at least one of the \( a_i \in p \).

An ideal \( m \) in \( A \) is \textbf{maximal} if it is a maximal element of the set of proper ideals in \( A \). Therefore an ideal \( m \) is maximal if and only if the quotient ring \( A/m \) is nonzero and has no proper nonzero ideals (by (2)), and so is a field. Note that

\[
\text{m maximal } \implies \text{m prime.}
\]

**A multiplicative subset** of a ring \( A \) is a subset \( S \) with the property:

\[
1 \in S, \quad a, b \in S \implies ab \in S.
\]

For example, the following are multiplicative subsets:

- the multiplicative subset \( \{1, f, \ldots, f', \ldots\} \) generated by an element \( f \) of \( A \);
- the complement of a prime ideal (or of a union of prime ideals);
- \( 1 + a \overset{def}{=} \{1 + a \mid a \in \alpha\} \) for any ideal \( \alpha \) of \( A \).

**Proposition 2.1.** Let \( S \) be a subset of a ring \( A \), and let \( \alpha \) be an ideal disjoint from \( S \). The set of ideals in \( A \) containing \( \alpha \) and disjoint from \( S \) contains maximal elements (i.e., an element not properly contained in any other ideal in the set). If \( S \) is multiplicative, then any such maximal element is prime.

**Proof.** The set \( \Sigma \) of ideals containing \( \alpha \) and disjoint from \( S \) is nonempty (it contains \( \alpha \)). If \( A \) is noetherian (see [8] below), \( \Sigma \) automatically contains maximal elements. Otherwise, we apply Zorn’s lemma. Let \( b_1 \subset b_2 \subset \cdots \) be a chain of ideals in \( \Sigma \), and let \( b = \bigcup b_i \). Then \( b \in \Sigma \), because otherwise some element of \( S \) lies in \( b \), and hence in some \( b_i \), which contradicts the definition of \( \Sigma \). Therefore \( b \) is an upper bound for the chain. As every chain in \( \Sigma \) has an upper bound, Zorn’s lemma implies that \( \Sigma \) has a maximal element.

Assume that \( S \) is a multiplicative subset of \( A \), and let \( \epsilon \) be maximal in \( \Sigma \). Let \( bb' \in \epsilon \). If \( b \) is not in \( \epsilon \), then \( \epsilon + (b) \) properly contains \( \epsilon \), and so it is not in \( \Sigma \). Therefore there exist an \( f \in S \cap (\epsilon + (b)) \), say, \( f = c + ab \) with \( c \in \epsilon \). Similarly, if \( bb' \) is not in \( \epsilon \), then there exists an \( f' \in S \) such that \( f' = c' + a'b' \) with \( c' \in \epsilon \). Now

\[
ff' = cc' + abc' + a'b'c + aa'bb' \in \epsilon,
\]

which contradicts

\[
ff' \notin S.
\]

**Corollary 2.2.** Every proper ideal in a ring is contained in a maximal ideal.

**Proof.** For a proper ideal \( \alpha \) of \( A \), apply the proposition with \( S = \{1\} \).

**Exercise 2.3.** A multiplicative subset \( S \) of a ring \( A \) is said to be \textbf{saturated} if

\[
ab \in S \implies a, b \in S.
\]

Show the saturated multiplicative subsets are exactly the complements of unions of prime ideals (hence every multiplicative subset \( S \) is contained in a smallest saturated multiplicative subset, namely, \( A \setminus \bigcup \{p \mid \text{p prime, } p \cap S = \emptyset\} \)).
The proof of (2.1) is one of many in commutative algebra in which an ideal, maximal with respect to some property, is shown to be prime. For a general examination of this phenomenon, see Lam and Reyes 2008.

The radical \( \text{rad}(a) \) of an ideal \( a \) is

\[
\{ f \in A \mid f^r \in a, \text{some } r \in \mathbb{N}, r > 0 \}.
\]

An ideal \( a \) is said to be radical if it equals its radical. Thus \( a \) is radical if and only if the quotient ring \( A/a \) is reduced, i.e., without nonzero nilpotent elements (elements some power of which is zero). Since integral domains are reduced, prime ideals (\textit{a fortiori} maximal ideals) are radical. The radical of \( 0/0 \) consists of the nilpotent elements of \( A \)—it is called the nilradical of \( A \).

If \( b \leftrightarrow b' \) under the one-to-one correspondence \( 2 \), then \( A/b \simeq (A/a)/b' \), and so \( b \) is prime (resp. maximal, radical) if and only if \( b' \) is prime (resp. maximal, radical).

**Proposition 2.5.** Let \( a \) be an ideal in a ring \( A \).

(a) The radical of \( a \) is an ideal.

(b) \( \text{rad}(\text{rad}(a)) = \text{rad}(a) \).

**Proof.** (a) If \( a \in \text{rad}(a) \), then clearly \( fa \in \text{rad}(a) \) for all \( f \in A \). Suppose \( a, b \in \text{rad}(a) \), with say \( a^r \in a \) and \( b^s \in a \). When we expand \( (a + b)^{r+s} \) using the binomial theorem, we find that every term has a factor \( a^r \) or \( b^s \), and so lies in \( a \).

(b) If \( a^r \in \text{rad}(a) \), then \( a^{rs} = (a^r)^s \in a \) for some \( s > 0 \).

Note that (b) of the proposition shows that \( \text{rad}(a) \) is radical, and so is the smallest radical ideal containing \( a \).

If \( a \) and \( b \) are radical, then \( a \cap b \) is radical, but \( a + b \) need not be: consider, for example, \( a = (X^2 - Y) \) and \( b = (X^2 + Y) \); they are both prime ideals in \( k[X, Y] \) (by 4.7 below), but \( a + b = (X^2, Y) \), which contains \( X^2 \) but not \( X \).

**Proposition 2.6.** The radical of an ideal is equal to the intersection of the prime ideals containing it. In particular, the nilradical of a ring \( A \) is equal to the intersection of the prime ideals of \( A \).

**Proof.** If \( a = A \), then the set of prime ideals containing it is empty, and so the intersection is \( A \). Thus we may suppose that \( a \) is a proper ideal of \( A \). Then \( \text{rad}(a) \subseteq \bigcap_{p \supseteq a} p \) because prime ideals are radical and \( \text{rad}(a) \) is the smallest radical ideal containing \( a \).

Conversely, suppose that \( f \notin \text{rad}(a) \). According to Proposition 2.4, there exists a prime ideal containing \( a \) and disjoint the multiplicative subset \( \{1, f, \ldots\} \). Therefore \( f \notin \bigcap_{p \supseteq a} p \).

**Definition 2.7.** The Jacobson radical \( \mathcal{J} \) of a ring is the intersection of the maximal ideals of the ring:

\[
\mathcal{J}(A) = \bigcap \{m \mid m \text{ maximal in } A\}.
\]

A ring \( A \) is \textit{local} if it has exactly one maximal ideal. For such a ring, the Jacobson radical is \( m \).

**Proposition 2.8.** An element \( c \) of \( A \) is in the Jacobson radical of \( A \) if and only if \( 1 - ac \) is a unit for all \( a \in A \).
\textbf{PROOF.} We prove the contrapositive: there exists a maximal ideal \( m \) such that \( a \notin m \) if and only if there exists an \( a \in A \) such that \( 1-ac \) is not a unit.

\( \Leftarrow \): As \( 1-ac \) is not a unit, it lies in some maximal ideal \( m \) of \( A \) (by \( \text{2.4a} \)). Then \( c \notin m \), because otherwise \( 1 = (1-ac) + ac \in m \).

\( \Rightarrow \): Suppose that \( c \) is not in the maximal ideal \( m \). Then \( m + (c) = A \), and so \( 1 = m + ac \) for some \( m \in m \) and \( a \in A \). Now \( 1-ac \in m \), and so it is not a unit. \( \square \)

\textbf{Proposition 2.9.} Let \( p_1, \ldots, p_r, r \geq 1 \), be ideals in \( A \) with \( p_2, \ldots, p_r \) prime, and let \( a \) be an ideal in \( A \). Then

\[ a \subset \bigcup_{1 \leq i \leq r} p_i \implies a \subset p_i \text{ for some } i. \]

\textbf{PROOF.} We prove the contrapositive:

if the ideal \( a \) in not contained in any of the ideals \( p_i \), then it is not contained in their union.

For \( r = 1 \), there is nothing to prove, and so we may assume that \( r > 1 \) and (inductively) that the statement is true for \( r-1 \). As \( a \) is not contained in any of the ideals \( p_1, \ldots, p_r \), for each \( i \), there exists an \( a_i \in a \) not in the union of the ideals \( p_1, \ldots, p_{i-1}, p_{i+1}, \ldots, p_r \). If there exists an \( i \) such that \( a_i \) does not lie in \( p_i \), then \( a_i \in a \setminus p_1 \cup \ldots \cup p_r \), and the proof is complete. Thus suppose that every \( a_i \in p_i \), and consider

\[ a = a_1 \cdots a_{r-1} + a_r. \]

Because \( p_r \) is prime and none of the elements \( a_1, \ldots, a_{r-1} \) lies in \( p_r \), their product does not lie in \( p_r \); however, \( a_r \in p_r \), and so \( a \notin p_r \). Next consider a prime \( p_i \) with \( i \leq r-1 \). In this case \( a_1 \cdots a_{r-1} \in p_i \) because the product involves \( a_i \), but \( a_r \notin p_i \), and so again \( a \notin p_i \). Now \( a \in a \setminus p_1 \cup \ldots \cup p_r \) and so \( a \) is not contained in the union of the \( p_i \). \( \square \)

\textbf{EXTENSION AND CONTRACTION OF IDEALS}

Let \( \varphi: A \to B \) be a homomorphism of rings.

\textbf{Notation 2.10.} For an ideal \( b \) of \( B \), \( \varphi^{-1}(b) \) is an ideal in \( A \), called the \textit{contraction} of \( b \) to \( A \), which is often denoted \( b^e \). For an ideal \( a \) of \( A \), the ideal in \( B \) generated by \( \langle \varphi(a) \rangle \) is called the \textit{extension} of \( a \) to \( B \), and is often denoted \( a^z \).

When \( \varphi \) is surjective, \( \varphi(a) \) is already an ideal, and when \( A \) is a subring of \( B \), \( b^e = b \cap A \).

2.11. There are the following equalities \( (a, a^e) \) ideals in \( A; b, b^e \) ideals in \( B \):

\[(a + a')^e = a^e + a'^e, \quad (aa)^e = a^e a'^e, \quad (b \cap b')^e = b^e \cap b'^e, \quad \text{rad}(b)^e = \text{rad}(b^e). \]

2.12. Obviously (i) \( a \subset a^{ee} \) and (ii) \( b^{ee} \subset b \) (a an ideal of \( A \); \( b \) an ideal of \( B \)). On applying \( e \) to (i), we find that \( a^e \subset a^{e^e} \), and (ii) with \( b \) replaced by \( a^e \) shows that \( a^{ee} \subset a^e \); therefore \( a^e = a^{e^e} \). Similarly, \( b^{ee} = b^e \). It follows that extension and contraction define inverse bijections between the set of contracted ideals in \( A \) and the set of extended ideals in \( B \):

\[ \{b^e \subset A \mid b \text{ an ideal in } B \} \overset{e}{\cong} \{a^e \subset B \mid a \text{ an ideal in } A \} \]

Note that, for any ideal \( b \) in \( B \), the map \( A/b^e \to B/b \) is injective, and so \( b^e \) is prime (resp. radical) if \( b \) is prime (resp. radical).
THE CHINESE REMAINDER THEOREM

Recall the classical form of the theorem: let \( d_1, \ldots, d_n \) be integers, relatively prime in pairs; then for any integers \( x_1, \ldots, x_n \), the congruences
\[
x \equiv x_i \mod d_i
\]
have a simultaneous solution \( x \in \mathbb{Z} \); moreover, if \( x \) is one solution, then the other solutions are the integers of the form \( x + md \) with \( m \in \mathbb{Z} \) and \( d = \prod d_i \).

We want to translate this in terms of ideals. Integers \( m \) and \( n \) are relatively prime if and only if \( (m,n) = \mathbb{Z} \), i.e., if and only if \( (m) + (n) = \mathbb{Z} \). This suggests defining ideals \( a \) and \( b \) in a ring \( A \) to be relativeply prime (or coprime) if \( a + b = A \).

If \( m_1, \ldots, m_k \) are integers, then \( \bigcap (m_i) = (m) \) where \( m \) is the least common multiple of the \( m_i \). Thus \( \bigcap (m_i) \supset (\prod m_i) \), which equals \( \prod (m_i) \). If the \( m_i \) are relatively prime in pairs, then \( m = \prod m_i \), and so we have \( \bigcap (m_i) = \prod (m_i) \). Note that in general,
\[
a_1 \cdot a_2 \cdots a_n \subset a_1 \cap a_2 \cap \ldots \cap a_n,
\]
but the two ideals need not be equal.

These remarks suggest the following statement.

**Theorem 2.13 (Chinese Remainder Theorem).** Let \( a_1, \ldots, a_n \) be ideals in a ring \( A \). If \( a_i \) is relatively prime to \( a_j \) whenever \( i \neq j \), then the map
\[
a \mapsto (\ldots, a + a_i, \ldots): A \to A/a_1 \times \cdots \times A/a_n
\]
is surjective with kernel \( \prod a_i = \bigcap a_i \).

**Proof.** Suppose first that \( n = 2 \). As \( a_1 + a_2 = A \), there exist \( a_i \in a_i \) such that \( a_1 + a_2 = 1 \).

Then \( a_1 x_2 + a_2 x_1 \) maps to \( (x_1 \mod a_1, x_2 \mod a_2) \), which shows that (3) is surjective.

For each \( i \), there exist elements \( a_i \in a_1 \) and \( b_i \in a_i \) such that
\[
a_i + b_i = 1, \text{ all } i \geq 2.
\]
The product \( \prod_{i \geq 2} (a_i + b_i) = 1 \), and lies in \( a_1 + \prod_{i \geq 2} a_i \), and so
\[
a_1 + \prod_{i \geq 2} a_i = A.
\]

We can now apply the theorem in the case \( n = 2 \) to obtain an element \( y_1 \) of \( A \) such that
\[
y_1 \equiv 1 \mod a_1, \quad y_1 \equiv 0 \mod \prod_{i \geq 2} a_i.
\]
These conditions imply
\[
y_1 \equiv 1 \mod a_1, \quad y_1 \equiv 0 \mod a_j, \text{ all } j > 1.
\]

Similarly, there exist elements \( y_2, \ldots, y_n \) such that
\[
y_i \equiv 1 \mod a_i, \quad y_j \equiv 0 \mod a_j \text{ for } j \neq i.
\]
The element \( x = \sum x_i y_i \) maps to \( (x_1 \mod a_1, \ldots, x_n \mod a_n) \), which shows that (3) is surjective.
3 NOETHERIAN RINGS

It remains to prove that $\bigcap a_i = \prod a_i$. Obviously $\prod a_i \subseteq \bigcap a_i$. Suppose first that $n = 2$, and let $a_1 + a_2 = 1$, as before. For $c \in a_1 \cap a_2$, we have

$$c = a_1 c + a_2 c \in a_1 \cdot a_2$$

which proves that $a_1 \cap a_2 = a_1 a_2$. We complete the proof by induction. This allows us to assume that $\prod_{i \geq 2} a_i = \bigcap_{i \geq 2} a_i$. We showed above that $a_1$ and $\prod_{i \geq 2} a_i$ are relatively prime, and so

$$a_1 \cdot (\prod_{i \geq 2} a_i) = a_1 \cap (\prod_{i \geq 2} a_i)$$

by the $n = 2$ case. Now $a_1 \cdot (\prod_{i \geq 2} a_i) = \prod_{i \geq 1} a_i$ and $a_1 \cap (\prod_{i \geq 2} a_i) = a_1 \cap (\bigcap_{i \geq 2} a_i) = \bigcap_{i \geq 1} a_i$, which completes the proof.

\[\Box\]

3 Noetherian rings

PROPOSITION 3.1. The following three conditions on a ring $A$ are equivalent:

(a) every ideal in $A$ is finitely generated;

(b) every ascending chain of ideals $a_1 \subset a_2 \subset \cdots$ eventually becomes constant, i.e., for some $m$, $a_m = a_{m+1} = \cdots$.

(c) every nonempty set of ideals in $A$ has a maximal element.

PROOF. (a) \(\Rightarrow\) (b): If $a_1 \subset a_2 \subset \cdots$ is an ascending chain, then $a = \bigcup a_i$ is an ideal, and hence has a finite set $\{a_1, \ldots, a_n\}$ of generators. For some $m$, all the $a_i$ belong $a_m$, and then

$$a_m = a_{m+1} = \cdots = a.$$

(b) \(\Rightarrow\) (c): Let $\Sigma$ be a nonempty set of ideals in $A$. Then (b) certainly implies that every ascending chain of ideals in $\Sigma$ has an upper bound in $\Sigma$, and so Zorn’s lemma shows that $\Sigma$ has a maximal element.

(c) \(\Rightarrow\) (a): Let $a$ be an ideal, and let $\Sigma$ be the set of finitely generated ideals contained in $a$. Then $\Sigma$ is nonempty because it contains the zero ideal, and so it contains a maximal element $c = (a_1, \ldots, a_r)$. If $c \neq a$, then there exists an element $a \in a \setminus c$, and $(a_1, \ldots, a_r, a)$ will be a finitely generated ideal in $a$ properly containing $c$. This contradicts the definition of $c$.

\[\Box\]

A ring $A$ is noetherian if it satisfies the equivalent conditions of the proposition. For example, fields and principal ideal domains are noetherian. On applying (c) to the set of all proper ideals containing a fixed proper ideal, we see that every proper ideal in a noetherian ring is contained in a maximal ideal. We saw in (2.4) that this is, in fact, true for any ring, but the proof for non-noetherian rings requires Zorn’s lemma.

A quotient $A/a$ of a noetherian ring $A$ is noetherian, because the ideals in $A/a$ are all of the form $b/a$ with $b$ an ideal in $A$, and any set of generators for $b$ generates $b/a$.

PROPOSITION 3.2. Let $A$ be a ring. The following conditions on an $A$-module $M$ are equivalent:

(a) every submodule of $M$ is finitely generated (in particular, $M$ is finitely generated);

(b) every ascending chain of submodules $M_1 \subset M_2 \subset \cdots$ eventually becomes constant.

(c) every nonempty set of submodules of $M$ has a maximal element.
An $A$-module $M$ is noetherian if it satisfies the equivalent conditions of the proposition. Let $A$ denote $A$ regarded as a left $A$-module. Then the submodules of $A$ are exactly the ideals in $A$, and so $A$ is noetherian (as an $A$-module) if and only if $A$ is noetherian (as a ring).

**Proposition 3.3.** Let $M$ be an $A$-module, and let $N$ be a submodule of $M$. The module $M$ is noetherian if and only if both $N$ and $M/N$ are noetherian.

**Proof.** $\Rightarrow$: An ascending chain of submodules in $N$ or in $M/N$ gives rise to an ascending chain in $M$, and therefore becomes constant.

$\Leftarrow$: I claim that if $M' \subset M''$ are submodules of $M$ such that $M' \cap N = M'' \cap N$ and $M'$ and $M''$ have the same image in $M/N$, then $M' = M''$. To see this, let $x \in M''$; the second condition implies that there exists a $y \in M'$ with the same image as $x$ in $M/N$, i.e., such that $x - y \in N$. Then $x - y \in M'' \cap N \subset M'$, and so $x \in M'$.

Now consider an ascending chain of submodules of $M$. If $M/N$ is Noetherian, the image of the chain in $M/N$ becomes stationary, and if $N$ is Noetherian, the intersection of the chain with $N$ becomes stationary. Now the claim shows that the chain itself becomes stationary.

More generally, consider an exact sequence

$$0 \rightarrow M' \xrightarrow{i} M \xrightarrow{q} M'' \rightarrow 0$$

of $A$-modules. The module $M$ is noetherian if and only if $M'$ and $M''$ are both noetherian. For example, a direct sum

$$M = M_1 \oplus M_2$$

of $A$-modules is noetherian if and only if $M_1$ and $M_2$ are both noetherian (because $0 \rightarrow M_1 \rightarrow M \rightarrow M_2 \rightarrow 0$ is exact).

**Proposition 3.4.** Let $A$ be a noetherian ring. Then every finitely generated $A$-module is noetherian.

**Proof.** If $M$ is generated by a single element, then $M \approx A/\alpha$ for some ideal $\alpha$ in $A$, and the statement is obvious. We argue by induction on the minimum number $n$ of generators of $M$. Since $M$ contains a submodule $N$ generated by $n-1$ elements such that the quotient $M/N$ is generated by a single element, the statement follows from (3.3).

**Proposition 3.5.** Every finitely generated module $M$ over a noetherian ring $A$ contains a finite chain of submodules $M \supset M_2 \supset \cdots \supset M_1 \supset 0$ such that each quotient $M_i/M_{i-1}$ is isomorphic to $A/p_i$ for some prime ideal $p_i$.

**Proof.** The annihilator $\text{ann}(x)$ of an element $x$ of $M$ is $\{a \in A \mid ax = 0\}$. It is an ideal in $A$, which is proper if $x \neq 0$. I claim that any ideal $\alpha$ that is maximal among the annihilators of nonzero elements of $A$ is prime. Suppose $\alpha = \text{ann}(x)$, and let $ab \in \alpha$, so that $abx = 0$. Then $\alpha \supset (\alpha) + \alpha \subset \text{ann}(bx)$. If $b \notin \alpha$, then $bx \neq 0$, and so $\alpha = \text{ann}(bx)$ by maximality, which implies that $a \in \alpha$.

We now prove the proposition. Note that, for any $x \in M$, the submodule $Ax$ of $M$ is isomorphic to $A/\text{ann}(x)$. Therefore, if $M$ is nonzero, then it contains a submodule $M_1$
isomorphic to $A/p_1$ for some prime ideal $p_1$. Similarly, $M/M_1$ contains a submodule $M_2/M_1$ isomorphic $A/p_2$ for some prime ideal $p_2$, and so on. The chain $0 \subseteq M_1 \subseteq M_2 \subseteq \cdots$ terminates because $M$ is noetherian (by 3.4).

**Theorem 3.6 (Hilbert Basis Theorem).** Every finitely generated algebra over a noetherian ring is noetherian.

**Proof.** Let $A$ be noetherian. Since every finitely generated $A$-algebra is a quotient of a polynomial algebra, it suffices to prove the theorem for $A[X_1, \ldots, X_n]$. Note that

$$A[X_1, \ldots, X_n] = A[X_1, \ldots, X_{n-1}][X_n].$$

This simply says that every polynomial $f$ in $n$ symbols $X_1, \ldots, X_n$ can be expressed uniquely as a polynomial in $X_n$ with coefficients in $k[X_1, \ldots, X_{n-1}]$.

$$f(X_1, \ldots, X_n) = a_0(X_1, \ldots, X_{n-1})X_n^r + \cdots + a_r(X_1, \ldots, X_{n-1}).$$

Thus an induction argument shows that it suffices to prove the theorem for $A[X]$.

Recall that for a polynomial

$$f(X) = c_0 X^r + c_1 X^{r-1} + \cdots + c_r, \quad c_i \in A, \quad c_0 \neq 0,$$

$c_0$ is the **leading coefficient** of $f$.

Let $\alpha$ be an ideal in $A[X]$, and let $\mathcal{c}_i$ be the set of elements of $A$ that occur as the leading coefficient of a polynomial in $\alpha$ of degree $i$ (we also include 0). Then $\mathcal{c}_i$ is an ideal in $A$, and $\mathcal{c}_{i-1} \subseteq \mathcal{c}_i$, because if $cX^{i-1} + \cdots \in \alpha$, then so also does $X(cX^{i-1} + \cdots) = cX^i + \cdots$.

As $A$ is noetherian, the sequence of ideals

$$\mathcal{c}_1 \subseteq \mathcal{c}_2 \subseteq \cdots \subseteq \mathcal{c}_i \subseteq \cdots$$

eventually becomes constant, say, $\mathcal{c}_d = \mathcal{c}_{d+1} = \cdots$ (and then $\mathcal{c}_d$ contains the leading coefficients of all polynomials in $\alpha$).

For each $i \leq d$, choose a finite generating set \{$c_{i1}, c_{i2}, \ldots$\} for $\mathcal{c}_i$, and for each $(i, j)$, choose a polynomial $f_{ij} \in \alpha$ of degree $i$ with leading coefficient $c_{ij}$. We shall show that the $f_{ij}$’s generate $\alpha$.

Let $f \in \alpha$; we have to show that $f \in (f_{ij})$. Suppose first that $f$ has degree $s \geq d$. Then $f = cX^s + \cdots$ with $c \in \mathcal{c}_d$, and so

$$c = \sum_j a_j c_{dj}, \quad \text{some } a_j \in A.$$

Now

$$f - \sum_j a_j f_{dj} X^{s-d}$$

is either zero and $f \in (f_{ij})$, or it has degree $< \deg(f)$. In the second case, we repeat the argument, until we obtain a polynomial $f$ with degree $s < d$ that differs from the original polynomial by an element of $(f_{ij})$. By a similar argument, we then construct elements $a_j \in A$ such that

$$f - \sum_j a_j f_{sj}$$

is either zero or has degree $< \deg(f)$. In the second case, we repeat the argument, until we obtain zero.
**Proposition 3.7 (Nakayama’s Lemma).** Let $a$ be an ideal in a ring $A$ contained in all maximal ideals of $A$, and let $M$ be a finitely generated $A$-module.

(a) If $M = aM$, then $M = 0$.

(b) If $N$ is a submodule of $M$ such that $M = N + aM$, then $M = N$.

**Proof.** (a) Suppose $M \neq 0$. Choose a minimal set of generators $\{e_1, \ldots, e_n\}$ for $M$, $n \geq 1$, and write

$$e_1 = a_1 e_1 + \cdots + a_n e_n, \quad a_j \in a.$$

Then

$$(1 - a_1)e_1 = a_2 e_2 + \cdots + a_n e_n$$

and, as $1 - a_1$ is a unit (see 2.8), $e_2, \ldots, e_n$ generate $M$. This contradicts the minimality of the set.

(b) The hypothesis implies that $M/N = a(M/N)$, and so $M/N = 0$. $\square$

Recall that the Jacobson radical $\mathfrak{J}$ of $A$ is the intersection of the maximal ideals of $A$, and so the condition on $a$ is that $a \subseteq \mathfrak{J}$. For example, if $A$ is local, then the proposition holds for every proper ideal.

**Corollary 3.8.** Let $A$ be a local ring with maximal ideal $\mathfrak{m}$ and residue field $k \overset{\text{def}}{=} A/\mathfrak{m}$, and let $M$ be a finitely generated module over $A$. The action of $A$ on $M/\mathfrak{m}M$ factors through $k$, and elements $a_1, \ldots, a_n$ of $M$ generate it as an $A$-module if and only if $a_1 + \mathfrak{m}M, \ldots, a_n + \mathfrak{m}M$ span $M/\mathfrak{m}M$ as $k$-vector space.

**Proof.** If $a_1, \ldots, a_n$ generate $M$, then it is obvious that their images generate the vector space $M/\mathfrak{m}M$. Conversely, suppose that $a_1 + \mathfrak{m}M, \ldots, a_n + \mathfrak{m}M$ span $M/\mathfrak{m}M$, and let $N$ be the submodule of $M$ generated by $a_1, \ldots, a_n$. The composite $N \rightarrow M \rightarrow M/\mathfrak{m}M$ is surjective, and so $M = N + \mathfrak{m}M$. Now Nakayama’s lemma shows that $M = N$. $\square$

**Corollary 3.9.** Let $A$ be a noetherian local ring with maximal ideal $\mathfrak{m}$. Elements $a_1, \ldots, a_n$ of $\mathfrak{m}$ generate $\mathfrak{m}$ as an ideal if and only if $a_1 + \mathfrak{m}^2, \ldots, a_n + \mathfrak{m}^2$ span $\mathfrak{m}/\mathfrak{m}^2$ as a vector space over $k \overset{\text{def}}{=} A/\mathfrak{m}$. In particular, the minimum number of generators for the maximal ideal is equal to the dimension of the vector space $\mathfrak{m}/\mathfrak{m}^2$.

**Proof.** Because $A$ is noetherian, $\mathfrak{m}$ is finitely generated, and we can apply the preceding corollary with $M = \mathfrak{m}$. $\square$

**Definition 3.10.** Let $A$ be a noetherian ring.

(a) The **height** $\text{ht}(p)$ of a prime ideal $p$ in $A$ is the greatest length $d$ of a chain of distinct prime ideals

$$p = p_d \supset p_{d-1} \supset \cdots \supset p_0.$$  \hspace{1cm} (5)

(b) The **(Krull) dimension** of $A$ is $\sup\{\text{ht}(p) \mid p \subset A, \ p \text{ prime}\}$.

Thus, the Krull dimension of a ring $A$ is the supremum of the lengths of chains of prime ideals in $A$ (the length of a chain is the number of gaps, so the length of (5) is $d$). For example, a field has Krull dimension 0, and conversely an integral domain of Krull dimension 0 is a field. The height of every nonzero prime ideal in a principal ideal domain is 1, and so such a ring has Krull dimension 1 (provided it is not a field). It is convenient to define the Krull dimension of the zero ring to be $-1$. 

We shall see in §15 that the height of any prime ideal in a noetherian ring is finite. However, the Krull dimension of the ring may be infinite, because it may contain a sequence \( p_1, p_2, p_3, \ldots \) of prime ideals such that \( \text{ht}(p_i) \) tends to infinity (see [Krull 1938] or [Nagata 1962] p.203, for examples).

**Lemma 3.11.** In a noetherian ring, every set of generators for an ideal contains a finite generating set.

**Proof.** Let \( \mathfrak{a} \) be an ideal in a noetherian ring \( A \), and let \( S \) be a set of generators for \( \mathfrak{a} \). An ideal maximal in the set of ideals generated by finite subsets of \( S \) must contain every element of \( S \) (otherwise it wouldn’t be maximal), and so equals \( \mathfrak{a} \).

**Theorem 3.12 (Krull Intersection Theorem).** Let \( \mathfrak{a} \) be an ideal in a noetherian ring \( A \). If \( \mathfrak{a} \) is contained in all maximal ideals of \( A \), then \( \bigcap_{n \geq 1} \mathfrak{a}^n = \{0\} \).

**Proof.** We shall show that, for any ideal \( \mathfrak{a} \) in a noetherian ring,

\[
\bigcap_{n \geq 1} \mathfrak{a}^n = \mathfrak{a} \bigcap_{n \geq 1} \mathfrak{a}^n. \tag{6}
\]

When \( \mathfrak{a} \) is contained in all maximal ideals of \( A \), Nakayama’s lemma shows that \( \bigcap_{n \geq 1} \mathfrak{a}^n \) is zero.

Let \( a_1, \ldots, a_r \) generate \( \mathfrak{a} \). Then \( \mathfrak{a}^n \) consists of finite sums

\[
\sum_{i_1 + \cdots + i_r = n} c_{i_1, \ldots, i_r} a_1^{i_1} \cdots a_r^{i_r}, \quad c_{i_1, \ldots, i_r} \in A.
\]

In other words, \( \mathfrak{a}^n \) consists of the elements of \( A \) of the form \( g(a_1, \ldots, a_r) \) for some homogeneous polynomial \( g(X_1, \ldots, X_r) \in A[X_1, \ldots, X_r] \) of degree \( n \). Let \( S_m \) be the set of homogeneous polynomials \( f \) of degree \( m \) such that \( f(a_1, \ldots, a_r) \in \bigcap_{n \geq 1} \mathfrak{a}^n \), and let \( c \) be the ideal in \( A[X_1, \ldots, X_r] \) generated by all the \( S_m \). According to the lemma, there exists a finite set \( \{ f_1, \ldots, f_s \} \) of elements of \( \bigcup_m S_m \) that generates \( \mathfrak{c} \). Let \( d_i = \deg f_i \), and let \( d = \max d_i \). Let \( b \in \bigcap_{n \geq 1} \mathfrak{a}^n \); then \( b \in \mathfrak{a}^{d+1} \), and so \( b = f(a_1, \ldots, a_r) \) for some homogeneous polynomial \( f \) of degree \( d + 1 \). By definition, \( f \in S_{d+1} \subset \mathfrak{a} \), and so

\[
f = f_1 f_1 + \cdots + g_s f_s
\]

for some \( g_i \in A[X_1, \ldots, X_n] \). As \( f \) and the \( f_i \) are homogeneous, we can omit from each \( g_i \) all terms not of degree \( \deg f - \deg f_i \), since these terms cancel out. Thus, we may choose the \( g_i \) to be homogeneous of degree \( \deg f - \deg f_i = d + 1 - d_i > 0 \). Then \( g_i(a_1, \ldots, a_r) \in \mathfrak{a} \), and so

\[
b = f(a_1, \ldots, a_r) = \sum_i g_i(a_1, \ldots, a_r) \cdot f_i(a_1, \ldots, a_r) \in \mathfrak{a} \bigcap_{n \geq 1} \mathfrak{a}^n,
\]

which completes the proof of (6).

The equality (6) can also be proved using primary decompositions — see (13.15).

**Proposition 3.13.** In a noetherian ring, every ideal contains a power of its radical; in particular, some power of the nilradical of the ring is zero.

**Proof.** Let \( a_1, \ldots, a_n \) generate \( \text{rad}(\mathfrak{a}) \). For each \( i \), some power of \( a_i \), say \( a_i^{r_i} \), lies in \( \mathfrak{a} \). Then every term of the expansion of

\[
(c_1 a_1 + \cdots + c_n a_n)^{r_1 + \cdots + r_n}, \quad c_i \in A
\]

has a factor of the form \( a_i^{r_i} \) for some \( i \), and so lies in \( \mathfrak{a} \).


4 Unique factorization

Let $A$ be an integral domain, and let $a$ be an element of $A$ that is neither zero nor a unit. Then is said to be **irreducible** if it admits only trivial factorizations, i.e.,

$$a = bc \implies \text{b or c is a unit.}$$

The element $a$ is said to be **prime** if $(a)$ is a prime ideal, i.e.,

$$a | bc \implies a | b \text{ or } a | c.$$  

An integral domain $A$ is called a **unique factorization domain** if every nonzero nonunit in $A$ can be written as a finite product of irreducible elements in exactly one way up to units and the order of the factors. Every principal ideal domain, for example, the polynomial ring $k[X]$ over a field $k$, is a unique factorization domain (proved in most algebra courses).

**Proposition 4.1.** Let $A$ be an integral domain, and let $a$ be an element of $A$ that is neither zero nor a unit. If $a$ is prime, then $a$ is irreducible, and the converse holds when $A$ is a unique factorization domain.

**Proof.** Assume that $a$ is prime. If $a = bc$, then $a$ divides $bc$ and so $a$ divides $b$ or $c$. Suppose the first, and write $b = aq$. Now $a = bc = aqc$, which implies that $qc = 1$, and that $c$ is a unit. Therefore $a$ is irreducible.

For the converse, assume that $a$ is irreducible. If $a | bc$, then

$$bc = aq,$$  

some $q \in A$.  

On writing each of $b, c, q$ as a product of irreducible elements, and using the uniqueness of factorizations, we see that $a$ differs from one of the irreducible factors of $b$ or $c$ by a unit. Therefore $a$ divides $b$ or $c$. \qed

**Proposition 4.2 (Gauss’s Lemma).** Let $A$ be a unique factorization domain with field of fractions $F$. If $f(X) \in A[X]$ factors into the product of two nonconstant polynomials in $F[X]$, then it factors into the product of two nonconstant polynomials in $A[X]$.

**Proof.** Let $f = gh$ in $F[X]$. For suitable $c, d \in A$, the polynomials $g_1 = cg$ and $h_1 = dh$ have coefficients in $A$, and so we have a factorization

$$cdf = g_1 h_1 \text{ in } A[X].$$

If an irreducible element $p$ of $A$ divides $cd$, then, looking modulo $(p)$, we see that

$$0 = \overline{g_1} \cdot \overline{h_1} \text{ in } (A/(p))[X].$$

According to Proposition [4.1], the ideal $(p)$ is prime, and so $(A/(p))[X]$ is an integral domain. Therefore, $p$ divides all the coefficients of at least one of the polynomials $g_1, h_1$, say $g_1$, so that $g_1 = pg_2$ for some $g_2 \in A[X]$. Thus, we have a factorization

$$(cd/p)f = g_2 h_1 \text{ in } A[X].$$

Continuing in this fashion, we can remove all the irreducible factors of $cd$, and so obtain a factorization of $f$ in $A[X]$. \qed
Let $A$ be a unique factorization domain. A nonzero polynomial
\[ f = a_0 + a_1X + \cdots + a_mX^m \]
in $A[X]$ is said to be primitive if the coefficients $a_i$ have no common factor other than units. Every polynomial $f$ in $A[X]$ can be written $f = c(f) \cdot f_1$ with $c(f) \in A$ and $f_1$ primitive. The element $c(f)$, well-defined up to multiplication by a unit, is called the content of $f$.

**Lemma 4.3.** The product of two primitive polynomials is primitive.

**Proof.** Let
\[ f = a_0 + a_1X + \cdots + a_mX^m \]
and
\[ g = b_0 + b_1X + \cdots + b_nX^n, \]
be primitive polynomials, and let $p$ be an irreducible element of $A$. Let $a_{i_0}$ be the first coefficient of $f$ not divisible by $p$ and $b_{j_0}$ the first coefficient of $g$ not divisible by $p$. Then all the terms in $\sum_{i+j=i_0+j_0} a_i b_j$ are divisible by $p$, except $a_{i_0} b_{j_0}$, which is not divisible by $p$. Therefore, $p$ doesn’t divide the $(i_0 + j_0)$th-coefficient of $fg$. We have shown that no irreducible element of $A$ divides all the coefficients of $fg$, which must therefore be primitive. \qed

**Lemma 4.4.** For polynomials $f, g \in A[X]$, $c(fg) = c(f) \cdot c(g)$; hence every factor in $A[X]$ of a primitive polynomial is primitive.

**Proof.** Let $f = c(f) f_1$ and $g = c(g) g_1$ with $f_1$ and $g_1$ primitive. Then $fg = c(f)c(g) f_1 g_1$ with $f_1 g_1$ primitive, and so $c(fg) = c(f)c(g)$. \qed

**Proposition 4.5.** If $A$ is a unique factorization domain, then so also is $A[X]$.

**Proof.** From the factorization $f = c(f) f_1$, we see that the irreducible elements of $A[X]$ are to be found among the constant polynomials and the primitive polynomials, but a constant polynomial $a$ is irreducible if and only if $a$ is an irreducible element of $A$ (obvious) and a primitive polynomial is irreducible if and only if it has no primitive factor of lower degree (by 4.3). From this it is clear that every nonzero nonunit $f$ in $A[X]$ is a product of irreducible elements.

Let
\[ f = c_1 \cdots c_m f_1 \cdots f_n = d_1 \cdots d_r g_1 \cdots g_s \]
be two factorizations of an element $f$ of $A[X]$ into irreducible elements with the $c_i, d_j$ constants and the $f_i, g_j$ primitive polynomials. Then
\[ c(f) = c_1 \cdots c_m = d_1 \cdots d_r \] (up to units in $A$),
and, on using that $A$ is a unique factorization domain, we see that $m = r$ and the $c_i$’s differ from the $d_i$’s only by units and ordering. Hence,
\[ f_1 \cdots f_n = g_1 \cdots g_s \] (up to units in $A$).

Gauss’s lemma shows that the $f_i, g_j$ are irreducible polynomials in $F[X]$ and, on using that $F[X]$ is a unique factorization domain, we see that $n = s$ and that the $f_i$’s differ from the $g_i$’s only by units in $F$ and by their ordering. But if $f_i = a g_j$ with $a$ and $b$ nonzero elements of $A$, then $bf_i = ag_j$. As $f_i$ and $g_j$ are primitive, this implies that $b = a$ (up to a unit in $A$), and hence that $\frac{a}{b}$ is a unit in $A$. \qed
Let $k$ be a field. A **monomial** in $X_1, \ldots, X_n$ is an expression of the form

$$X_1^{a_1} \cdots X_n^{a_n}, \quad a_j \in \mathbb{N}.$$ 

The **total degree** of the monomial is $\sum a_j$. The **degree**, $\deg(f)$, of a nonzero polynomial $f(X_1, \ldots, X_n)$ is the largest total degree of a monomial occurring in $f$ with nonzero coefficient. Since

$$\deg(fg) = \deg(f) + \deg(g),$$

$k[X_1, \ldots, X_n]$ is an integral domain and $k[X_1, \ldots, X_n]^\times = k^\times$. Therefore, an element $f$ of $k[X_1, \ldots, X_n]$ is irreducible if it is nonconstant and $f = gh \implies g$ or $h$ is constant.

**Theorem 4.6.** The ring $k[X_1, \ldots, X_n]$ is a unique factorization domain.

**Proof.** This is trivially true when $n = 0$, and an induction argument using [4], p.10, proves it for all $n$. \qed

**Corollary 4.7.** A nonzero proper principal ideal $(f)$ in $k[X_1, \ldots, X_n]$ is prime if and only $f$ is irreducible.

**Proof.** Special case of (4.1). \qed

## 5 Integrality

Let $A$ be a subring of a ring $B$. An element $\alpha$ of $B$ is said to be **integral** over $A$ if it is a root of a monic\(^5\) polynomial with coefficients in $A$, i.e., if it satisfies an equation

$$\alpha^n + a_1\alpha^{n-1} + \cdots + a_n = 0, \quad a_j \in A.$$ 

If every element of $B$ is integral over $A$, then $B$ is said to be **integral** over $A$.

In the next proof, we shall need to apply Cramer’s formula. As usually stated in linear algebra courses, this says that, if $x_1, \ldots, x_m$ is a solution to the system of linear equations

$$\sum_{j=1}^m c_{ij}x_j = d_i, \quad i = 1, \ldots, m,$$

then

$$x_j = \frac{\det(C_j)}{\det(C)}, \quad \text{where } C = (c_{ij}) \text{ and }$$

$$C_j = \begin{pmatrix} c_{11} & \cdots & c_{1,j-1} & d_1 & c_{1,j+1} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{m1} & \cdots & c_{m,j-1} & d_m & c_{m,j+1} & \cdots & c_{mm} \end{pmatrix}.$$

When one restates the formula as

$$\det(C) \cdot x_j = \det(C_j)$$

---

\(^5\)A polynomial is **monic** if its leading coefficient is 1, i.e., $f(X) = X^n + \text{terms of degree less than } n$. 
it becomes true over any ring (whether or not \( \det(C) \) is a unit). The proof is elementary—
expand out the right hand side of
\[
\det C_j = \det \begin{pmatrix}
c_{11} & \cdots & \sum c_{1j} x_j & \cdots & c_{1m} \\
\vdots & & \vdots & & \vdots \\
c_{m1} & \cdots & \sum c_{mj} x_j & \cdots & c_{mm}
\end{pmatrix}
\]
using standard properties of determinants.

**Proposition 5.1.** Let \( A \) be a subring of a ring \( B \). An element \( \alpha \) of \( B \) is integral over \( A \) if and only if there exists a faithful finitely generated \( A \)-submodule \( M \) of \( B \) such that \( \alpha M \subset M \).

**Proof.** \( \Rightarrow \): Suppose
\[
\alpha^n + a_1 \alpha^{n-1} + \cdots + a_n = 0, \quad a_i \in A.
\]
Then the \( A \)-submodule \( M \) of \( B \) generated by \( 1, \alpha, ..., \alpha^{n-1} \) has the property that \( \alpha M \subset M \), and it is faithful because it contains \( 1 \).

\( \Leftarrow \): Let \( M \) be a nonzero \( A \)-module in \( B \) such that \( \alpha M \subset M \), and let \( e_1, \ldots, e_n \) be a finite set of generators for \( M \). Then, for each \( i \),
\[
\alpha e_i = \sum a_{ij} e_j, \text{ some } a_{ij} \in A.
\]
We can rewrite this system of equations as
\[
\begin{align*}
(\alpha - a_{11}) e_1 - a_{12} e_2 - a_{13} e_3 - & \cdots = 0 \\
-a_{21} e_1 + (\alpha - a_{22}) e_2 - a_{23} e_3 - & \cdots = 0 \\
& \vdots = 0.
\end{align*}
\]
Let \( C \) be the matrix of coefficients on the left-hand side. Then Cramer’s formula tells us that \( \det(C) \cdot e_i = 0 \) for all \( i \). As the \( e_i \) generate \( M \) and \( M \) is faithful, this implies that \( \det(C) = 0 \). On expanding out the determinant, we obtain an equation
\[
\alpha^n + c_1 \alpha^{n-1} + c_2 \alpha^{n-2} + \cdots + c_n = 0, \quad c_i \in A.
\]

**Proposition 5.2.** An \( A \)-algebra \( B \) is finite if and only if it is finitely generated and integral over \( A \).

**Proof.** \( \Leftarrow \): Suppose \( B = A[\alpha_1, \ldots, \alpha_m] \) and that
\[
\alpha_i^{n_i} + a_{i1} \alpha_i^{n_{i1}} + \cdots + a_{in_i} = 0, \quad a_{ij} \in A, \quad i = 1, \ldots, m.
\]
Any monomial in the \( \alpha_i \)'s divisible by \( \alpha_i^{n_i} \) is equal (in \( B \)) to a linear combination of monomials of lower degree. Therefore, \( B \) is generated as an \( A \)-module by the monomials \( \alpha_1^{r_1} \cdots \alpha_m^{r_m}, 1 \leq r_j < n_j \).

\( \Rightarrow \): As an \( A \)-module, \( B \) is faithful (because \( a \cdot 1_B = a \)), and so \( (5.1) \) implies that every element of \( B \) is integral over \( A \). As \( B \) is finitely generated as an \( A \)-module, it is certainly finitely generated as an \( A \)-algebra.
Theorem 5.3. Let $A$ be a subring of the ring $B$. The elements of $B$ integral over $A$ form a subring of $B$.

Proof. Let $\alpha$ and $\beta$ be two elements of $B$ integral over $A$. The argument in the proof of (5.2) shows that $A[\alpha, \beta]$ is finitely generated as an $A$-module. It is obviously a faithful $A$-module, and it is stable under multiplication by $\alpha \pm \beta$ and $\alpha \beta$. Therefore (5.1) shows that $\alpha \beta$ and $\alpha \beta$ are integral over $A$. \hfill \Box

Definition 5.4. Let $A$ be a subring of the ring $B$. The integral closure of $A$ in $B$ is the subring of $B$ consisting of the elements integral over $A$.

Proposition 5.5. Let $A$ be an integral domain with field of fractions $F$, and let $L$ be a field containing $F$. If $\alpha \in L$ is algebraic over $F$, then there exists a $d \in A$ such that $d\alpha$ is integral over $A$.

Proof. By assumption, $\alpha$ satisfies an equation

$$\alpha^m + a_1\alpha^{m-1} + \cdots + a_m = 0, \quad a_i \in F.$$ 

Let $d$ be a common denominator for the $a_i$, so that $da_i \in A$ for all $i$, and multiply through the equation by $d^m$:

$$d^m \alpha^m + a_1 d^m \alpha^{m-1} + \cdots + a_m d^m = 0.$$ 

We can rewrite this as

$$(d\alpha)^m + a_1 d (d\alpha)^{m-1} + \cdots + a_m d^m = 0.$$ 

As $a_1 d, \ldots, a_m d^m \in A$, this shows that $d\alpha$ is integral over $A$. \hfill \Box

Corollary 5.6. Let $A$ be an integral domain and let $L$ be an algebraic extension of the field of fractions of $A$. Then $L$ is the field of fractions of the integral closure of $A$ in $L$.

Proof. In fact, the proposition shows that every element of $L$ is a quotient $\beta/d$ with $\beta$ integral over $A$ and $d \in A$. \hfill \Box

Definition 5.7. An integral domain $A$ is integrally closed if it is equal to its integral closure in its field of fractions $F$, i.e., if

$$\alpha \in F, \quad \alpha \text{ integral over } A \implies \alpha \in A.$$ 

Proposition 5.8. Every unique factorization domain is integrally closed.

Proof. An element of the field of fractions of $A$ not in $A$ can be written $a/b$ with $a, b \in A$ and $b$ divisible by some irreducible element $p$ not dividing $a$. If $a/b$ is integral over $A$, then it satisfies an equation

$$(a/b)^n + a_1(a/b)^{n-1} + \cdots + a_n = 0, \quad a_i \in A.$$ 

On multiplying through by $b^n$, we obtain the equation

$$a^n + a_1 a^{n-1} b + \cdots + a_n b^n = 0.$$ 

The element $p$ then divides every term on the left except $a^n$, and hence must divide $a^n$. Since it doesn’t divide $a$, this is a contradiction. \hfill \Box
Proposition 5.9. Let $A$ be an integrally closed integral domain, and let $L$ be a finite extension of the field of fractions $F$ of $A$. An element of $L$ is integral over $A$ if and only if its minimum polynomial over $F$ has coefficients in $A$.

Proof. Let $\alpha$ be integral over $A$, so that
$$\alpha^m + a_1 \alpha^{m-1} + \cdots + a_m = 0, \quad \text{some } a_i \in A, \quad m > 0.$$ Let $\alpha'$ be a conjugate of $\alpha$, i.e., a root of the minimum polynomial $f(X)$ of $\alpha$ over $F$ in some field containing $L$. Then there is an $F$-isomorphism
$$\sigma: F[\alpha] \to F[\alpha'], \quad \sigma(\alpha) = \alpha'.$$

On applying $\sigma$ to the above equation we obtain the equation
$$\alpha'^m + a_1 \alpha'^{m-1} + \cdots + a_m = 0,$$
which shows that $\alpha'$ is integral over $A$. Hence all the conjugates of $\alpha$ are integral over $A$, and it follows from (5.3) that the coefficients of $f(X)$ are integral over $A$. They lie in $F$, and $A$ is integrally closed, and so they lie in $A$. This proves the “only if” part of the statement, and the “if” part is obvious.

Corollary 5.10. Let $A$ be an integrally closed integral domain with field of fractions $F$, and let $f(X)$ be a monic polynomial in $A[X]$. Then every monic factor of $f(X)$ in $F[X]$ has coefficients in $A$.

Proof. It suffices to prove this for an irreducible monic factor $g$ of $f$ in $F[X]$. Let $\alpha$ be a root of $g$ in some extension field of $F$. Then $g$ is the minimum polynomial $\alpha$, which, being also a root of $f$, is integral. Therefore $g$ has coefficients in $A$.

Theorem 5.11 (Noether Normalization Theorem). Every finitely generated algebra $A$ over a field $k$ contains a polynomial algebra $R$ such that $A$ is a finite $R$-algebra.

In other words, there exist elements $y_1, \ldots, y_r$ of $A$ such that $A$ is a finite $k[y_1, \ldots, y_r]$-algebra and $y_1, \ldots, y_r$ are algebraically independent over $k$.

Proof. We use induction on the minimum number $n$ of generators of $A$ as a $k$-algebra. If $n = 0$, there is nothing to prove, and so we may suppose that $n \geq 1$ and that the statement is true for $k$-algebras generated by $n - 1$ (or fewer) elements.

Let $A = k[x_1, \ldots, x_n]$. If the $x_i$ are algebraically independent, then there is nothing to prove, and so we may suppose that there exists a nonconstant polynomial $f(T_1, \ldots, T_n)$ such that $f(x_1, \ldots, x_n) = 0$. Some $T_i$ occurs in $f$, say $T_1$, and we can write
$$f = c_0 T_1^N + c_1 T_1^{N-1} + \cdots + c_N, \quad c_i \in k[T_2, \ldots, T_n], \quad c_0 \neq 0.$$

Most authors write “minimal polynomial” but the polynomial in question is in fact minimum (smallest element in the set of monic polynomials having $\alpha$ as a root).

Recall that the homomorphism $X \mapsto \alpha: F[X] \to F[\alpha]$ defines an isomorphism $F[X]/(f) \to F[\alpha]$.

Recall that this means that the homomorphism of $k$-algebras $k[x_1, \ldots, x_n] \to k[y_1, \ldots, y_n]$ sending $x_i$ to $y_i$ is an isomorphism, or, equivalently, that if
$$P(y_1, \ldots, y_n) = 0, \quad P(x_1, \ldots, x_n) \in k[x_1, \ldots, x_n],$$
then $P = 0$. 


6 RINGS OF FRACTIONS

If \( c_0 \in k \), then the equation
\[
c_0 x_1^N + c_1(x_2, \ldots, x_n) x_1^{N-1} + \cdots + c_N(x_2, \ldots, x_n) = 0
\]
shows that \( x_1 \) is integral over \( k[x_2, \ldots, x_n] \). By induction, there exist algebraically independent elements \( y_1, \ldots, y_r \) such that \( k[x_2, \ldots, x_n] \) is finite over \( k[y_1, \ldots, y_r] \). It follows that \( A \) is finite over \( k[y_1, \ldots, y_r] \).

If \( c_0 \not\in k \), then we choose different generators for \( A \). Fix an integer \( m > 0 \), and let
\[
y_1 = x_1, y_2 = x_2 - x_1^m, \ldots, y_r = x_r - x_1^m.
\]
Then
\[
k[y_1, \ldots, y_n] = k[x_1, \ldots, x_n] = A
\]
and
\[
f(y_1, y_2 + y_1^m, \ldots, y_r + y_1^m) = 0.
\]
In other words, \( g(y_1, \ldots, y_n) = 0 \) where \( g(T_1, \ldots, T_n) = f(T_1, T_2 + T_1^m, \ldots, T_r + T_1^m) \).
When \( m \) is chosen sufficiently large,
\[
g(T_1, \ldots, T_n) = c_0' T_1^N - c_1' T_1^{N-1} - \cdots - c_N' = 0
\]
with \( c_0' \in k \). Therefore, the previous argument applies.

Remark 5.12. When \( k \) is infinite, there is a simpler proof of a somewhat stronger result: let \( A = k[x_1, \ldots, x_n] \); then there exist algebraically independent elements \( f_1, \ldots, f_r \) that are linear combinations of the \( x_i \) such that \( A \) is finite over \( k[f_1, \ldots, f_r] \) (see 8.13 of my algebraic geometry notes).

6 Rings of fractions

Recall that a multiplicative subset of a ring is a nonempty subset closed under the formation of finite products.

Let \( S \) be a multiplicative subset of \( A \), and define an equivalence relation on \( A \times S \) by
\[
(a, s) \sim (b, t) \iff u(at - bs) = 0 \text{ for some } u \in S.
\]
Write \( \frac{a}{s} \) for the equivalence class containing \( (a, s) \), and define addition and multiplication of equivalence classes in the way suggested by the notation:
\[
\frac{a}{s} + \frac{b}{t} = \frac{at + bs}{st}, \quad \frac{a}{s} \frac{b}{t} = \frac{ab}{st}
\]
Let
\[
f(T_1, \ldots, T_r) = \sum c_{j_1} \cdots c_j \frac{T_1^{j_1} \cdots T_r^{j_r}}{j_1 + m^2 j_2 + \cdots + m^r j_r}
\]
with \( j_1 \ldots j_r \) running over the \( r \)-tuples such that \( c_{j_1} \cdots c_j \neq 0 \), are distinct, say with largest value \( N \), then
\[
f(T_1, T_2 + T_1^m, \ldots, T_r + T_1^m) = c T_1^N + c_1 T_1^{N-1} + \cdots
\]
with \( c \in k \setminus \{0\} \).
It is easy to show that these do not depend on the choices of representatives for the equivalence classes, and that we obtain in this way a ring

\[ S^{-1}A = \{ \frac{a}{s} \mid a \in A, s \in S \} \]

and a ring homomorphism \( a \mapsto \frac{a}{1} : A \rightarrow S^{-1}A \) whose kernel is

\[ \{ a \in A \mid sa = 0 \text{ for some } s \in S \} \].

If \( S \) contains no zero-divisors, for example, if \( A \) is an integral domain and \( 0 \notin S \), then \( i_S : A \rightarrow S^{-1}A \) is injective. At the opposite extreme, if \( 0 \in S \), then \( S^{-1}A \) is the zero ring.

**Proposition 6.1.** The pair \((S^{-1}A, i_S)\) has the following universal property:

Every element of \( S \) maps to a unit in \( S^{-1}A \), and any other ring homomorphism \( \alpha : A \rightarrow B \) with this property factors uniquely through \( i_S \).

**Proof.** Let \( \alpha : A \rightarrow B \) be a homomorphism, and let \( \beta : S^{-1}A \rightarrow B \) be a homomorphism such that \( \beta \circ i_S = \alpha \). Then

\[ \frac{s}{a} \frac{t}{1} = \frac{a}{s} \quad \implies \quad \beta(\frac{a}{s})\beta(\frac{t}{1}) = \beta(\frac{at}{st}) \]

and so

\[ \beta(\frac{at}{st}) = \alpha(a)\alpha(s)^{-1}. \quad (7) \]

This shows that there can be at most one \( \beta \) such that \( \beta \circ i_S = \alpha \). When \( \alpha \) maps the elements of \( S \) to units in \( B \), we define \( \beta \) by the formula \((7)\). Then

\[ \frac{a}{s} = \frac{b}{t} \quad \implies \quad u(at - bs) = 0 \quad \text{some } u \in S \quad \implies \quad \alpha(a)\alpha(t) - \alpha(b)\alpha(s) = 0, \]

which shows that \( \beta \) is well-defined, and it is easy to check that it is a homomorphism. \( \square \)

As usual, this universal property determines the pair \((S^{-1}A, i_S)\) uniquely up to a unique isomorphism.\(^{11}\)

When \( A \) is an integral domain and \( S = A \setminus \{0\} \), the ring \( S^{-1}A \) is the field of fractions \( F \) of \( A \). In this case, for any other multiplicative subset \( T \) of \( A \) not containing 0, the ring \( T^{-1}A \) can be identified with the subring of \( F \) consisting of the fractions \( \frac{a}{t} \) with \( a \in A \) and \( t \in T \).

**Example 6.2.** Let \( h \in A \). Then \( S_h = \{1, h, h^2, \ldots \} \) is a multiplicative subset of \( A \), and we let \( A_h = S_h^{-1}A \). Thus every element of \( A_h \) can be written in the form \( a/h^m \), where \( a \in A \) and \( m \in \mathbb{N} \).

If \( h \) is nilpotent, then \( A_h = 0 \), and if \( A \) is an integral domain with field of fractions \( F \) and \( h \neq 0 \), then \( A_h \) is the subring of \( F \) of elements of the form \( a/h^m \), where \( a \in A \), \( m \in \mathbb{N} \).

---

\(^{11}\)Recall the proof: let \((A_1, i_1)\) and \((A_2, i_2)\) have the universal property in the proposition; because every element of \( S \) maps to a unit in \( A_2 \), there exists a unique homomorphism \( \alpha : A_1 \rightarrow A_2 \) such that \( \alpha \circ i_1 = i_2 \) (universal property of \( A_1, i_1 \)); similarly, there exists a unique homomorphism \( \alpha' : A_2 \rightarrow A_1 \) such that \( \alpha' \circ i_2 = i_1 \); now

\[ \alpha' \circ \alpha \circ i_1 = \alpha' \circ i_2 = i_1 = \text{id}_{A_1} \circ i_1, \]

and so \( \alpha' \circ \alpha = \text{id}_{A_1} \) (universal property of \( A_1, i_1 \)); similarly, \( \alpha \circ \alpha' = \text{id}_{A_2} \), and so \( \alpha \) and \( \alpha' \) are inverse isomorphisms (and they are uniquely determined by the conditions \( \alpha \circ i_1 = i_2 \) and \( \alpha' \circ i_2 = i_1 \)).
PROPOSITION 6.3. For any ring $A$ and $h \in A$, the map $\sum a_i X^i \mapsto \sum \frac{a_i}{h^i}$ defines an isomorphism

$$A[X]/(1-hX) \rightarrow A_h.$$ 

PROOF. If $h = 0$, both rings are zero, and so we may assume $h \neq 0$. In the ring $A[x] = A[X]/(1-hX)$, $1 = hx$, and so $h$ is a unit. Let $\alpha: A \rightarrow B$ be a homomorphism of rings such that $\alpha(h)$ is a unit in $B$. The homomorphism $\sum a_i X^i \mapsto \sum \alpha(a_i)\alpha(h)^{-i}: A[X] \rightarrow B$ factors through $A[x]$ because $1-hX \mapsto 1 - \alpha(h)\alpha(h)^{-1} = 0$, and this is the unique extension of $\alpha$ to $A[x]$. Therefore $A[x]$ has the same universal property as $A_h$, and so the two are (uniquely) isomorphic by an $A$-algebra isomorphism that makes $h^{-1}$ correspond to $x$. $\square$

Let $S$ be a multiplicative subset of a ring $A$, and let $S^{-1}A$ be the corresponding ring of fractions. For any ideal $a$ in $A$, the ideal generated by the image of $a$ in $S^{-1}A$ is

$$S^{-1}a = \{ \frac{a}{s} \mid a \in a, \ s \in S \}.$$ 

If $a$ contains an element of $S$, then $S^{-1}a$ contains 1, and so is the whole ring. Thus some of the ideal structure of $A$ is lost in the passage to $S^{-1}A$, but, as the next lemma shows, some is retained.

PROPOSITION 6.4. Let $S$ be a multiplicative subset of the ring $A$, and consider extension $a \mapsto a^e = S^{-1}a$ and contraction $a \mapsto a^c = \{ a \in A \mid a^e \in a \}$ of ideals with respect to the homomorphism $A \rightarrow S^{-1}A$. Then

$$a^{ec} = a \quad \text{for all ideals of } S^{-1}A$$

$$a^{ce} = a \quad \text{if } a \text{ is a prime ideal of } A \text{ disjoint from } S.$$ 

Moreover, the $p \mapsto p^e$ is a bijection from the set of prime ideals of $A$ disjoint from $S$ onto the set of all prime ideals of $S^{-1}A$; the inverse map is $p \mapsto p^c$.

PROOF. Let $a$ be an ideal in $S^{-1}A$. Certainly $a^{ce} \subset a$. For the reverse inclusion, let $b \in a$. We can write $b = \frac{a}{s}$ with $a \in A, s \in S$. Then $\frac{a}{s} = s(\frac{a}{s}) \in a$, and so $a \in a^c$. Thus $b = \frac{a}{s} \in a^{ce}$, and so $a \subset a^{ce}$.

Let $p$ be a prime ideal of $A$ disjoint from $S$. Clearly $p^{ce} \subset p$. For the reverse inclusion, let $a \in p^{ce}$ so that $\frac{a}{s} = \frac{a'}{s'}$ for some $a' \in p, s \in S$. Then $t(as - a') = 0$ for some $t \in S$, and so $ast \in p$. Because $st \notin p$ and $p$ is prime, this implies that $a \in p$, and so $p \supset p^{ce}$.

Let $p$ be a prime ideal of $A$ disjoint from $S$, and let $\tilde{S}$ be the image of $S$ in $A/p$. Then $(S^{-1}A)/p^e \simeq S^{-1}(A/p)$ because $S^{-1}A/p^e$ has the correct universal property, and $S^{-1}(A/p)$ is an integral domain because $A/p$ is an integral domain and $\tilde{S}$ doesn’t contain 0. Therefore $p^e$ is prime. From §6.2 we know that $p^e$ is prime if $p$ is, and so $p \mapsto p^e$ and $p \mapsto p^c$ are inverse bijections on the two sets. $\square$

COROLLARY 6.5. If $A$ is noetherian, then so also is $S^{-1}A$ for any multiplicative set $S$.

PROOF. As $b^c$ is finitely generated, so also is $(b^c)^e = b$. $\square$

EXAMPLE 6.6. Let $p$ be a prime ideal in $A$. Then $S_p = A \setminus p$ is a multiplicative subset of $A$, and we let $A_p = S_p^{-1}A$. Thus each element of $A_p$ can be written in the form $\frac{a}{c}$, $c \notin p$, and

$$\frac{a}{c} = \frac{b}{d} \iff s(ad - bc) = 0, \text{ some } s \notin p.$$ 

According to (6.4b), the prime ideals of $A_p$ correspond to the prime ideals of $A$ disjoint from $A \setminus p$, i.e., contained in $p$. Therefore, $A_p$ is a local ring with maximal ideal $m = p^e = \{ \frac{a}{s} \mid a \in p, s \notin p \}$. $\square$
Proposition 6.7. Let \( m \) be a maximal ideal of a noetherian ring \( A \), and let \( n = mA_m \) be the maximal ideal of \( A_m \). For all \( n \), the map

\[
a + m^n \mapsto a + n^n : A/m^n \to A_m/n^n
\]

is an isomorphism. Moreover, it induces isomorphisms

\[
m^r/m^n \to n^r/n^n
\]

for all pairs \((r, n)\) with \( r < n \).

Proof. The second statement follows from the first, because of the exact commutative diagram \((r < n)\):

\[
\begin{array}{cccccc}
0 & \longrightarrow & m^r/m^n & \longrightarrow & A/m^n & \longrightarrow & A/m^r & \longrightarrow & 0 \\
\downarrow & & \downarrow \cong & & \downarrow \cong & & \\
0 & \longrightarrow & n^r/n^n & \longrightarrow & A_m/n^n & \longrightarrow & A_m/n^r & \longrightarrow & 0.
\end{array}
\]

We consider extension and contraction with respect to \( a \mapsto \frac{a}{r}: A \to A_m \). In order to show that the map \( A/m^n \to A_m/n^n \) is injective, we have to show that \((m^n)^e^c = m^n\). If \( a \in (m^n)^e^c \), then \( \frac{a}{r} = \frac{b}{s} \) with \( b \in m^n \) and \( s \in S \). Then \( s'sa = 0 \) in \( A/m^n \). The only maximal ideal containing \( m^n \) is \( m \), and so the only maximal ideal in \( A/m^n \) is \( m/m^n \). As \( s's \) is not in \( m/m^n \), it must be a unit in \( A/m^n \), and so \( a = 0 \) in \( A/m^n \), i.e., \( a \in m^n \). We have shown that \((m^n)^e^c \subset m \), and the reverse inclusion is always true.

We now prove that \( A/m^n \to A_m/n^n \) is surjective. Let \( \frac{a}{s} \in A_m, a \in A, s \in A \setminus m \). The only maximal ideal of \( A \) containing \( m^n \) is \( m \), and so no maximal ideal contains both \( s \) and \( m^n \); it follows that \((s) + m^n = A \). Therefore, there exist \( b \in A \) and \( q \in m^n \) such that \( sb + q = 1 \). Because \( s \) is invertible in \( A_m/n^n \), \( \frac{a}{s} \) is the unique element of this ring such that \( s\frac{a}{s} = a \). As \( s(ba) = a(1 - q) \), the image of \( ba \) in \( A_m \) also has this property and therefore equals \( \frac{a}{s} \).

Proposition 6.8. In a noetherian ring, only 0 lies in all powers of all maximal ideals.

Proof. Let \( a \) be an element of a noetherian ring \( A \). If \( a \neq 0 \), then \( \{ b \mid ba = 0 \} \) is a proper ideal, and so it is contained in some maximal ideal \( m \). Then \( \frac{a}{r} \) is nonzero in \( A_m \), and so \( \frac{a}{r} \notin (mA_m)^n \) for some \( n \) (by the Krull intersection theorem [3.12]), which implies that \( a \notin m^n \) (by 6.7).

Modules of Fractions

Let \( S \) be a multiplicative subset of the ring \( A \), and let \( M \) be an \( A \)-module. Define an equivalence relation on \( M \times S \) by

\[
(m, s) \sim (n, t) \iff u(mt - ns) = 0 \text{ for some } u \in S.
\]

Write \( \frac{m}{s} \) for the equivalence class containing \( (m, s) \), and define addition and multiplication of equivalence classes by the formulas:

\[
\frac{m}{s} + \frac{n}{t} = \frac{mnt + ns}{st}, \quad \frac{am}{st}, \quad m, n \in M, \quad s, t \in S, \quad a \in A.
\]
It is easy to show that these definitions do not depend on the choices of representatives for the equivalence classes, and that we obtain in this way an $S^{-1}A$-module

$$S^{-1}M = \{ \frac{m}{s} \mid m \in M, s \in S \}$$

and a homomorphism $m \mapsto \frac{m}{s}: M \xrightarrow{i_S} S^{-1}M$ of $A$-modules whose kernel is

$$\{ a \in M \mid sa = 0 \text{ for some } s \in S \}.$$

**Proposition 6.9.** The pair $(S^{-1}M, i_S)$ has the following universal property:

1. Every element of $S$ acts invertibly on $S^{-1}M$,
2. Any other homomorphism $\alpha: M \rightarrow N$ of $A$-modules such that the elements of $S$ act invertibly on $N$ factors uniquely through $i_S$.

**Proof.** Similar to that of Proposition 6.1. \(\square\)

**Example 6.10.** Let $M$ be an $A$-module. For $h \in A$, let $M_h = S_h^{-1}M$ where $S_h = \{1, h, h^2, \ldots\}$. Then every element of $M_h$ can be written in the form $\frac{m}{hr}$, $m \in M$, $r \in \mathbb{N}$, and $\frac{m}{hr} = \frac{m'}{hr'}$ if and only if $h^N (hr' m - hr m') = 0$ for some $N \in \mathbb{N}$.

**Proposition 6.11.** The functor $M \mapsto S^{-1}M$ is exact. In other words, if the sequence of $A$-modules

$$M' \xrightarrow{\alpha} M \xrightarrow{\beta} M''$$

is exact, then so also is the sequence of $S^{-1}A$-modules

$$S^{-1}M' \xrightarrow{S^{-1}\alpha} S^{-1}M \xrightarrow{S^{-1}\beta} S^{-1}M''.$$

**Proof.** Because $\beta \circ \alpha = 0$, we have $0 = S^{-1}(\beta \circ \alpha) = S^{-1}\beta \circ S^{-1}\alpha$. Therefore $\text{Im}(S^{-1}\alpha) \subseteq \text{Ker}(S^{-1}\beta)$. For the reverse inclusion, let $\frac{m}{s} \in \text{Ker}(S^{-1}\beta)$ where $m \in M$ and $s \in S$. Then $\frac{\beta(m)}{s} = 0$ and so, for some $t \in S$, we have $t\beta(m) = 0$. Then $\beta(tm) = 0$, and so $tm = \alpha(m')$ for some $m' \in M'$. Now

$$\frac{m}{s} = \frac{tm}{ts} = \frac{\alpha(m')}{ts} \in \text{Im}(S^{-1}\alpha).$$

**Exercise 6.12.** Let $A$ be an integral domain. A multiplicative subset $S$ of $A$ is said to be saturated if

$$ab \in S \Rightarrow a \text{ and } b \in S.$$

(a) Show that $S$ is saturated \iff its complement is a union of prime ideals.

(b) Show that given a multiplicative system $S$, there is a unique smallest saturated multiplicative system $S'$ containing $S$, and that $S' = A \setminus \bigcup \mathfrak{p}$, where $\mathfrak{p}$ runs over the prime ideals disjoint from $S$. Show that $S'^{-1}A = S^{-1}A$. Deduce that $S^{-1}A$ is characterized by the set of prime ideals of $A$ that remain prime in $S^{-1}A$. 
7 Direct limits

**Definition 7.1.** A partial ordering \( \leq \) on a set \( I \) is said to be **directed**, and the pair \((I, \leq)\) is called a **directed set**, if for all \( i, j \in I \) there exists a \( k \in I \) such that \( i, j \leq k \).

**Definition 7.2.** Let \((I, \leq)\) be a directed set, and let \( A \) be a ring. A **direct system** of \( A \)-modules indexed by \((I, \leq)\) is a family \((M_i)_{i \in I}\) of \( A \)-modules together with a family \((\alpha^i_j; M_i \to M_j)_{i \leq j}\) of \( A \)-linear maps such that \( \alpha^i_j = \text{id}_{M_i} \) and \( \alpha^k_j \circ \alpha^i_k = \alpha^i_j \) all \( i \leq j \leq k \).

An \( A \)-module \( M \) together with a family \((\alpha^i; M_i \to M)_{i \in I}\) of \( A \)-linear maps satisfying \( \alpha^i = \alpha^j \circ \alpha^i_j \) all \( i \leq j \) is said to be a **direct limit** of the system \(((M_i), (\alpha^i_j))\) if it has the following universal property: for any other \( A \)-module \( N \) and family \((\beta^i; M_i \to N)\) of \( A \)-linear maps such that \( \beta^i = \beta^j \circ \alpha^i_j \) all \( i \leq j \), there exists a unique morphism \( \alpha: M \to N \) such that \( \alpha \circ \alpha^i = \beta^i \) for all \( i \).

As usual, the universal property determines the direct limit (if it exists) uniquely up to a unique isomorphism. We denote it \( \lim \alpha(M_i, \alpha^i_j) \), or just \( \lim \alpha M_i \).

**Criterion**

An \( A \)-module \( M \) together with \( A \)-linear maps \( \alpha^i: M_i \to M \) is the direct limit of a system \((M_i, \alpha^i_j)\) if and only if

(a) \( M = \bigcup_{i \in I} \alpha^i(M_i) \), and
(b) \( m_i \in M_i \) maps to zero in \( M \) if and only if it maps to zero in \( M_j \) for some \( j \geq i \).

**Construction**

Let

\[
M = \bigoplus_{i \in I} M_i / M'
\]

where \( M' \) is the \( A \)-submodule generated by the elements

\[
m_i - \alpha^i_j(m_i) \quad \text{all } i < j, m_i \in M_i.
\]

Let \( \alpha^i(m_i) = m_i + M' \). Then certainly \( \alpha^i = \alpha^j \circ \alpha^i_j \) for all \( i \leq j \). For any \( A \)-module \( N \) and \( A \)-linear maps \( \beta^i: M_j \to N \), there is a unique map

\[
\bigoplus_{i \in I} M_i \to N,
\]

namely, \( \sum m_i \mapsto \sum \beta^i(m_i) \), sending \( m_i \) to \( \beta^i(m_i) \), and this map factors through \( M \) and is the unique \( A \)-linear map with the required properties.

Direct limits of \( A \)-algebras, etc., are defined similarly.
8 Tensor Products

Tensor Products of Modules

Let $A$ be a ring, and let $M$, $N$, and $P$ be $A$-modules. A map $\phi: M \times N \to P$ of $A$-modules is said to be $A$-bilinear if

\[
\begin{align*}
\phi(x + x', y) &= \phi(x, y) + \phi(x', y), & x, x' &\in M, & y &\in N \\
\phi(x, y + y') &= \phi(x, y) + \phi(x, y'), & x &\in M, & y, y' &\in N \\
\phi(ax, y) &= a\phi(x, y), & a &\in A, & x &\in M, & y &\in N \\
\phi(x, ay) &= a\phi(x, y), & a &\in A, & x &\in M, & y &\in N,
\end{align*}
\]

i.e., if $\phi$ is $A$-linear in each variable.

An $A$-module $T$ together with an $A$-bilinear map $\phi: M \times N \to T$ is called the tensor product of $M$ and $N$ over $A$ if it has the following universal property: every $A$-bilinear map $\phi': M \times N \to T'$ factors uniquely through $\phi$.

As usual, the universal property determines the tensor product uniquely up to a unique isomorphism. We write it $M \otimes_A N$.

Note that

\[\text{Hom}_{A\text{-bilinear}}(M \times N, T) \cong \text{Hom}_{A\text{-linear}}(M \otimes_A N, T).\]

Construction

Let $M$ and $N$ be $A$-modules, and let $A^{(M \times N)}$ be the free $A$-module with basis $M \times N$. Thus each element $A^{(M \times N)}$ can be expressed uniquely as a finite sum

\[\sum a_i (x_i, y_i), \quad a_i \in A, \quad x_i \in M, \quad y_i \in N.\]

Let $P$ be the submodule of $A^{(M \times N)}$ generated by the following elements

\[
\begin{align*}
(x + x', y) - (x, y) - (x', y), & \quad x, x' \in M, & y &\in N \\
(x, y + y') - (x, y) - (x, y'), & \quad x \in M, & y, y' &\in N \\
(ax, y) - a(x, y), & \quad a \in A, & x &\in M, & y &\in N \\
(x, ay) - a(x, y), & \quad a \in A, & x &\in M, & y &\in N,
\end{align*}
\]
and define
\[ M \otimes_A N = A^{(M \times N)}/P. \]
Write \( x \otimes y \) for the class of \((x, y)\) in \( M \otimes_A N \). Then
\[
(x, y) \mapsto x \otimes y: M \times N \to M \otimes_A N
\]
is \( A \)-bilinear — we have imposed the fewest relations necessary to ensure this. Every element of \( M \otimes_A N \) can be written as a finite sum
\[
\sum a_i (x_i \otimes y_i), \quad a_i \in A, \quad x_i \in M, \quad y_i \in N,
\]
and all relations among these symbols are generated by the following relations
\[
\begin{align*}
(x + x') \otimes y &= x \otimes y + x' \otimes y \\
x \otimes (y + y') &= x \otimes y + x \otimes y' \\
a(x \otimes y) &= (ax) \otimes y = x \otimes ay.
\end{align*}
\]
The pair \((M \otimes_A N, (x, y) \mapsto x \otimes y)\) has the correct universal property because any bilinear map \( \phi': M \times N \to T' \) defines an \( A \)-linear map \( A^{(M \times N)} \to T' \), which factors through \( A^{(M \times N)}/K \), and gives a commutative triangle.

**Extension of scalars**

Let \( A \) be a commutative ring and let \( B \) be an \( A \)-algebra (not necessarily commutative) such that the image of \( A \to B \) lies in the centre of \( B \). Then \( M \to B \otimes_A M \) is a functor from left \( A \)-modules to left \( B \)-modules, which has the following universal property:
\[
\text{Hom}_{A\text{-linear}}(M, N) \simeq \text{Hom}_{B\text{-linear}}(B \otimes_A M, N), \quad N \text{ a } B\text{-module}. \tag{8}
\]

If \((e_\alpha)_{\alpha \in I}\) is a family of generators (resp. basis) for \( M \) as an \( A \)-module, then \((1 \otimes e_\alpha)_{\alpha \in I}\) is a family of generators (resp. basis) for \( B \otimes_A M \) as a \( B \)-module.

**Behaviour with respect to direct limits**

**Proposition 8.1.** Direct limits commute with tensor products:
\[
\lim_{i \in I} M_i \otimes_A \lim_{j \in J} N_j \simeq \lim_{(i, j) \in I \times J} (M_i \otimes_A N_j).
\]

**Proof.** Using the universal properties of direct limits and tensor products, one sees easily that \( \lim (M_i \otimes_A N_j) \) has the universal property to be the tensor product of \( \lim M_i \) and \( \lim N_j \). \( \square \)

**Tensor products of algebras**

Let \( k \) be a ring, and let \( A \) and \( B \) be \( k \)-algebras. A \( k \)-algebra \( C \) together with homomorphisms \( i: A \to C \) and \( j: B \to C \) is called the tensor product of \( A \) and \( B \) if it has the following universal property:

\[
\text{for every pair of homomorphisms (of } k\text{-algebras)} \quad \alpha: A \to R \text{ and } \beta: B \to R, \text{ there exists a unique homomorphism } \gamma: C \to R \text{ such that } \gamma \circ i = \alpha \text{ and } \gamma \circ j = \beta.
\]
If it exists, the tensor product, is uniquely determined up to a unique isomorphism by this property. We write it $A \otimes_k B$. Note that the universal property says that

$$\text{Hom}_{k\text{-algebra}}(A \otimes_k B, R) \cong \text{Hom}_{k\text{-algebra}}(A, R) \times \text{Hom}_{k\text{-algebra}}(B, R).$$

(9)

Construction

Regard $A$ and $B$ as $k$-modules, and form the tensor product $A \otimes_k B$. There is a multiplication map $A \otimes_k B \times A \otimes_k B \rightarrow A \otimes_k B$ for which

$$(a \otimes b)(a' \otimes b') = aa' \otimes bb', \quad \text{all } a, a' \in A, \ b, b' \in B.$$ 

This makes $A \otimes_k B$ into a ring, and the homomorphism $c \mapsto c(1 \otimes 1) = c \otimes 1 = 1 \otimes c$ makes it into a $k$-algebra. The maps $a \mapsto a \otimes 1: A \rightarrow A \otimes_k B$ and $b \mapsto 1 \otimes b: B \rightarrow A \otimes_k B$ are homomorphisms, and they make $A \otimes_k B$ into the tensor product of $A$ and $B$ in the above sense.

**Example 8.2.** The algebra $A$, together with the given map $k \rightarrow A$ and the identity map $A \rightarrow A$, has the universal property characterizing $k \otimes_k A$. In terms of the constructive definition of tensor products, the map $c \otimes A \mapsto c(1 \otimes 1) \otimes 1$ is an isomorphism.

**Example 8.3.** The ring $k[X_1, \ldots, X_m, X_{m+1}, \ldots, X_{m+n}]$, together with the obvious inclusions

$$k[X_1, \ldots, X_n] \hookrightarrow k[X_1, \ldots, X_{m+n}] \hookrightarrow k[X_{m+1}, \ldots, X_{m+n}]$$

is the tensor product of $k[X_1, \ldots, X_m]$ and $k[X_{m+1}, \ldots, X_{m+n}]$. To verify this we only have to check that, for every $k$-algebra $R$, the map

$$\text{Hom}_{k\text{-alg}}(k[X_1, \ldots, X_{m+n}], R) \rightarrow \text{Hom}_{k\text{-alg}}(k[X_1, \ldots], R) \times \text{Hom}_{k\text{-alg}}(k[X_{m+1}, \ldots], R)$$

induced by the inclusions is a bijection. But this map can be identified with the bijection

$$R^{m+n} \rightarrow R^m \times R^n.$$ 

In terms of the constructive definition of tensor products, the map

$$k[X_1, \ldots, X_m] \otimes_k k[X_{m+1}, \ldots, X_{m+n}] \rightarrow k[X_1, \ldots, X_{m+n}]$$

sending $f \otimes g$ to $fg$ is an isomorphism.

**Remark 8.4.** (a) Let $k \leftarrow k'$ be a homomorphism of rings. Then

$$k' \otimes_k k[X_1, \ldots, X_n] \cong k'[1 \otimes X_1, \ldots, 1 \otimes X_n] \cong k'[X_1, \ldots, X_n].$$

If $A = k[X_1, \ldots, X_n]/(g_1, \ldots, g_m)$, then

$$k' \otimes_k A \cong k'[X_1, \ldots, X_n]/(g_1, \ldots, g_m).$$

(b) If $A$ and $B$ are algebras of $k$-valued functions on sets $S$ and $T$ respectively, then definition

$$(f \otimes g)(x, y) = f(x)g(y), \quad f \in A, \ g \in B, \ x \in S, \ y \in T,$n

realizes $A \otimes_k B$ as an algebra of $k$-valued functions on $S \times T$.  

The Tensor Algebra of a Module

Let $M$ be a module over a ring $A$. For each $A \geq 0$, set

$$T^r M = M \otimes_A \cdots \otimes_A M \quad (r \text{ factors}),$$

so that $T^0 M = A$ and $T^1 M = M$, and define

$$TM = \bigoplus_{r \geq 0} T^r M.$$ 

This can be made into a noncommutative $A$-algebra, called the tensor algebra of $M$, by requiring that the multiplication map

$$T^r M \times T^s M \to T^{r+s} M$$

send $(m_1 \otimes \cdots \otimes m_r, m_{r+1} \otimes \cdots \otimes m_{r+s})$ to $m_1 \otimes \cdots \otimes m_{r+s}$.

The pair $(TM, M \to TM)$ has the following universal property: any $A$-linear map from $M$ to an $A$-algebra $R$ (not necessarily commutative) extends uniquely to an $A$-algebra homomorphism $TM \to R$.

If $M$ is a free $A$-module with basis $x_1, \ldots, x_n$, then $TM$ is the (noncommutative) polynomial ring over $A$ in the noncommuting symbols $x_i$ (because this $A$-algebra has the same universal property as $TM$).

The Symmetric Algebra of a Module

The symmetric algebra $\text{Sym}(M)$ of an $A$-module $M$ is the quotient of $TM$ by the ideal generated by all elements of $T^2 M$ of the form

$$m \otimes n - n \otimes m, \quad m, n \in M.$$ 

It is a graded algebra $\text{Sym}(M) = \bigoplus_{r \geq 0} \text{Sym}^r(M)$ with $\text{Sym}^r(M)$ equal to the quotient of $M^{\otimes r}$ by the $A$-submodule generated by all elements of the form

$$m_1 \otimes \cdots \otimes m_r - m_{\sigma(1)} \otimes \cdots \otimes m_{\sigma(r)}, \quad m_i \in M, \quad \sigma \in B_r \text{ (symmetric group)}.$$ 

The pair $(\text{Sym}(M), M \to \text{Sym}(M))$ has the following universal property: any $A$-linear map $M \to R$ from $M$ to a commutative $A$-algebra $R$ extends uniquely to an $A$-algebra homomorphism $\text{Sym}(M) \to R$ (because it extends to an $A$-algebra homomorphism $TM \to R$, which factors through $\text{Sym}(M)$ because $R$ is commutative).

If $M$ is a free $A$-module with basis $x_1, \ldots, x_n$, then $\text{Sym}(M)$ is the polynomial ring over $A$ in the (commuting) symbols $x_i$ (because this $A$-algebra has the same universal property as $TM$).
9 Flatness

Let $M$ be an $A$-module. If the sequence of $A$-modules

$$0 \to N' \to N \to N'' \to 0 \quad (10)$$

is exact, then the sequence

$$M \otimes_A N' \to M \otimes_A N \to M \otimes_A N'' \to 0$$

is exact, but $M \otimes_A N' \to M \otimes_A N$ need not be injective. For example, when we tensor the exact sequence of $\mathbb{Z}$-modules

$$0 \to \mathbb{Z} \to \mathbb{Z}/m\mathbb{Z} \to \mathbb{Z}/m\mathbb{Z} \to 0$$

with $\mathbb{Z}/m\mathbb{Z}$, we get the sequence

$$\mathbb{Z}/m\mathbb{Z} \xrightarrow{m=0} \mathbb{Z}/m\mathbb{Z} \xrightarrow{} \mathbb{Z}/m\mathbb{Z} \to 0.$$

Moreover, $M \otimes_A N$ may be zero even when neither $M$ nor $N$ is nonzero. For example,

$$\mathbb{Z}/2\mathbb{Z} \otimes \mathbb{Z}/3\mathbb{Z} = 0$$

because it is killed by both 2 and 3.\footnote{It was once customary to require a ring to have an identity element $1 \neq 0$ (see, for example, Northcott 1953, p.3). However, the example shows that tensor products do not always exist in the category of such objects.}

**Definition 9.1.** An $A$-module $M$ is flat if

$$N' \to N \text{ injective } \implies M \otimes_A N' \to M \otimes_A N \text{ injective.}$$

It is **faithfully flat** if, in addition,

$$M \otimes_A N = 0 \implies N = 0.$$

A homomorphism of rings $A \to B$ is said to be (faithfully) flat when $B$ is (faithfully) flat as an $A$-module.

Thus, an $A$-module $M$ is flat if and only if $M \otimes_A -$ is an exact functor, i.e.,

$$0 \to M \otimes_A N' \to M \otimes_A N \to M \otimes_A N'' \to 0 \quad (11)$$

is exact whenever \((10)\) is exact.

The functor $M \otimes -$ takes direct sums to direct sums, and therefore split-exact sequences to split-exact sequences. Therefore, all vector spaces over a field are flat, and nonzero vector spaces are faithfully flat.

**Proposition 9.2.** Let $i: A \to B$ be a homomorphism of rings. If $i$ is faithfully flat, then a sequence of $A$-modules

$$0 \to N' \to N \to N'' \to 0 \quad (12)$$

is exact if and only if

$$0 \to B \otimes_A N' \to B \otimes_A N \to B \otimes_A N'' \to 0 \quad (13)$$

is exact. Conversely, if \(\text{(12) exact } \iff \text{(13) exact,}\)

then $i: A \to B$ is faithfully flat.
PROOF. For the first statement, we have to show that (12) is exact if (13) is exact. Let $N_0$ be the kernel of $N'$. Then, because $A \to B$ is flat, $B \otimes_A N_0$ is the kernel of $B \otimes_A N' \to B \otimes_A N$, which is zero by assumption. Because $A \to B$ is faithfully flat, this implies that $N_0 = 0$. This proves the exactness at $N'$, and the proof of exactness elsewhere is similar.

For the converse statement, the condition implies that $i$ is flat (this is the definition). Now let $N$ be an $A$-module, and consider the sequence

$$0 \to 0 \to N \to 0 \to 0.$$ 

If $B \otimes_A N = 0$, then this sequence becomes exact when tensored with $B$, and so is itself exact, which implies that $N = 0$. This shows that $i$ is faithfully flat. 

PROPOSITION 9.3. Let $i: A \to B$ be a faithfully flat homomorphism. For any $A$-module $M$, the sequence

$$0 \to M \xrightarrow{d_0} B \otimes_A M \xrightarrow{d_1} B \otimes_A B \otimes_A M$$

(*)

is exact.

PROOF. Assume first that there exists an $A$-linear section to $A \to B$, i.e., an $A$-linear map $f: B \to A$ such that $f \circ i = \text{id}_A$, and define

$$k_0: B \otimes_A M \to M, \quad k_0(b \otimes m) = f(b)m$$

$$k_1: B \otimes_A B \otimes_A M \to B \otimes_A M, \quad k_1(b \otimes b' \otimes m) = f(b)b' \otimes m.$$ 

Then $k_0d_0 = \text{id}_M$, which shows that $d_0$ is injective. Moreover,

$$k_1 \circ d_1 + d_0 \circ k_0 = \text{id}_{B \otimes_A M}$$

which shows that, if $d_1(x) = 0$, then $x = d_0(k_0(x))$, as required.

We now consider the general case. Because $A \to B$ is faithfully flat, it suffices to prove that the sequence (*) becomes exact after tensoring in $B$. But the sequence obtained from (*) by tensoring with $B$ is isomorphic to the sequence (*) for the homomorphism of rings $B \mapsto 1 \otimes B: B \to B \otimes_A B$ and the $B$-module $B \otimes_A M$, because, for example,

$$B \otimes_A (B \otimes_A M) \cong (B \otimes_A B) \otimes_B (B \otimes_A M).$$

Now $B \to B \otimes_A B$ has an $B$-linear section, namely, $f(B \otimes B') = BB'$, and so we can apply the first part. 

COROLLARY 9.4. If $A \to B$ is faithfully flat, then it is injective with image the set of elements on which the maps

$$\begin{cases} 
    b & \mapsto 1 \otimes b \\
    b & \mapsto b \otimes 1 : B \to B \otimes_A B 
\end{cases}$$

agree.
PROOF. This is the special case $M = A$ of the Proposition.

PROPOSITION 9.5. Let $A \to A'$ be a homomorphism of rings. If $A \to B$ is flat (or faithfully flat), then so also is $A' \to B \otimes_A A'$.

PROOF. For any $A'$-module $M$,

$$(B \otimes_A A') \otimes_{A'} M \simeq B \otimes_A (A' \otimes_{A'} M) \simeq B \otimes_A M,$$

from which the statement follows.

PROPOSITION 9.6. For any multiplicative subset $S$ of a ring $A$ and $A$-module $M$,

$$S^{-1}A \otimes_A M \simeq S^{-1}M.$$

Therefore the homomorphism $a \mapsto \frac{a}{1}: A \to S^{-1}A$ is flat.

PROOF. To give an $S^{-1}A$-module is the same as giving an $A$-module on which the elements of $S$ act invertibly. Therefore $S^{-1}A \otimes_A M$ and $S^{-1}M$ satisfy the same universal property (see §8, especially (8)), which proves the first statement. As $M \twoheadrightarrow S^{-1}M$ is exact (6.11), so also is $M \twoheadrightarrow S^{-1}A \otimes_A M$, which proves the second statement.

PROPOSITION 9.7. The following conditions on a flat homomorphism $\varphi: A \to B$ are equivalent:

(a) $\varphi$ is faithfully flat;

(b) for every maximal ideal $m$ of $A$, the ideal $\varphi(m)B \neq B$;

(c) every maximal ideal $m$ of $A$ is of the form $\varphi^{-1}(n)$ for some maximal ideal $n$ of $B$.

PROOF. (a) $\Rightarrow$ (b): Let $m$ be a maximal ideal of $A$, and let $M = A/m$; then

$$B \otimes_A M \simeq B/\varphi(m)B.$$

As $B \otimes_A M \neq 0$, we see that $\varphi(m)B \neq B$.

(b) $\Rightarrow$ (c): If $\varphi(m)B \neq B$, then $\varphi(m)$ is contained in a maximal ideal $n$ of $B$. Now $\varphi^{-1}(n)$ is a proper ideal in $A$ containing $m$, and hence equals $m$.

(c) $\Rightarrow$ (a): Let $M$ be a nonzero $A$-module. Let $x$ be a nonzero element of $M$, and let $a = \{a \in A \mid ax = 0\}$. Then $a$ is an ideal in $A$, and $M' \overset{\text{def}}{=} Ax \simeq A/a$. Moreover, $B \otimes_A M' \simeq B/\varphi(a) \cdot B$ and, because $A \to B$ is flat, $B \otimes_AM'$ is a submodule of $B \otimes_A M$. Because $a$ is proper, it is contained in a maximal ideal $m$ of $A$, and therefore

$$\varphi(a) \subseteq \varphi(m) \subseteq n$$

for some maximal ideal $n$ of $A$. Hence $\varphi(a) \cdot B \subseteq n \neq B$, and so $B \otimes_A M \supset B \otimes_A M' \neq 0$.

THEOREM 9.8 (GENERIC FLATNESS). Let $A$ an integral domain with field of fractions $F$, and let $B$ be a finitely generated $A$-algebra such that $B \subset F \otimes_A B$. Then for some nonzero elements $a$ of $A$ and $b$ of $B$, the homomorphism $A_a \to B_b$ is faithfully flat.
The first and third arrows realize their targets as nonzero free modules over their sources, and so are faithfully flat. The middle arrow is flat by (9.6). Let \( m \) be a maximal ideal in \( A \). Then \( m A_d \times \times m \) does not contain the polynomial \( q \) because the coefficient \( a \) of \( q \) is invertible in \( A_d \). Hence \( m A_d \times \times m q \) is a proper ideal of \( A_d \times \times m q \), and so the map \( A_d \times \times m q \) is faithfully flat (apply 9.7). This completes the proof. \( \square \)

**Remark 9.9.** The theorem holds for any finitely generated \( B \)-algebra, i.e., without the requirement that \( B \subset F \otimes_A B \). To see this, note that \( F \otimes_A B \) is the ring of fractions of \( B \) with respect to the multiplicative subset \( A \setminus \{0\} \) (see 9.6), and so the kernel of \( B \to F \otimes_A B \) is the ideal

\[
\mathfrak{n} = \{ b \in B \mid ab = 0 \text{ for some nonzero } a \in A \}.
\]

This is finitely generated (Hilbert basis theorem 3.6), and so there exists a nonzero \( c \in A \) such that \( cb = 0 \) for all \( b \in \mathfrak{n} \). I claim that the homomorphism \( B_c \to F \otimes_A B_c \) is injective. If \( b \) lies in its kernel, then \( \frac{b}{c} \) is nonzero. Therefore, \( \frac{b}{c} \) is in \( B \) for some nonzero \( \frac{b}{c} \in A \), and so \( c^N ab = 0 \) in \( B \), for some \( N \); therefore \( b \in \mathfrak{n} \), and so \( cb = 0 \), which implies that \( \frac{b}{c} \) is already in \( B_c \).
Therefore, after replacing $A$, $B$, and $M$ with $A_c$, $B_c$, and $M_c$, we may suppose that the map $B \to F \otimes_A B$ is injective. On identifying $B$ with its image, we arrive at the situation of the theorem.

## 10 The Hilbert Nullstellensatz

**Theorem 10.1 (Zariski's Lemma).** Let $k \subset K$ be fields. If $K$ is finitely generated as a $k$-algebra, then it is algebraic over $k$ (hence $K$ is finite over $k$, and equals it if $k$ is algebraically closed).

**Proof.** We shall prove this by induction on $r$, the smallest number of elements required to generate $K$ as a $k$-algebra. The case $r = 0$ being trivial, we may suppose that

$$K = k[x_1, \ldots, x_r]$$

with $r \geq 1$.

If $K$ is not algebraic over $k$, then at least one $x_i$, say $x_1$, is not algebraic over $k$. Then, $k[x_1]$ is a polynomial ring in one symbol over $k$, and its field of fractions $k(x_1)$ is a subfield of $K$. Clearly $K$ is generated as a $k(x_1)$-algebra by $x_2, \ldots, x_r$, and so the induction hypothesis implies that $x_2, \ldots, x_r$ are algebraic over $k(x_1)$. Proposition 5.5 shows that there exists a $c \in k[x_1]$ such that $cx_2, \ldots, cx_r$ are integral over $k[x_1]$. Let $f \in K$. For a sufficiently large $N$, $c^N f \in k[x_1, cx_2, \ldots, cx_r]$, and so $c^N f$ is integral over $k[x_1]$ by 5.3. When we apply this statement to an element $f$ of $k(x_1)$, it shows that $c^N f \in k[x_1]$ because $k[x_1]$ is integrally closed. Therefore, $k(x_1) = \bigcup_N c^{-N} k[x_1]$, but this is absurd, because $k[x_1]$ (which equals $k[X]$) has infinitely many distinct monic irreducible polynomials that can occur as denominators of elements of $k(x_1)$.

Recall that $k^{al}$ denotes an algebraic closure of the field $k$.

---

13 The following alternative proof of 10.1 is a simplification by Swan of a proof of Munshi — see www.math.uchicago.edu/~swan/

**Lemma:** For an integral domain $A$, there does not exist an $f \in A[X]$ such that $A[X]/f$ is a field.

**Proof:** Suppose, on the contrary, that $A[X]/f$ is a field. Then $\deg f > 0$, and so $f - 1 \notin B$. Write $(f - 1)^{-1} = g/f^n$ with $g \in A[X]$ and $n \geq 1$. Then $(f - 1)g = f^n = (1 + (f - 1))^n = 1 + (f - 1)h$ with $h \in A[X]$. It follows that $f - 1$ is a unit, which is absurd.

**Lemma:** Consider rings $A \subset B$. If $B$ is integral over $A$, then $A \cap B^\times = A^\times$. In particular, if $B$ is a field, then so also is $A$.

**Proof:** Let $a$ be an element of $A$ that becomes a unit in $B$, say, $ab = 1$ with $b \in B$. Write $b^n + a_1b^{n-1} + \ldots + a_n = 0$ with $a_1, \ldots, a_n \in A$. On multiplying by $a^{-1}$, we find that $b = -a_1 - \ldots - a_n a^{-1}$ in $A$, and so $a \in A^\times$.

**Proposition:** Let $A$ be an integral domain, and let $m$ be a maximal ideal of $A[X_1, \ldots, X_n]$. If $A \cap m = \{0\}$, then there exists a nonzero element $a$ in $A$ such that $A_a$ is a field and $A[X_1, \ldots, X_n]/m$ is a finite extension of $A_a$.

**Proof:** We argue by induction on $n$. The statement being trivial for $n = 0$, we may suppose that $n \geq 1$. Regard $A[X_1, \ldots, X_n]$ as a polynomial ring in $n - 1$ symbols over $A[X_1]$. The induction hypothesis and the first lemma show that there exists a nonzero element $P_i(X_1) = a_i X_i^{m_i} + \ldots \in m \cap A[X_1]$. Let $a = a_1 \cdots a_n$, and let $K = A[X_1, \ldots, X_n]/m$. The image $x_i$ of $X_i$ in $K$ satisfies the monic equation $a_i^{m_i} P_i = 0$, and so $K$ is integral over $A_a$. By the second lemma, $A_a$ is a field, and $K$ is finite over it because it is integral (algebraic) and finitely generated.

**Corollary:** Let $A$ be a finitely generated algebra over a field $k$. For any maximal ideal $m$ of $A$, $A/m$ is a finite extension of $k$.

**Proof:** Take $A$ in the proposition to be a field.

14 When $k$ is infinite, there are infinitely many monomials $X - a$, and when $k$ is finite, we can adapt Euclid’s argument: if $p_1, \ldots, p_r$ are monic irreducible polynomials in $k[X]$, then $p_1 \cdots p_r + 1$ is divisible by a monic irreducible polynomial distinct from $p_1, \ldots, p_r$. 


THEOREM 10.2 (NULLSTELLENSATZ). Every proper ideal \( \mathfrak{a} \) in \( k[X_1, \ldots, X_n] \) has a zero in \( (k^a)^n \cong k^a \times \cdots \times k^a \), i.e., there exists a point \((a_1, \ldots, a_n) \in (k^a)^n \) such that \( f(a_1, \ldots, a_n) = 0 \) for all \( f \in \mathfrak{a} \).

PROOF. We have to show that there exists a \( k \)-algebra homomorphism \( k[X_1, \ldots, X_n] \rightarrow k^a \) containing \( \mathfrak{a} \) in its kernel. Let \( \mathfrak{m} \) be a maximal ideal containing \( \mathfrak{a} \). Then \( k[X_1, \ldots, X_n]/\mathfrak{m} \) is a field, which is algebraic over \( k \) by Zariski’s lemma, and so there exists a \( k \)-algebra homomorphism \( k[X_1, \ldots, X_n]/\mathfrak{m} \rightarrow k^a \). The composite of this with the quotient map \( k[X_1, \ldots, X_n] \rightarrow k[X_1, \ldots, X_n]/\mathfrak{m} \) contains \( \mathfrak{a} \) in its kernel.

COROLLARY 10.3. When \( k \) is algebraically closed, the maximal ideals in \( k[X_1, \ldots, X_n] \) are exactly the ideals \((X_1-a_1, \ldots, X_n-a_n), (a_1, \ldots, a_n) \in k^n \).

PROOF. Clearly, \( k[X_1, \ldots, X_n]/(X_1-a_1, \ldots, X_n-a_n) \cong k \), and so \((X_1-a_1, \ldots, X_n-a_n) \) is maximal. Conversely, because \( k \) is algebraically closed, a proper ideal \( \mathfrak{a} \) has a zero \((a_1, \ldots, a_n) \) in \( k^n \). Let \( f \in k[X_1, \ldots, X_n] \); when we write \( f \) as a polynomial in \( X_1-a_1, \ldots, X_n-a_n \), its constant term is \( f(a_1, \ldots, a_n) \). Therefore, if \( f \in \mathfrak{a} \), then \( f \in (X_1-a_1, \ldots, X_n-a_n) \).

THEOREM 10.4 (STRONG NULLSTELLENSATZ). For an ideal \( \mathfrak{a} \) in \( k[X_1, \ldots, X_n] \), let \( Z(\mathfrak{a}) \) be the set of zeros of \( \mathfrak{a} \) in \( (k^a)^n \). If a polynomial \( h \in k[X_1, \ldots, X_n] \) is zero on \( Z(\mathfrak{a}) \), then some power of \( h \) lies in \( \mathfrak{a} \).

PROOF. We may assume \( h \neq 0 \). Let \( g_1, \ldots, g_m \) generate \( \mathfrak{a} \), and consider the system of \( m+1 \) equations in \( n+1 \) variables, \( X_1, \ldots, X_n, Y \).

\[
\begin{align*}
g_i(X_1, \ldots, X_n) &= 0, \quad i = 1, \ldots, m \\
1 - Yh(X_1, \ldots, X_n) &= 0.
\end{align*}
\]

If \((a_1, \ldots, a_n, b)\) satisfies the first \( m \) equations, then \((a_1, \ldots, a_n) \in Z(\mathfrak{a}) \); consequently, \( h(a_1, \ldots, a_n) = 0 \), and \((a_1, \ldots, a_n, b)\) doesn’t satisfy the last equation. Therefore, the equations are inconsistent, and so, according to the Nullstellensatz \([10.2]\), there exist \( f_i \in k[X_1, \ldots, X_n, Y] \) such that

\[
1 = \sum_{i=1}^{m} f_i \cdot g_i + f_{m+1} \cdot (1 - Yh)
\]

in \( k[X_1, \ldots, X_n, Y] \). On applying the homomorphism

\[
\begin{align*}
X_i &\mapsto X_i \\
Y &\mapsto h^{-1}
\end{align*}
\]

\( k[X_1, \ldots, X_n, Y] \rightarrow k(X_1, \ldots, X_n) \)

to the above equality, we obtain the identity

\[
1 = \sum_{i} f_i(X_1, \ldots, X_n, h^{-1}) \cdot g_i(X_1, \ldots, X_n)
\]

\hspace{1cm} \text{(15)}

in \( k(X_1, \ldots, X_n) \). Clearly

\[
f_i(X_1, \ldots, X_n, h^{-1}) = \frac{\text{polynomial in } X_1, \ldots, X_n}{h^{N_i}}
\]
for some $N_i$. Let $N$ be the largest of the $N_i$. On multiplying (15) by $h^N$ we obtain an identity

$$h^N = \sum_i \text{(polynomial in } X_1, \ldots, X_n) \cdot g_i(X_1, \ldots, X_n),$$

which shows that $h^N \in a$.

**Proposition 10.5.** The radical of an ideal $a$ in a finitely generated $k$-algebra $A$ is equal to the intersection of the maximal ideals containing it: $\text{rad}(a) = \bigcap_{m \supseteq a} m$. In particular, if $A$ is reduced, then $\bigcap_{m \text{ maximal}} m = 0$.

**Proof.** Because of the correspondence (2), p.3, it suffices to prove this for $A = k[X_1, \ldots, X_n]$. Let $a$ be an ideal in $k[X_1, \ldots, X_n]$. Because $\text{rad}(a)$ is the smallest radical ideal containing $a$ and maximal ideals are radical $\text{rad}(a) \subset \bigcap_{m \supseteq a} m$. Conversely, suppose $h$ is contained in all maximal ideals containing $a$, and let $(a_1, \ldots, a_n) \in Z(a)$. The evaluation map

$$f \mapsto f(a_1, \ldots, a_n) : k[X_1, \ldots, X_n] \to k^{al}$$

has image a subring of $k^{al}$ which is algebraic over $k$, and hence is a field (see §1). Therefore, the kernel of the map is a maximal ideal, which contains $a$, and therefore also contains $h$. This shows that $h(a_1, \ldots, a_n) = 0$, and we conclude from the strong Nullstellensatz that $h \in \text{rad}(a)$.

### 11 The Max Spectrum of a Ring

Let $A$ be a ring, and let $V$ be the set of maximal ideals in $A$. For an ideal $a$ in $A$, let

$$V(a) = \{ m \in V \mid m \supseteq a \}.$$

**Proposition 11.1.** There are the following relations:

(a) $a \subset b \implies V(a) \supset V(b)$;
(b) $V(0) = V$; $V(A) = \emptyset$;
(c) $V(ab) = V(a \cap b) = V(a) \cup V(b)$;
(d) $V(\sum_{i \in I} a_i) = \bigcap_{i \in I} V(a_i)$ for any family of ideals $(a_i)_{i \in I}$.

**Proof.** The first two statements are obvious. For (c), note that

$$ab \subset a \cap b \subset a, b \implies V(ab) \supset V(a \cap b) \supset V(a) \cup V(b).$$

For the reverse inclusions, observe that if $m \notin V(a) \cup V(b)$, then there exist an $f \in a \setminus m$ and a $g \in b \setminus m$; but then $fg \in ab \setminus m$, and so $m \notin V(ab)$. For (d) recall that, by definition, $\sum a_i$ consists of all finite sums of the form $\sum f_i$, $f_i \in a_i$. Thus (d) is obvious.

Statements (b), (c), and (d) show that the sets $V(a)$ satisfy the axioms to be the closed subsets for a topology on $V$: both the whole space and the empty set are closed; a finite union of closed sets is closed; an arbitrary intersection of closed sets is closed. This topology is called the Zariski topology on $V$. We let $\text{spm}(A)$ denote the set of maximal ideals in $A$ endowed with its Zariski topology.

For $h \in A$, let

$$D(h) = \{ m \in V \mid h \notin m \}.$$
Then $D(h)$ is open in $V$, being the complement of $V((h))$. If $S$ is a set of generators for an ideal $a$, then $$V \setminus V(a) = \bigcup_{h \in S} D(h),$$ and so the sets $D(h)$ form a base for the topology on $V$. Note that, because maximal ideals are prime, $$D(h_1 \cdots h_n) = D(h_1) \cap \cdots \cap D(h_n).$$ For any element $h$ of $A$, $\text{spm}(A_h) \simeq D(h)$ (see §6.4), and for any ideal $\alpha$ in $A$, $\text{spm}(A)/\alpha \simeq V(\alpha)$ (isomorphisms of topological spaces).

The ideals in a finite product of rings $A = A_1 \times \cdots \times A_n$ are all of the form $a_1 \times \cdots \times a_n$ with $a_i$ an ideal in $A_i$ (cf. p.7). The prime (resp. maximal) ideals are those of the form $$A_1 \times \cdots \times A_{i-1} \times a_i \times A_{i+1} \times \cdots \times A_n$$ with $a_i$ prime (resp. maximal). It follows that $\text{spm}(A) = \bigsqcup_i \text{spm}(A_i)$ (disjoint union of open subsets).

**The Max Spectrum of a Finitely Generated $k$-algebra**

Let $k$ be a field, and let $A$ be a finitely generated $k$-algebra. For any maximal ideal $m$ of $A$, the field $k(m) \overset{\text{def}}{=} A/m$ is a finitely generated $k$-algebra, and so $k(m)$ is finite over $k$ (Zariski’s lemma, §10.1). In particular, it equals $k(m) = k$ when $k$ is algebraically closed.

Now fix an algebraic closure $k^{\text{alg}}$. The image of any $k$-algebra homomorphism $A \to k^{\text{alg}}$ is a subring of $k^{\text{alg}}$ which is an integral domain algebraic over $k$ and therefore a field (see §11). Hence the kernel of the homomorphism is a maximal ideal in $A$. In this way, we get a surjective map $$\text{Hom}_{k\text{-alg}}(A, k^{\text{alg}}) \to \text{spm}(A).$$ (16)

Two homomorphisms $A \to k^{\text{alg}}$ with the same kernel $m$ factor as $$A \to k(m) \to k^{\text{alg}},$$ and so differ by an automorphism of $k^{\text{alg}}$. Therefore, the fibres of (16) are exactly the orbits of $\text{Gal}(k^{\text{alg}}/k)$. When $k$ is perfect, each extension $k(m)/k$ is separable, and so each orbit has $[k(m):k]$ elements, and when $k$ is algebraically closed, the map (16) is a bijection.

Set $A = k[X_1, \ldots, X_n]/\alpha$. Then to give a homomorphism $A \to k^{\text{alg}}$ is the same as giving an $n$-tuple $(a_1, \ldots, a_n)$ of elements of $k^{\text{alg}}$ (the images of the $X_i$) such that $f(a_1, \ldots, a_n) = 0$ for all $f \in \alpha$, i.e., an element of the zero-set $Z(\alpha)$ of $\alpha$. The homomorphism corresponding to $(a_1, \ldots, a_n)$ maps $k(m)$ isomorphically onto the subfield of $k^{\text{alg}}$ generated by the $a_i$’s. Therefore, we have a canonical surjection $$Z(\alpha) \to \text{spm}(A)$$ (17)

whose fibres are the orbits of $\text{Gal}(k^{\text{alg}}/k)$. When the field $k$ is perfect, each orbit has $[k[a_1, \ldots, a_n]:k]$-elements, and when $k$ is algebraically closed, $Z(\alpha) \simeq \text{spm}(A)$.

---

15Let $f$ and $g$ be two $k$-homomorphisms from a finite field extension $k'$ of $k$ into $k^{\text{alg}}$. We consider the set of pairs $(K, \alpha)$ in which $\alpha$ is a $k$-homomorphism from a subfield $K$ of $k^{\text{alg}}$ containing $f(k')$ into $k^{\text{alg}}$ such that $\alpha \circ f = g$. The set is nonempty, and Zorn’s lemma can be applied to show that it has a maximal element $(K', \alpha')$. For such an element $K'$ will be algebraically closed, and hence equal to $k^{\text{alg}}$. 

---
ASIDE 11.2. Let $k = \mathbb{R}$ or $\mathbb{C}$. Let $X$ be a set and let $A$ be a $k$-algebra of $k$-valued functions on $X$. In analysis, $X$ is called the spectrum of $A$ if, for each $k$-algebra homomorphism $\varphi: A \rightarrow k$, there exists a unique $x \in X$ such that $\varphi(f) = f(x)$ for all $f \in A$, and every $x$ arises from a $\varphi$ (cf. [Cartier 2007, 3.3.1, footnote]).

Let $A$ be a finitely generated algebra over an arbitrary algebraically closed field $k$, and let $X = \text{spm}(A)$. An element $f$ of $A$ defines a $k$-valued function

$$m \mapsto f \mod m$$
on $X$. When $A$ is reduced, Proposition [10.5] shows that this realizes $A$ as a ring of $k$-valued functions on $X$. Moreover, because [17] is an isomorphism in this case, for each $k$-algebra homomorphism $\varphi: A \rightarrow k$, there exists a unique $x \in X$ such that $\varphi(f) = f(x)$ for all $f \in A$. In particular, when $k = \mathbb{C}$ and $A$ is reduced, $\text{spm}(A)$ is the spectrum of $A$ in the sense of analysis.

JACOBSON RINGS

DEFINITION 11.3. A ring $A$ is Jacobson if every prime ideal in $A$ is an intersection of maximal ideals.

A field is Jacobson. The ring $\mathbb{Z}$ is Jacobson because every nonzero prime ideal is maximal and $(0) = \bigcap_{p=2,3,5,\ldots}(p)$. A principal ideal domain (more generally, a Dedekind domain) is Jacobson if it has an infinite number of maximal ideals. A local ring is Jacobson if and only if its maximal ideal is its only prime ideal. Proposition [10.5] shows that every finitely generated algebra over a field is Jacobson.

PROPOSITION 11.4. The radical of an ideal in a Jacobson ring is equal to the intersection of the maximal ideals containing it. (Therefore, the radical ideals are precisely the intersections of maximal ideals.)

PROOF. Proposition [2.6] says that the radical of an ideal is an intersection of prime ideals, and so this follows from the definition of a Jacobson ring.

ASIDE 11.5. Any ring of finite type over a Jacobson ring is a Jacobson ring (EGA IV 10.4.6). Moreover, if $B$ is of finite type over $A$ and $A$ is Jacobson, then the map $A \rightarrow B$ defines a continuous map $\text{spm}(B) \rightarrow \text{spm}(A)$.

THE TOPOLOGICAL SPACE $\text{spm}(A)$

We study more closely the Zariski topology on $\text{spm}(A)$. For each subset $S$ of $A$, let $V(S)$ denote the set of maximal ideals containing $S$, and for each subset $W$ of $\text{spm}(A)$, let $I(W)$ denote the intersection of the maximal ideals in $W$:

$$S \subset A, \quad V(S) = \{m \in \text{spm}(A) \mid S \subset m\},$$

$$W \subset \text{spm}(A), \quad I(W) = \bigcap_{m \in W} m.$$

Thus $V(S)$ is a closed subset of $\text{spm}(A)$ and $I(W)$ is a radical ideal in $A$. If $V(a) \supset W$, then $a \subset I(W)$, and so $V(a) \supset V(I(W))$. Therefore $V(I(W))$ is the closure of $W$ (smallest closed subset of $\text{spm}(A)$ containing $W$); in particular, $V(I(W)) = W$ if $W$ is closed.

16In a principal ideal domain, a nonzero element $a$ factors as $a = up_1^{t_1} \cdots p_s^{t_s}$ with $u$ a unit and the $p_i$ prime. The only prime divisors of $a$ are $p_1, \ldots, p_s$, and so $a$ is contained in only finitely many prime ideals. Similarly, in a Dedekind domain, a nonzero ideal $a$ factors as $a = p_1^{t_1} \cdots p_s^{t_s}$ with the $p_i$ prime ideals (cf. 13.17 below), and $p_1, \ldots, p_s$ are the only prime ideals containing $a$. On taking $a = (a)$, we see that again $a$ is contained in only finitely many prime ideals.
11. THE MAX SPECTRUM OF A RING

PROPOSITION 11.6. Let \( V \) be a closed subset of \( \text{spm}(A) \).

(a) The points of \( V \) are closed for the Zariski topology.

(b) If \( A \) is noetherian, then every ascending chain of open subsets \( U_1 \subset U_2 \subset \cdots \) of \( V \) eventually becomes constant; equivalently, every descending chain of closed subsets of \( V \) eventually becomes constant.

(c) If \( A \) is noetherian, every open covering of \( V \) has a finite subcovering.

PROOF. (a) Clearly \( \{m\} = V(m) \), and so it is closed.

(b) We prove the second statement. A sequence \( V_1 \supset V_2 \supset \cdots \) of closed subsets of \( V \) gives rise to a sequence of ideals \( I(V_1) \supset I(V_2) \supset \cdots \), which eventually becomes constant. If \( I(V_m) = I(V_{m+1}) \), then \( VI(V_m) = VI(V_{m+1}) \), i.e., \( V_m = V_{m+1} \).

(c) Let \( V = \bigcup_{i \in I} U_i \) with each \( U_i \) open. Choose an \( i_0 \in I \); if \( U_{i_0} \neq V \), then there exists an \( i_1 \in I \) such that \( U_{i_0} \supsetneq U_{i_0} \cup U_{i_1} \). If \( U_{i_0} \cup U_{i_1} \neq V \), then there exists an \( i_2 \in I \) etc.. Because of (b), this process must eventually stop. \( \square \)

A topological space \( V \) having the property (b) is said to be noetherian. This condition is equivalent to the following: every nonempty set of closed subsets of \( V \) has a minimal element. A topological space \( V \) having property (c) is said to be quasicompact (by Bourbaki at least; others call it compact, but Bourbaki requires a compact space to be Hausdorff). The proof of (c) shows that every noetherian space is quasicompact. Since an open subspace of a noetherian space is again noetherian, it will also be quasicompact.

DEFINITION 11.7. A nonempty topological space is said to be irreducible if it is not the union of two proper closed subsets. Equivalent conditions: any two nonempty open subsets have a nonempty intersection; every nonempty open subset is dense.

If an irreducible space \( W \) is a finite union of closed subsets, \( W = W_1 \cup \ldots \cup W_r \), then \( W = W_i \) or \( W_2 \cup \ldots \cup W_r \); if the latter, then \( W = W_2 \) or \( W_3 \cup \ldots \cup W_r \), etc.. Continuing in this fashion, we find that \( W = W_i \) for some \( i \).

The notion of irreducibility is not useful for Hausdorff topological spaces, because the only irreducible Hausdorff spaces are those consisting of a single point — two points would have disjoint open neighbourhoods.

PROPOSITION 11.8. Let \( W \) be a closed subset of \( \text{spm}(A) \). If \( W \) is irreducible, then \( I(W) \) is prime; the converse is true if \( A \) is a Jacobson ring. In particular, the max spectrum of a Jacobson ring \( A \) is irreducible if and only if the nilradical of \( A \) is prime.

PROOF. \( \Rightarrow \): Let \( W \) be an irreducible closed subset of \( \text{spm}(A) \), and suppose \( fg \in I(W) \). Then \( fg \) lies in each \( m \) in \( W \), and so either \( f \in m \) or \( g \in m \); hence \( W \subset V(f) \cup V(g) \), and so

\[
W = (W \cap V(f)) \cup (W \cap V(g)).
\]

As \( W \) is irreducible, one of these sets, say \( W \cap V(f) \), must equal \( W \). But then \( f \in I(W) \).

We have shown that \( I(W) \) is prime.

\( \Leftarrow \): Assume \( I(W) \) is prime, and suppose \( W = V(a) \cup V(b) \) with \( a \) and \( b \) radical ideals — we have to show that \( W \) equals \( V(a) \) or \( V(b) \). Recall that \( V(a) \cup V(b) = V(a \cap b) \) (see \([11.1]\) ) and that \( a \cap b \) is radical; hence \( I(W) = a \cap b \) (by \([11.4]\) ). If \( W \neq V(a) \), then there exists an \( f \in a \setminus I(W) \). For all \( g \in b \),

\[
fg \in a \cap b = I(W).
\]

Because \( I(W) \) is prime, this implies that \( b \subset I(W) \); therefore \( W \subset V(b) \). \( \square \)
Thus, in the max spectrum of a Jacobson ring, there are one-to-one correspondences

- radical ideals $\leftrightarrow$ closed subsets
- prime ideals $\leftrightarrow$ irreducible closed subsets
- maximal ideals $\leftrightarrow$ one-point sets.

**Example 11.9.** Let $f \in k[X_1, \ldots, X_n]$. According to Theorem 4.6, $k[X_1, \ldots, X_n]$ is a unique factorization domain, and so $(f)$ is a prime ideal if and only if $f$ is irreducible (4.1). Thus

$$V(f) \text{ is irreducible } \iff f \text{ is irreducible.}$$

On the other hand, suppose $f$ factors,

$$f = \prod f_i^{m_i}, \quad f_i \text{ distinct irreducible polynomials.}$$

Then

- $(f) = \bigcap (f_i^{m_i})$, distinct ideals,
- $\text{rad}(f) = \bigcap (f_i)$, distinct prime ideals,
- $V(f) = \bigcup V(f_i)$, $V(f_i)$ distinct irreducible algebraic sets.

**Proposition 11.10.** Let $V$ be a noetherian topological space. Then $V$ is a finite union of irreducible closed subsets, $V = V_1 \cup \ldots \cup V_m$. If the decomposition is irredundant in the sense that there are no inclusions among the $V_i$, then the $V_i$ are uniquely determined up to order.

**Proof.** Suppose that $V$ can not be written as a finite union of irreducible closed subsets. Then, because $V$ is noetherian, there will be a closed subset $W$ of $V$ that is minimal among those that cannot be written in this way. But $W$ itself cannot be irreducible, and so $W = W_1 \cup W_2$, with each $W_i$ a proper closed subset of $W$. Because $W$ is minimal, both $W_1$ and $W_2$ can be expressed as finite unions of irreducible closed subsets, but then so can $W$. We have arrived at a contradiction.

Suppose that

$$V = V_1 \cup \ldots \cup V_m = W_1 \cup \ldots \cup W_n$$

are two irredundant decompositions. Then $V_i = \bigcup_j (V_i \cap W_j)$, and so, because $V_i$ is irreducible, $V_i = V_i \cap W_j$ for some $j$. Consequently, there exists a function $f : \{1, \ldots, m\} \to \{1, \ldots, n\}$ such that $V_i \subset W_{f(i)}$ for each $i$. Similarly, there is a function $g : \{1, \ldots, n\} \to \{1, \ldots, m\}$ such that $W_j \subset V_{g(j)}$ for each $j$. Since $V_i \subset W_{f(i)} \subset V_{g(f(i))}$, we must have $gf(i) = i$ and $V_i = W_{f(i)}$, similarly $fg = \text{id}$. Thus $f$ and $g$ are bijections, and the decompositions differ only in the numbering of the sets.

The $V_i$ given uniquely by the proposition are called the **irreducible components** of $V$. They are the maximal closed irreducible subsets of $V$. In Example 11.9, the $V(f_i)$ are the irreducible components of $V(f)$.

**Corollary 11.11.** A radical ideal $a$ in a noetherian Jacobson ring is a finite intersection of prime ideals, $a = p_1 \cap \ldots \cap p_n$; if there are no inclusions among the $p_i$, then the $p_i$ are uniquely determined up to order.
PROOF. Write \( V(\alpha) \) as a union of its irreducible components, \( V(\alpha) = \bigcup V_i \), and take \( p_i = I(V_i) \).

REMARK 11.12. (a) An irreducible topological space is connected, but a connected topological space need not be irreducible. For example, \( Z(X_1X_2) \) is the union of the coordinate axes in \( k^2 \), which is connected but not irreducible. A closed subset \( V \) of \( \text{spm}(A) \) is not connected if and only if there exist ideals \( \alpha \) and \( \beta \) such that \( \alpha \cap \beta = I(V) \) and \( \alpha + \beta = A \).

(b) A Hausdorff space is noetherian if and only if it is finite, in which case its irreducible components are the one-point sets.

(c) In a noetherian ring, every proper ideal \( \alpha \) has a decomposition into primary ideals: \( \alpha = \bigcap q_i \) (see \([13]\)). For radical ideals, this becomes a simpler decomposition into prime ideals, as in the corollary. For an ideal \( \alpha \) in \( k[X_1, \ldots, X_n] \) with \( \alpha = \prod f_i^{m_i} \), it is the decomposition \( \alpha = \bigcap (f_i^{m_i}) \) noted in Example 11.9.

MAPS OF MAX SPECTRA

Let \( \varphi: A \to B \) be a homomorphism of finitely generated \( k \)-algebras (\( k \) a field). Because \( B \) is finitely generated over \( k \), its quotient \( B/\mathfrak{m} \) by any maximal ideal \( \mathfrak{m} \) is a finite field extension of \( k \) (Zariski's lemma, \([10, 1]\)). Therefore the image of \( A \) in \( B/\mathfrak{m} \) is an integral domain finite over \( k \), and hence is a field (see \([\ ]\)). Since this image is isomorphic to \( A/\varphi^{-1}(\mathfrak{m}) \), this shows that the ideal \( \varphi^{-1}(\mathfrak{m}) \) is maximal in \( A \). Therefore \( \varphi \) defines a map

\[
\varphi^*: \text{spm}(B) \to \text{spm}(A), \quad \mathfrak{m} \mapsto \varphi^{-1}(\mathfrak{m}),
\]

which is continuous because \( (\varphi^*)^{-1}(D(f)) = D(\varphi(f)) \). In this way, \( \text{spm} \) becomes a functor from finitely generated \( k \)-algebras to topological spaces.

THEOREM 11.13. Let \( \varphi: A \to B \) be a homomorphism of finitely generated \( k \)-algebras. Let \( U \) be a nonempty open subset of \( \text{spm}(B) \), and let \( \varphi^*(U)^- \) be the closure of its image in \( \text{spm}(A) \). Then \( \varphi^*(U)^- \) contains a nonempty open subset of each irreducible component of \( \varphi^*(U)^- \).

PROOF. Let \( W = \text{spm}(B) \) and \( V = \text{spm}(A) \), so that \( \varphi^* \) is a continuous map \( W \to V \).

We first prove the theorem in the case that \( \varphi \) is an injective homomorphism of integral domains. For some \( b \neq 0 \), \( D(b) \subset U \). According to Proposition 11.14 below, there exists a nonzero element \( \alpha \in A \) such that every homomorphism \( \alpha: A \to k^{\text{al}} \) such that \( \alpha(a) \neq 0 \) extends to a homomorphism \( \beta: B \to k^{\text{al}} \) such that \( \beta(b) \neq 0 \). Let \( m \in D(a) \), and choose \( \alpha \) to be a homomorphism \( A \to k^{\text{al}} \) with kernel \( m \). The kernel of \( \beta \) is a maximal ideal \( n \in D(b) \) such that \( \varphi^{-1}(n) = m \), and so \( D(a) \subset \varphi^*(D(b)) \).

We now prove the general case. If \( W_1, \ldots, W_r \) are the irreducible components of \( W \), then \( \varphi^*(W_i)^- \) is a union of the sets \( \varphi^*(W_i)^- \), and any irreducible component \( C \) of \( \varphi^*(U)^- \) is contained in one of \( \varphi^*(W_i)^- \), say \( \varphi^*(W_1)^- \). Let \( q = I(W_1) \) and let \( p = \varphi^{-1}(q) \). Because \( W_1 \) is irreducible, they are both prime ideals. The homomorphism \( \varphi: A \to B \) induces an injective homomorphism \( \tilde{\varphi}: A/p \to B/q \), and \( \varphi^* \) can be identified with the restriction of \( \varphi^* \) to \( W_1 \). From the first case, we know that \( \varphi^*(U \cap W_1) \) contains a nonempty open subset of \( C \), which implies that \( \varphi^*(U) \) does also.

In the next two statements, \( A \) and \( B \) are arbitrary commutative rings — they need not be \( k \)-algebras.
Proposition 11.14. Let $A \subset B$ be integral domains with $B$ finitely generated as an algebra over $A$, and let $b$ be a nonzero element of $B$. Then there exists an element $a \neq 0$ in $A$ with the following property: every homomorphism $\alpha : A \to \Omega$ from $A$ into an algebraically closed field $\Omega$ such that $\alpha(b) \neq 0$ can be extended to a homomorphism $\beta : B \to \Omega$ such that $\beta(b) \neq 0$.

We first need a lemma.

Lemma 11.15. Let $B \subset A$ be integral domains, and assume $B = A[t] = A[T]/a$. Let $c \subset A$ be the ideal of leading coefficients of the polynomials in $a$. Then every homomorphism $\alpha : A \to \Omega$ from $A$ into an algebraically closed field $\Omega$ such that $\alpha(c) \neq 0$ can be extended to a homomorphism of $B$ into $\Omega$.

Proof. If $a = 0$, then $c = 0$, and every $\alpha$ extends. Thus we may assume $a \neq 0$. Let $\alpha$ be a homomorphism $A \to \Omega$ such that $\alpha(c) \neq 0$. Then there exist polynomials $a_m T^m + \cdots + a_0$ in $a$ such that $\alpha(a_m) \neq 0$, and we choose one, denoted $f$, of minimum degree. Because $B \neq 0$, the polynomial $f$ is nonconstant.

Extend $\alpha$ to a homomorphism $A[T] \to \Omega[T]$, again denoted $\alpha$, by sending $T$ to $T$, and consider the subset $\alpha(a)$ of $\Omega[T]$.

First case: $\alpha(a)$ does not contain a nonzero constant. If the $\Omega$-subspace of $\Omega[T]$ spanned by $\alpha(a)$ contained 1, then so also would $\alpha(a)$\footnote{Use that, if a system of linear equation with coefficients in a field $k$ has a solution in some larger field, then it has a solution in $k$.} contrary to hypothesis. Because

$$T \cdot \sum c_i \alpha(g_i) = \sum c_i \alpha(g_i T), \quad c_i \in \Omega, \quad g_i \in a,$$

this $\Omega$-subspace an ideal, which we have shown to be proper, and so it has a zero $\alpha(c)$ in $\Omega$. The composite of the homomorphisms

$$A[T] \xrightarrow{\alpha} \Omega[T] \longrightarrow \Omega, \quad T \mapsto T \mapsto \alpha(c),$$

factors through $A[T]/a = B$ and extends $\alpha$.

Second case: $\alpha(a)$ contains a nonzero constant. This means that $\alpha$ contains a polynomial

$$g(T) = b_n T^n + \cdots + b_0 \quad \text{such that} \quad \alpha(b_0) \neq 0, \quad \alpha(b_1) = \alpha(b_2) = \cdots = 0.$$  

On dividing $f(T)$ into $g(T)$ we obtain an equation

$$a_m g(T) = q(T) f(T) + r(T), \quad d \in \mathbb{N}, \quad q, r \in A[T], \quad \deg r < m.$$  

When we apply $\alpha$, this becomes

$$\alpha(a_m)^d \alpha(b_0) = \alpha(q) \alpha(f) + \alpha(r).$$  

Because $\alpha(f)$ has degree $m > 0$, we must have $\alpha(q) = 0$, and so $\alpha(r)$ is a nonzero constant. After replacing $g(T)$ with $r(T)$, we may suppose $n < m$. If $m = 1$, such a $g(T)$ can’t exist, and so we may suppose $m > 1$ and (by induction) that the lemma holds for smaller values of $m$. 


For \( h(T) = c_r T^r + c_{r-1} T^{r-1} + \cdots + c_0 \), let \( h'(T) = c_r + \cdots + c_0 T^r \). Then the \( A \)-module generated by the polynomials \( T^s h'(T), s \geq 0, h \in a \), is an ideal \( a' \) in \( A[T] \). Moreover, \( a' \) contains a nonzero constant if and only if \( a \) contains a nonzero polynomial \( c T^r \), which implies \( t = 0 \) and \( A = B \) (since \( B \) is an integral domain).

When \( a' \) does not contain a nonzero constant, we set \( B' = A[T]/a' = A[t] \). Then \( a' \) contains the polynomial \( g' = b_n + \cdots + b_0 T^n \), and \( \alpha(b_0) \neq 0 \). Because \( \deg g' < m \), the induction hypothesis implies that \( \alpha \) extends to a homomorphism \( B' \to \Omega \). Therefore, there exists a \( c \in \Omega \) such that, for all \( h(T) = c_r T^r + c_{r-1} T^{r-1} + \cdots + c_0 \in a \),

\[
\alpha(c_r) + \alpha(c_{r-1}) c + \cdots + c_0 c^r = 0.
\]

On taking \( h = g \), we see that \( c = 0 \), and on taking \( h = f \), we obtain the contradiction \( \alpha(a_m) = 0 \).

**Proof (of 11.14)*** Suppose that we know the proposition in the case that \( B \) is generated by a single element, and write \( B = A[t_1, \ldots, t_n] \). Then there exists an element \( b_{n-1} \) such that any homomorphism \( \alpha: A[t_1, \ldots, t_{n-1}] \to \Omega \) such that \( \alpha(b_{n-1}) \neq 0 \) extends to a homomorphism \( \beta: B \to \Omega \) such that \( \beta(b) \neq 0 \). Continuing in this fashion (with \( b_{n-1} \) for \( b \)), we eventually obtain an element \( a \in A \) with the required property.

Thus we may assume \( B = A[t] \). Let \( a \) be the kernel of the homomorphism \( T \mapsto t \), \( A[T] \to A[t] \).

Case (i). The ideal \( a = (0) \). Write

\[
b = f(t) = a_0 t^n + a_1 t^{n-1} + \cdots + a_n, \quad a_i \in A,
\]

and take \( a = a_0 \). If \( \alpha: A \to \Omega \) is such that \( \alpha(a_0) \neq 0 \), then there exists a \( c \in \Omega \) such that \( f(c) \neq 0 \), and we can take \( \beta \) to be the homomorphism \( \sum d_i t^i \mapsto \sum \alpha(d_i) c^i \).

Case (ii). The ideal \( a \neq (0) \). Let \( f(T) = a_m T^m + \cdots + a_0, a_m \neq 0 \), be an element of \( a \) of minimum degree. Let \( h(T) \in A[T] \) represent \( b \). Since \( b \neq 0 \), \( h \not\in a \). Because \( f \) is irreducible over the field of fractions of \( A \), \( h \) and \( a \) are coprime over that field. In other words, there exist \( u, v \in A[T] \) and a nonzero \( c \in A \) such that

\[
u h + vf = c.
\]

It follows now that \( ca_m \) satisfies our requirements, for if \( \alpha(ca_m) \neq 0 \), then \( \alpha \) can be extended to \( \beta: B \to \Omega \) by the lemma, and \( \beta(u(t) \cdot b) = \beta(c) \neq 0 \), and so \( \beta(b) \neq 0 \).

**Remark 11.16.** In case (ii) of the last proof, both \( b \) and \( b^{-1} \) are algebraic over \( A \), and so there exist equations

\[
a_0 b^m + \cdots + a_m = 0, \quad a_i \in A, \quad a_0 \neq 0;
\]

\[
a_0' b^{-n} + \cdots + a'_n = 0, \quad a_i' \in A, \quad a_0' \neq 0.
\]

One can show that \( a = a_0 a'_0 \) has the property required by the proposition.

**Aside 11.17.** The spectrum \( \text{spec}(A) \) of a ring \( A \) is the set of prime ideals in \( A \) endowed with the topology for which the closed subsets are those of the form

\[
V(a) = \{ p \mid p \supset a \}, \quad a \text{ an ideal in } A.
\]

Thus \( \text{spm}(A) \) is the subspace of \( \text{spec}(A) \) consisting of the closed points. When \( A \) is Jacobson, the map \( U \mapsto U \cap \text{spm}(A) \) is a bijection from the set of open subsets of \( \text{spec}(A) \) onto the set of open subsets of \( \text{spm}(A) \); therefore \( \text{spm}(A) \) and \( \text{spec}(A) \) have the same topologies — only the underlying sets differ.
12 Dimension theory for finitely generated $k$-algebras

Throughout this section, $A$ is both a finitely generated algebra over field $k$ and an integral domain. We define the transcendence degree of $A$ over $k$, $\text{trdeg}_k A$, to be the transcendence degree over $k$ of the field of fractions of $A$ (see FT [13] §8). Thus $A$ has transcendence degree $d$ if it contains an algebraically independent set of $d$ elements, but no larger set (FT 8.12).

Proposition 12.1. For any linear forms $\ell_1, \ldots, \ell_m$ in $X_1, \ldots, X_n$, the quotient ring

$$k[X_1, \ldots, X_n]/(\ell_1, \ldots, \ell_m)$$

is an integral domain of transcendence degree equal to the dimension of the subspace of $k^n$ defined by the equations

$$\ell_i = 0, \quad i = 1, \ldots, m.$$

Proof. This follows from the more precise statement:

Let $\mathfrak{c}$ be an ideal in $k[X_1, \ldots, X_n]$ generated by linearly independent linear forms $\ell_1, \ldots, \ell_r$, and let $X_{i_1}, \ldots, X_{i_{n-r}}$ be such that

$$\{\ell_1, \ldots, \ell_r, X_{i_1}, \ldots, X_{i_{n-r}}\}$$

is a basis for the linear forms in $X_1, \ldots, X_n$. Then

$$k[X_1, \ldots, X_n]/\mathfrak{c} \simeq k[X_{i_1}, \ldots, X_{i_{n-r}}].$$

This is obvious if the forms $\ell_i$ are $X_1, \ldots, X_r$. In the general case, because $\{X_1, \ldots, X_n\}$ and $\{\ell_1, \ldots, \ell_r, X_{i_1}, \ldots, X_{i_{n-r}}\}$ are both bases for the linear forms, each element of one set can be expressed as a linear combination of the elements of the other. Therefore,

$$k[X_1, \ldots, X_n] = k[\ell_1, \ldots, \ell_r, X_{i_1}, \ldots, X_{i_{n-r}}],$$

and so

$$k[X_1, \ldots, X_n]/\mathfrak{c} = k[\ell_1, \ldots, \ell_r, X_{i_1}, \ldots, X_{i_{n-r}}]/\mathfrak{c} \simeq k[X_{i_1}, \ldots, X_{i_{n-r}}].$$

Proposition 12.2. For any irreducible polynomial $f$ in $k[X_1, \ldots, X_n]$, the quotient ring $k[X_1, \ldots, X_n]/(f)$ has transcendence degree $n - 1$.

Proof. Let

$$k[x_1, \ldots, x_n] = k[X_1, \ldots, X_n]/(f),$$

and let $k(x_1, \ldots, x_n)$ be the field of fractions of $k[x_1, \ldots, x_n]$. Since $f$ is not zero, some $X_i$, say, $X_n$, occurs in it. Then $X_n$ occurs in every nonzero multiple of $f$, and so no nonzero polynomial in $X_1, \ldots, X_{n-1}$ belongs to $(f)$. This means that $x_1, \ldots, x_{n-1}$ are algebraically independent. On the other hand, $x_n$ is algebraic over $k(x_1, \ldots, x_{n-1})$, and so $\{x_1, \ldots, x_{n-1}\}$ is a transcendence basis for $k(x_1, \ldots, x_n)$ over $k$.

18FT = Fields and Galois Theory, available on my website.
Proposition 12.3. For any nonzero prime ideal \( p \) in a \( k \)-algebra \( A \),
\[
\trdeg_k (A/p) < \trdeg_k (A).
\]

Proof. We may suppose
\[
A = k[X_1, \ldots, X_n]/a = k[x_1, \ldots, x_n].
\]
For \( f \in A \), let \( \tilde{f} \) denote the image of \( f \) in \( A/p \), so that \( A/p = k[\tilde{x}_1, \ldots, \tilde{x}_n] \). Let \( d = \trdeg_k A/p \), and number the \( X_i \) so that \( \tilde{x}_1, \ldots, \tilde{x}_d \) are algebraically independent (see FT 8.9 for the proof that this is possible). I shall show that, for any nonzero \( f \in p \), the \( d \) elements \( x_1, \ldots, x_d, f \) are algebraically independent, which shows that \( \trdeg_k A = d + 1 \).

Suppose otherwise. Then there is a nontrivial algebraic relation, which we can write\( a_0(x_1, \ldots, x_d)^m + a_1(x_1, \ldots, x_d)^{m-1} + \cdots + a_m(x_1, \ldots, x_d) = 0 \), with \( a_i \in k[X_1, \ldots, X_d] \) and \( a_0 \neq 0 \). Because \( A \) is an integral domain, we can cancel a power of \( f \) if necessary to make \( a_m(x_1, \ldots, x_d) \) nonzero. On applying the homomorphism \( A \to A/p \) to the above equality, we find that
\[
a_m(\tilde{x}_1, \ldots, \tilde{x}_d) = 0,
\]
which contradicts the algebraic independence of \( \tilde{x}_1, \ldots, \tilde{x}_d \). \( \square \)

Proposition 12.4. Let \( A \) be a unique factorization domain. If \( p \) is a prime ideal in \( A \) such that \( \trdeg_k A/p = \trdeg_k A - 1 \), then \( p = (f) \) for some \( f \in A \).

Proof. The ideal \( p \) is nonzero because otherwise \( A \) and \( A/p \) would have the same transcendence degree. Therefore \( p \) contains a nonzero polynomial, and even an irreducible polynomial \( f \), because it is prime. According to (4.1), the ideal \( (f) \) is prime. If \( (f) \neq p \), then
\[
\trdeg_k A/p > \trdeg_k A/(f) = \trdeg_k A - 1,
\]
which contradicts the hypothesis. \( \square \)

Theorem 12.5. Let \( f \in A \) be neither zero nor a unit, and let \( p \) be a prime ideal that is minimal among those containing \( (f) \); then
\[
\trdeg_k A/p = \trdeg_k A - 1.
\]

We first need a lemma.

Lemma 12.6. Let \( A \) be an integrally closed integral domain, and let \( L \) be a finite extension of the field of fractions \( K \) of \( A \). If \( \alpha \in L \) is integral over \( A \), then \( \Nm_{L/K} \alpha \in A \), and \( \alpha \) divides \( \Nm_{L/K} \alpha \) in the ring \( A[\alpha] \).

Proof. Let \( X^r + a_{r-1}X^{r-1} + \cdots + a_0 \) be the minimum polynomial of \( \alpha \) over \( K \). Then \( r \) divides the degree \( n \) of \( L/K \), and \( \Nm_{L/K}(\alpha) = \pm a_0^\frac{2}{n} \) (FT 5.40). Moreover, \( a_0 \) lies in \( A \) by (5.9). From the equation
\[
0 = \alpha(\alpha^{r-1} + a_{r-1} \alpha^{r-2} + \cdots + a_1) + a_0,
\]
we see that \( \alpha \) divides \( a_0 \) in \( A[\alpha] \), and therefore it also divides \( \Nm_{L/K} \alpha \). \( \square \)
PROOF (OF THEOREM 12.5). Write \( \text{rad}(f) \) as an irredundant intersection of prime ideals \( \text{rad}(f) = p_1 \cap \ldots \cap p_r \) (see 11.11). Then \( V(\alpha) = V(p_1) \cup \cdots \cup V(p_r) \) is the decomposition of \( V(\alpha) \) into its irreducible components. There exists an \( m_0 \in V(p_1) \setminus \bigcup_{j \geq 2} V(p_j) \) and an open neighbourhood \( D(h) \) of \( m_0 \) disjoint from \( \bigcup_{j \geq 2} V(p_j) \). The ring \( A_h \) (resp. \( A_h/\mathfrak{S}^{-1}p \)) is an integral domain with the same transcendance degree as \( A \) (resp. \( A/p \)) — in fact, with the same field of fractions. In \( A_h \), \( \text{rad}(f^e) = \text{rad}(f)^e = p_1^e \). Therefore, after replacing \( A \) with \( A_h \), we may suppose that \( \text{rad}(f) \) is prime, say, equal to \( p \).

According to the Noether normalization theorem (5.11), there exist algebraically indepen-
dent elements \( x_1, \ldots, x_d \) in \( A \) such that \( A \) is a finite \( k[x_1, \ldots, x_d] \)-algebra. Note that \( d = \text{trdeg}_k A \). According to the lemma, \( f_0 \overset{\text{def}}{=} \text{Nm}(f) \) lies in \( k[x_1, \ldots, x_d] \), and we shall show that \( p \cap k[x_1, \ldots, x_d] = \text{rad}(f_0) \). Therefore, the homomorphism

\[
k[x_1, \ldots, x_d]/\text{rad}(f_0) \to A/p
\]
is injective. As it is also finite, this implies that

\[
\text{trdeg}_k A/p = \text{trdeg}_k k[x_1, \ldots, x_d]/\text{rad}(f_0) = d - 1.
\]
as required.

By assumption \( A \) is finite (hence integral) over its subring \( k[x_1, \ldots, x_d] \). The lemma shows that \( f \) divides \( f_0 \) in \( A \), and so \( f_0 \in (f) \supset p \). Hence \( (f_0) \subset p \cap k[x_1, \ldots, x_d] \), which implies

\[
\text{rad}(f_0) \subset p \cap k[x_1, \ldots, x_d]
\]
because \( p \) is radical. For the reverse inclusion, let \( g \in p \cap k[x_1, \ldots, x_d] \). Then \( g \in \text{rad}(f) \), and so \( g^m = fh \) for some \( h \in A, m \in \mathbb{N} \). Taking norms, we find that

\[
g^m_e = \text{Nm}(fh) = f_0 \cdot \text{Nm}(h) \in (f_0),
\]
where \( e \) is the degree of the extension of the fields of fractions, which proves the claim. \( \square \)

COROLLARY 12.7. Let \( p \) be a minimal nonzero prime ideal in \( A \); then \( \text{trdeg}_k (A/p) = \text{trdeg}_k (A) - 1 \).

PROOF. Let \( f \) be a nonzero element of \( p \). Then \( f \) is not a unit, and \( p \) is minimal among the prime ideals containing \( f \). \( \square \)

THEOREM 12.8. The length \( d \) of any maximal (i.e., nonrefinable) chain of distinct prime ideals

\[
p_d \supset p_{d-1} \supset \cdots \supset p_0
\]
in \( A \) is \( \text{trdeg}_k (A) \). In particular, every maximal ideal of \( A \) has height \( \text{trdeg}_k (A) \), and so the Krull dimension of \( A \) is equal to \( \text{trdeg}_k (A) \).

PROOF. From (12.7), we find that

\[
\text{trdeg}_k (A) = \text{trdeg}_k (A/p_1) + 1 = \cdots = \text{trdeg}_k (A/p_d) + d.
\]
But \( p_d \) is maximal, and so \( A/p_d \) is a finite field extension of \( k \). In particular, \( \text{trdeg}_k (A/p_d) = 0 \). \( \square \)
13 PRIMARY DECOMPOSITIONS

Example 12.9. Let \( f(X, Y) \) and \( g(X, Y) \) be nonconstant polynomials with no common factor. Then \( k[X, Y]/(f) \) has Krull dimension 1, and so \( k[X, Y]/(f, g) \) has dimension zero.

Example 12.10. We classify the prime ideals \( p \) in \( A = k[X, Y] \). If \( A/p \) has dimension 2, then \( p = (0) \). If \( A/p \) has dimension 1, then \( p = (f) \) for some irreducible polynomial \( f \) of \( A \) (by 12.4). Finally, if \( A/p \) has dimension zero, then \( p \) is maximal. Thus, when \( k \) is algebraically closed, the prime ideals in \( k[X, Y] \) are exactly the ideals \((0)\), \((f)\) (with \( f \) irreducible), and \((X-a,Y-b)\) (with \( a, b \in k \)).

Remark 12.11. Let \( A \) be a finitely generated \( k \)-algebra (not necessarily an integral domain). Every maximal chain of prime ideals in \( A \) ending in fixed prime ideal \( p \) has length \( \text{trdeg}_k(A/p) \), and so the Krull dimension of \( A \) is \( \max \text{trdeg}_k(A/p) \) where \( p \) runs over the minimal prime ideals of \( A \). In the next section, we show that a noetherian ring has only finitely many minimal prime ideals, and so the Krull dimension of \( A \) is finite.

13 Primary decompositions

In this section, \( A \) is an arbitrary commutative ring.

Definition 13.1. An ideal \( q \) in \( A \) is primary if it is proper and

\[
ab \in q, \ b \notin q \implies a^n \in q \text{ for some } n \geq 1.
\]

Thus, a proper ideal \( q \) in \( A \) is primary if and only if all zero-divisors in \( A/q \) are nilpotent. A radical ideal is primary if and only if it is prime. An ideal \( (m) \) in \( \mathbb{Z} \) is primary if and only if \( m \) is a power of a prime.

Proposition 13.2. The radical of a primary ideal \( q \) is a prime ideal containing \( q \), and it is contained in every other prime ideal containing \( q \) (i.e., it is the smallest prime ideal containing \( p \)).

Proof. Suppose \( ab \in \text{rad}(q) \) but \( b \notin \text{rad}(q) \). Then some power, say \( a^n b^n \), of \( ab \) lies in \( q \), but \( b^n \notin q \), and so \( a \in \text{rad}(q) \). The shows that \( \text{rad}(q) \) is primary, and hence prime (because it is radical).

Let \( p \) be a second prime ideal containing \( q \), and let \( a \in \text{rad}(q) \). For some \( n, a^n \in q \subseteq p \), which implies that \( a \in p \). \( \square \)

When \( q \) is a primary ideal and \( p \) is its radical, we say that \( q \) is \( p \)-primary.

Proposition 13.3. Every ideal \( q \) whose radical is a maximal ideal \( m \) is primary (in fact, \( m \)-primary); in particular, every power of a maximal ideal \( m \) is \( m \)-primary.

Proof. Every prime ideal containing \( q \) contains its radical \( m \), and therefore equals \( m \). This shows that \( A/m \) is local with maximal ideal \( m/a \). Therefore, every element of \( A/a \) is either a unit, and hence is not a zero-divisor, or it lies in \( m/a \), and hence is nilpotent. \( \square \)

Proposition 13.4. Let \( \varphi : A \to B \) be a homomorphism of rings. If \( q \) is a \( p \)-primary ideal in \( B \), then \( q^{c} \overset{\text{def}}{=} \varphi^{-1}(q) \) is a \( p^{c} \)-primary ideal in \( A \).
13 PRIMARY DECOMPOSITIONS

**Proposition 13.6.** A finite intersection of $p$-primary ideals is $p$-primary.

**Proof.** Let $q_1, \ldots, q_n$ be $p$-primary, and let $q = q_1 \cap \cdots \cap q_n$. We show that the pair of ideals $q \subset p$ satisfies the conditions of (13.5).

Let $a \in p$; since some power of $a$ belongs to each $q_i$, a sufficiently high power of it will belong to all of them, and so $p \subset \text{rad}(q)$.

Let $ab \in q$ but $a \notin p$. Then $ab \in q_i$ but $a \notin q_i$, and so $b \in q_i$. Since this is true for all $i$, we have that $b \in q$. □

The **minimal prime ideals** of an ideal $a$ are the minimal elements of the set of prime ideals containing $a$.

**Definition 13.7.** A **primary decomposition** of an ideal $a$ is a finite set of primary ideals whose intersection is $a$. A primary decomposition $S$ of $a$ is **minimal** if

(a) the prime ideals $\text{rad}(q)$, $q \in S$, are distinct, and

(b) no element of $S$ can be omitted, i.e., for no $q_0 \in S$ is $q_0 \subset \bigcap \{q \mid q \in S, q \neq q_0\}$.

If $a$ admits a primary decomposition, then it admits a minimal primary decomposition, because Proposition 13.6 can be used to combine primary ideals with the same radical, and any $q_0$ that fails (b) can simply be omitted. The prime ideals occurring as the radical of an ideal in a minimal primary decomposition of $a$ are said to **belong to** $a$.

**Proposition 13.8.** Suppose $a = q_1 \cap \cdots \cap q_n$ where $q_i$ is $p_i$-primary for $i = 1, \ldots, n$. Then the minimal prime ideals of $a$ are the minimal elements of the set $\{p_1, \ldots, p_n\}$.

**Proof.** Let $p$ be a prime ideal containing $a$, and let $q_i'$ be the image of $q_i$ in the integral domain $A/p$. Then $p$ contains $q_1' \cdots q_n'$, and so $q_1' \cdots q_n' = q$. This implies that, for some $i$, $q_i' = 0$, and so $p$ contains $q_i$. Now (13.2) shows that $p$ contains $p_i$. □

In particular, if $a$ admits a primary decomposition, then it has only finitely many minimal prime ideals, and so its radical is a **finite** intersection of prime ideals.

For an ideal $a$ in $A$ and an element $x \in A$, we let

$$ (a : x) = \{a \in A \mid ax \in a\}. $$

It is again an ideal in $A$, which equals $A$ if $x \in a$. 

**Proof.** The map $A/q^c \to B/q$ is injective, and so every zero-divisor in $A/q^c$ is nilpotent. This shows that $q^c$ is primary, and therefore $\text{rad}(q^c)$-primary. But (see 2.11), $\text{rad}(q^c) = \text{rad}(q)^c = p^c$, as claimed. □

**Lemma 13.5.** Let $q$ and $p$ be a pair of ideals in $A$ such that $q \subset p \subset \text{rad}(q)$ and

$$ ab \in q \implies a \in p \text{ or } b \in q. $$

Then $p$ is a prime ideal and $q$ is $p$-primary.

**Proof.** Clearly $q$ is primary, hence $\text{rad}(q)$-primary, and $\text{rad}(q)$ is prime. By assumption $p \subset \text{rad}(q)$, and it remains to show that they are equal. Let $a \in \text{rad}(q)$, and let $n$ be the smallest positive integer such that $a^n \in q$. If $n = 1$, then $a \in q \subset p$; on the other hand, if $n > 1$, then $a^n = aa^{n-1} \in q$ and $a^{n-1} \notin q$, and so $a \in p$ by (19). □

**Proposition 13.7.** Let $q_1, \ldots, q_n$ be $p$-primary, and let $q = q_1 \cap \cdots \cap q_n$. We show that the pair of ideals $q \subset p$ satisfies the conditions of (13.5).

Let $a \in p$; since some power of $a$ belongs to each $q_i$, a sufficiently high power of it will belong to all of them, and so $p \subset \text{rad}(q)$.

Let $ab \in q$ but $a \notin p$. Then $ab \in q_i$ but $a \notin q_i$, and so $b \in q_i$. Since this is true for all $i$, we have that $b \in q$. □

The minimal prime ideals of an ideal $a$ are the minimal elements of the set of prime ideals containing $a$.
LEMMA 13.9. Let \( q \) be a \( p \)-primary ideal and let \( x \in A \setminus q \). Then \( (q:x) \) is \( p \)-primary (and hence \( \text{rad}(q:x) = p \)).

PROOF. For any \( a \in (q:x) \), we know that \( ax \in q \) and \( x \notin q \), and so \( a \in p \). Hence \( (q:x) \subseteq p \).

On taking radicals, we find that \( \text{rad}(q:x) = p \). Let \( ab \in (q:x) \). Then \( xab \in q \), and so either \( a \in p \) or \( xb \in q \) (because \( q \) is \( p \)-primary); in the second case, \( b \in (q:x) \) as required.

THEOREM 13.10. Let \( a = q_1 \cap \ldots \cap q_n \) be a minimal primary decomposition of \( a \), and let \( \mathfrak{p}_i = \text{rad}(q_i) \). Then

\[
\{\mathfrak{p}_1, \ldots, \mathfrak{p}_n\} = \{\text{rad}(a:x) \mid x \in A, \text{ rad}(a:x) \text{ prime}\}.
\]

In particular, the set \( \{\mathfrak{p}_1, \ldots, \mathfrak{p}_n\} \) is independent of the choice of the minimal primary decomposition.

PROOF. For any \( a \in A \),

\[
(a:a) = (\bigcap q_i : a) = (q_i : a),
\]

and so

\[
\text{rad}(a:a) = \text{rad} \bigcap (q_i : a) = \bigcap_{a \notin q_i} \mathfrak{p}_i. \tag{20}
\]

If \( \text{rad}(a:a) \) is prime, then it equals one of the \( \mathfrak{p}_i \) (otherwise, for each \( i \) there exists an \( a_i \in \mathfrak{p}_i \setminus p \), and \( a_1 \cdots a_n \in \bigcap_{a \notin q_i} \mathfrak{p}_i \) but not \( p \), which is a contradiction). Hence \( \text{RHS} \supset \text{LHS} \).

For each \( i \), there exists an \( a \in \bigcap_{j \neq i} q_j \setminus q_i \) because the decomposition is minimal, and \( \tag{20} \) shows that \( \text{rad}(a:a) = \mathfrak{p}_i \).

THEOREM 13.11. In a noetherian ring, every ideal admits a primary decomposition.

The theorem is a consequence of the following more precise statement, but first we need a definition: an ideal \( a \) is said to be \textbf{irreducible} if

\[
a = b \cap c \text{ (b, c ideals)} \implies a = b \text{ or } a = c.
\]

PROPOSITION 13.12. Let \( A \) be a noetherian ring.

(a) Every ideal in \( A \) can be expressed as a finite intersection of irreducible ideals.

(b) Every irreducible ideal in \( A \) is primary.

PROOF. (a) Suppose (a) fails, and let \( a \) be maximal among the ideals for which it fails. Then, in particular, \( a \) itself is not irreducible, and so \( a = b \cap c \) with \( b \) and \( c \) properly containing \( a \). Because \( a \) is maximal, both \( b \) and \( c \) can be expressed as finite intersections of irreducible ideals, but then so can \( a \).

(b) Let \( a \) be irreducible in \( A \), and consider the quotient ring \( A' \equiv A/ \mathfrak{a} \). Let \( a \) be a zero-divisor in \( A' \), say \( ab = 0 \) with \( b \neq 0 \). We have to show that \( a \) is nilpotent. As \( A' \) is noetherian, the chain of ideals

\[
((0):a) \subset ((0):a^2) \subset \cdots
\]

becomes constant, say, \( ((0):a^m) = ((0):a^{m+1}) = \cdots \). Let \( c \in (a^m) \cap (b) \). Then \( c \in (b) \) implies \( ca = 0 \), and \( c \in (a^m) \) implies that \( c = da^m \) for some \( d \in A \). Now

\[
(da^m)a = 0 \Rightarrow d \in (0:a^{m+1}) = (0:a^m) \Rightarrow c = 0.
\]

Hence \( (a^m) \cap (b) = (0) \). Because \( a \) is irreducible, so also is the zero ideal in \( A' \), and it follows that \( a^m = 0 \).
A $p$-primary ideal $a$ in a noetherian ring contains a power of $p$ by Proposition 3.13. The next result proves a converse when $p$ is maximal.

**Proposition 13.13.** Let $m$ be a maximal ideal of a noetherian ring. Any proper ideal $a$ of $A$ that contains a power of a maximal ideal $m$ is $m$-primary.

**Proof.** Suppose that $m^r \subset a$, and let $p$ be a prime ideal belonging to $a$. Then $m^r \subset a \subset p$, so that $m \subset p$, which implies that $m = p$. Thus $m$ is the only prime ideal belonging to $a$, which means that $a$ is $m$-primary.

**Example 13.14.** We give an example of a power of a prime ideal $p$ that is not $p$-primary. Let

$$A = k[X, Y, Z]/(Y^2 - XZ) = k[x, y, z].$$

The ideal $(X, Y)$ in $k[X, Y, Z]$ is prime and contains $(Y^2 - XZ)$, and so the ideal $p = (x, y)$ in $A$ is prime. Now $xz = y^2 \in p^2$, but one checks easily that $x \notin p^2$ and $z \notin p$, and so $p^2$ is not $p$-primary.

**Remark 13.15.** Let $a$ be an ideal in a noetherian ring, and let $b = \bigcap_{n \geq 1} a^n$. We give another proof that $ab = b$ (see p.12). Let

$$ab = q_1 \cap \ldots \cap q_s, \quad \text{rad}(q_i) = p_i,$$

be a minimal primary decomposition of $ab$. We shall show that $b \subset ab$ by showing that $b \subset q_i$ for each $i$.

If there exists a $b \in b \setminus q_i$, then

$$ab \subset ab \subset q_i,$$

from which it follows that $a \subset p_i$. We know that $p_i^r \subset q_i$ for some $r$ (see 3.13), and so

$$b = \bigcap a^n \subset a^r \subset p_i^r \subset q_i,$$

which is a contradiction. This completes the proof.

**Definition 13.16.** A *Dedekind domain* is a noetherian integrally closed integral domain of dimension 1.

**Theorem 13.17.** Every proper nonzero ideal $a$ in a Dedekind domain can be written in the form

$$a = p_1^{r_1} \cdots p_s^{r_s}$$

with the $p_i$ distinct prime ideals and the $r_i > 0$; the ideals $p_i$ are exactly the prime ideals containing $a$, and the exponents $r_i$ are uniquely determined.

**Proof.** For the proof, which is quite elementary, see Chapter 3 of my notes Algebraic Number Theory.
14 Artinian rings

A ring $A$ is **artinian** if every descending chain of ideals $a_1 \supset a_2 \supset \cdots$ in $A$ eventually becomes constant; equivalently, if every nonempty set of ideals has a minimal element. Similarly, a module $M$ over a ring $A$ is **artinian** if every descending chain of submodules $N_1 \supset N_2 \supset \cdots$ in $M$ eventually becomes constant.

**Proposition 14.1.** An artinian ring has Krull dimension zero; in other words, every prime ideal is maximal.

**Proof.** Let $p$ be a prime ideal of an artinian ring $A$, and let $A' = A/p$. Then $A'$ is an artinian integral domain. For any nonzero element $a$ of $A'$, the chain $(a) \supset (a^2) \supset \cdots$ eventually becomes constant, and so $a^n = a^{n+1}b$ for some $b \in A'$ and $n \geq 1$. We can cancel $a^n$ to obtain $1 = ab$. Thus $a$ is a unit, $A'$ is a field, and $p$ is maximal. \hfill $\Box$

**Corollary 14.2.** In an artinian ring, the nilradical and the Jacobson radical coincide.

**Proof.** The first is the intersection of the prime ideals (2.6), and the second is the intersection of the maximal ideals (2.7). \hfill $\Box$

**Proposition 14.3.** An artinian ring has only finitely many maximal ideals.

**Proof.** Let $m_1 \cap \ldots \cap m_n$ be a minimal element in the set of all finite intersections of maximal ideals in the artinian ring $A$, and let $m$ be a maximal ideal in $A$. Then $m$ equals one of the $m_i$, because otherwise there exists an $a_i \in m_i \setminus m$ for each $i$, and $a_1 \cdots a_n$ lies in $m_1 \cap \ldots \cap m_n$ but not $m$ (because $m$ is prime); thus $m \cap m_1 \cap \ldots \cap m_n$ is smaller than $m_1 \cap \ldots \cap m_n$, which contradicts the definition of $m_1 \cap \ldots \cap m_n$. \hfill $\Box$

**Proposition 14.4.** In an artinian ring, some power of the nilradical is zero.

**Proof.** Let $\mathfrak{N}$ be the nilradical of the artinian ring $A$. The chain $\mathfrak{N} \supset \mathfrak{N}^2 \supset \cdots$ eventually becomes constant, and so $\mathfrak{N}^n = \mathfrak{N}^{n+1} = \cdots$ for some $n \geq 1$. Suppose $\mathfrak{N}^n \neq 0$. Then there exist ideals $a$ such that $a \cdot \mathfrak{N}^n \neq 0$, for example $\mathfrak{N}$, and we may suppose that $a$ has been chosen to be minimal among such ideals. There exists an $a \in a$ such that $a \cdot \mathfrak{N}^n \neq 0$, and so $a = (a)$ (by minimality). Now $(a \mathfrak{N}^n)\mathfrak{N}^n = a\mathfrak{N}^{2n} = a\mathfrak{N}^n \neq 0$ and $a\mathfrak{N}^n \subset (a)$, and so $a\mathfrak{N}^n = (a)$ (by minimality again). Hence $a = ax$ for some $x \in \mathfrak{N}^n$. Now $a = ax = ax^2 = \cdots = a0 = 0$ because $x \in \mathfrak{N}$. This contradicts the definition of $a$, and so $\mathfrak{N}^n = 0$. \hfill $\Box$

**Lemma 14.5.** Let $A$ be a ring in which some finite product of maximal ideals is zero. Then $A$ is artinian if and only if it is noetherian.

**Proof.** Suppose $m_1 \cdots m_n = 0$ with the $m_i$ maximal ideals (not necessarily distinct), and consider $A \supset m_1 \supset \cdots \supset m_1 \cdots m_{r-1} \supset m_1 \cdots m_r \supset \cdots \supset m_1 \cdots m_n = 0$. The action of $A$ on the quotient $M_r = \frac{m_1 \cdots m_{r-1}}{m_1 \cdots m_r}$ factors through the field $A/m_r$, and the subspaces of the vector space $M_r$ are in one-to-one correspondence with the ideals of $A$ contained between $m_1 \cdots m_{r-1}$ and $m_1 \cdots m_r$. If $A$ is either artinian or noetherian, then $M_r$ satisfies a chain condition on subspaces and so it is finite-dimensional as a vector space and both artinian and noetherian as an $A$-module. Now repeated applications of Proposition 5.3 (resp. its analogue for artinian modules) show that if $A$ is artinian (resp. noetherian), then it is noetherian (resp. artinian) as an $A$-module, and hence as a ring. \hfill $\Box$
15 Dimension theory for noetherian rings

Let \( A \) be a noetherian ring and let \( p \) be a prime ideal in \( A \). Let \( A_p = S^{-1}A \) where \( S = A \setminus p \). We begin by studying extension and contraction of ideals with respect to the homomorphism \( A \rightarrow A_p \) (cf. 2.10). Recall (6.6) that \( A_p \) is a local ring with maximal ideal \( p^e \), which equals \( pA_p \). The ideal

\[
(p^n)^e = \{ a \in A \mid sa = p^n \text{ for some } s \in S \}
\]

is called the \( n \)th symbolic power of \( p \), and is denoted \( p^{(n)} \). If \( m \) is maximal, then \( m^{(n)} = m^n \) (see 6.7).

**Lemma 15.1.** The ideal \( p^{(n)} \) is \( p \)-primary.

**Proof.** According to Proposition 13.3, the ideal \( (p^e)^n \) is \( p^e \)-primary. Hence (see 13.4), \((p^e)^n)^c \) is \((p^e)^c \)-primary. But \( p^e = p \) (see 6.4), and

\[
(((p^e)^n)^c)^c = ((p^n)^e)^c \overset{\text{def}}{=} p^{(n)}. \tag{21}
\]
LEMMA 15.2. Consider ideals $a \subseteq p' \subseteq p$ with $p'$ prime. If $p'$ is a minimal prime ideal of $a$, then $p'^e$ is a minimal prime ideal of $a^e$ (extension relative to $A \to A_p$).

**Proof.** If not, there exists a prime ideal $p'' \neq p'^e$ such that $p'^e \supseteq p'' \supseteq a^e$. Now, by (6.4), $p' = p'^e c$ and $p'^e \neq p'^e c$, and so $p' = p'^e c \not\supseteq p'^e c \supseteq a$ contradicts the minimality of $p'$.

THEOREM 15.3 (KRULL’S PRINCIPAL IDEAL THEOREM). Let $A$ be a noetherian ring. For any nonunit $b \in A$, the height of a minimal prime ideal $p$ of $(b)$ is at most one.

**Proof.** Consider $A \to A_p$. According to Lemma 15.2, $p^e$ is a minimal prime ideal of $(b)^e = (b_1^e)$, and (6.4) shows that the theorem for $A_p \supseteq p^e \supseteq (b_1^e)$ implies it for $A \supseteq p \supseteq (b)$. Therefore, we may replace $A$ with $A_p$, and so assume that $A$ is a noetherian local ring with maximal ideal $p$.

Suppose that $p$ properly contains a prime ideal $p_1$: we have to show that $p_1 \supseteq p_2 \implies p_1 = p_2$.

Let $p_1^{(r)}$ be the $r$th symbolic power of $p_1$. The only prime ideal of the ring $A/(b)$ is $p/(b)$, and so $A/(b)$ is artinian (apply 14.6). Therefore the descending chain of ideals

$$
\left( p_1^{(1)} + (b) \right) / (b) \supset \left( p_1^{(2)} + (b) \right) / (b) \supset \left( p_1^{(3)} + (b) \right) / (b) \supset \cdots
$$

eventually becomes constant: there exists an $s$ such that

$$
p_1^{(s)} + (b) = p_1^{(s+1)} + (b) = p_1^{(s+2)} + (b) = \cdots. \tag{22}
$$

We claim that, for any $m \geq s$,

$$
p_1^{(m)} \subseteq (b)p_1^{(m)} + p_1^{(m+1)}. \tag{23}
$$

Let $x \in p_1^{(m)}$. Then

$$
x \in (b) + p_1^{(m)} \supseteq (b) + p_1^{(m+1)},
$$

and so $x = ab + x'$ with $a \in A$ and $x' \in p_1^{(m+1)}$. As $p_1^{(m)}$ is $p_1$-primary (see 15.1) and $ab = x - x' \in p_1^{(m+1)}$ but $b \notin p_1$, we have that $a \in p_1^{(m)}$. Now $x = ab + x' \in (b)p_1^{(m)} + p_1^{(m+1)}$ as claimed.

We next show that, for any $m \geq s$,

$$
p_1^{(m)} = p_1^{(m+1)}. \tag{24}
$$

As $b \in p$, (23) shows that $p_1^{(m)}/p_1^{(m+1)} = p \cdot \left( p_1^{(m)}/p_1^{(m+1)} \right)$, and so $p_1^{(m)}/p_1^{(m+1)} = 0$ by Nakayama’s lemma (3.7).

Now

$$
p_1^{(s)} \subseteq p_1^{(s+1)} = p_1^{(s+2)} = \cdots
$$

and so $p_1^{(s)} \subseteq \cap_{m \geq s} p_1^{(m)}$. Note that

$$
\cap_{m \geq s} p_1^{(m)} = \bigcap_{m \geq s}(p_1^{(m)})^c = (\bigcap_{m \geq s}(p_1^{(m)})^c)^c = (0)^c,
$$

and so for any $x \in p_1^{(s)}$, there exists an $a \in A \setminus p_1$ such that $ax = 0$. Let $x \in p_1^{(s)}$; then $ax^s = 0$ for some $a \in A \setminus p_1 \supset A \setminus p_2$, and so $x \in p_2$ (because $p_2$ is prime). We have shown that $p_1 = p_2$, as required.
In order to extend Theorem 15.6 to non principal ideals, we shall need a lemma.

**Lemma 15.4.** Let \( p \) be a prime ideal in a noetherian ring \( A \), and let \( S \) be a finite set of prime ideals in \( A \), none of which contains \( p \). If there exists a chain of distinct prime ideals 
\[
\mathcal{p} \supseteq p_{d-1} \supseteq \cdots \supseteq p_0
\]
then there exists such a chain with \( p_1 \) not contained in any ideal in \( S \).

**Proof.** We first prove this in the special case that the chain has length 2. Suppose that \( \mathcal{p} \supset p_1 \supseteq p_0 \) are distinct prime ideals and that \( p \) is not contained in any prime ideal in \( S \). According to Proposition 2.9, there exists an element 
\[
a \in p \setminus (p_0 \cup \bigcup \{p' \in S\}).
\]
As \( p \) contains \( (a) + p_0 \), it also contains a minimal prime ideal \( p_1' \) of \( (a) + p_0 \). Now \( p_1'/p_0 \) is a minimal prime ideal of the principal ideal \((a) + p_0)/p_0\) in \( A/p_0\), and so has height 1, whereas the chain \( p/p_0 \supset p_1/p_0 \supset p_0/p_0 \) shows that \( p/p_0 \) has height at least 2. Therefore \( p \supset p_1' \supset p_0 \) are distinct primes, and \( p_1' \notin S \) because it contains \( a \). This completes the proof of the special case.

Now consider the general case. On applying the special case to \( p \supset p_{d-1} \supset p_{d-2} \), we see that there exists a chain of distinct prime ideals \( p \supset p_{d-1}' \supset p_{d-2} \) such that \( p_{d-1}' \) is not contained in any ideal in \( S \). Then on applying the special case to \( p_{d-1}' \supset p_{d-2} \supset p_{d-1} \), we see that there exists a chain of distinct prime ideals \( p \supset p_{d-1}' \supset p_{d-2}' \supset p_{d-2} \) such that \( p_{d-2}' \) is not contained in any ideal in \( S \). Repeat the argument until the proof is complete.

**Theorem 15.5.** Let \( A \) be a noetherian ring. For any proper ideal \( a = (a_1, \ldots, a_m) \), the height of a minimal prime ideal of \( a \) is at most \( m \).

**Proof.** For \( m = 1 \), this was just proved. Thus, we may suppose \( m \geq 2 \) and that the theorem has been proved for ideals generated by \( m - 1 \) elements. Let \( p \) be a minimal prime ideal of \( a \), and let \( p_1', \ldots, p_r' \) be the minimal prime ideals of \( (a_2, \ldots, a_m) \). Each \( p_i' \) has height at most \( m - 1 \). If \( p \) is contained in one of the \( p_i' \), it will have height \( \leq m - 1 \), and so we may suppose that it isn’t.

Let \( p \) have height \( d \). We have to show that \( d \leq m \). According to the lemma, there exists a chain of distinct prime ideals 
\[
\mathcal{p} = p_d \supset p_{d-1} \supset \cdots \supset p_0, \quad d \geq 1,
\]
with \( p_1 \) not contained in any \( p_i' \), and so Proposition 2.9 shows that there exists a 
\[
b \in p_1 \setminus \bigcup_{i=1}^r p_i'.
\]
We next show that \( p \) is a minimal prime ideal of \( b = (a_2, \ldots, a_m) \). Certainly \( p \) contains a minimal prime ideal \( p' \) of this ideal. As \( p' \supset (a_2, \ldots, a_m) \), \( p \) contains one of the \( p_i' \)s, but, by construction, it cannot equal it. If \( p \neq p_i' \), then 
\[
p \supset p' \supset p_i
\]
are distinct ideals, which shows that \( \widehat{p} \overset{\text{def}}{=} p/(a_2, \ldots, a_m) \) has height at least 2 in \( \widehat{A} \overset{\text{def}}{=} A/(a_2, \ldots, a_m) \). But \( \widehat{p} \) is a minimal ideal in \( \widehat{A} \) of the principal ideal \( (a_1, \ldots, a_n)/(a_2, \ldots, a_n) \), which contradicts Theorem 15.3. Hence \( p \) is minimal, as claimed.
But now \( p/(b) \) is a minimal prime ideal of \((b, a_2, \ldots, a_m)\) in \( R/(b) \), and so the height of \( p/(b) \) is at most \( m-1 \) (by induction). The prime ideals

\[
p/(b) = p_d/(b) \supset p_{d-1}/(b) \supset \cdots \supset p_1/(b)
\]

are distinct, and so \( d-1 \leq m-1 \). This completes the proof that \( d = m \).

The **height** of an ideal \( a \) in a noetherian ring is the minimum height of a prime ideal containing it,

\[
\text{ht}(a) = \min_{p \supseteq a, \ p \text{ prime}} \text{ht}(p).
\]

The theorem shows that \( \text{ht}(a) \) is finite.

The following provides a (strong) converse to Theorem 15.5.

**Theorem 15.6.** Let \( A \) be a noetherian ring, and let \( a \) be a proper ideal of \( A \) of height \( r \). Then there exist \( r \) elements \( a_1, \ldots, a_r \) of \( a \) such that, for each \( i \leq r \), \( (a_1, \ldots, a_i) \) has height \( i \).

**Proof.** If \( r = 0 \), then we take the empty set of \( a_1 \)'s. Thus, suppose \( r \geq 1 \). There are only finitely many prime ideals of height 0, because such an ideal is a minimal prime ideal of \((0)\), and none of these ideals can contain \( a \) because it has height \( \geq 1 \). Proposition 2.9 shows that there exists an \( a_1 \in a \setminus \bigcup \{\text{prime ideals of height 0}\} \).

By construction, \((a_1)\) has height at least 1, and so Theorem 15.3 shows it has height exactly 1.

This completes the proof when \( r = 1 \), and so suppose that \( r \geq 2 \). There are only finitely many prime ideals of height 1 containing \((a_1)\) because such an ideal is a minimal prime ideal of \((a_1)\), and none of these ideals can contain \( a \) because it has height \( \geq 2 \). Choose

\[
a_2 \in a \setminus \bigcup \{\text{prime ideals of height 1 containing } (a_1)\}.
\]

By construction, \((a_1, a_2)\) has height at least 2, and so Theorem 15.3 shows that it has height exactly 2.

This completes the proof when \( r = 2 \), and when \( r > 2 \) we can continue in this fashion until it is complete.

**Corollary 15.7.** Every prime ideal of height \( r \) in a noetherian ring arises as a minimal prime ideal for an ideal generated by \( r \) elements.

**Proof.** According to the theorem, an ideal \( a \) of height \( r \) contains an ideal \((a_1, \ldots, a_r)\) of height \( r \). If \( a \) is prime, then it is a minimal ideal of \((a_1, \ldots, a_r)\).

**Corollary 15.8.** Let \( A \) be a commutative noetherian ring, and let \( a \) be an ideal in \( A \) that can be generated by \( n \) elements. For any prime ideal \( p \) in \( A \) containing \( a \),

\[
\text{ht}(p/a) \leq \text{ht}(p) \leq \text{ht}(p/a) + n.
\]
16  REGULAR LOCAL RINGS

Proof. The first inequality follows immediately from the correspondence between ideals in $A$ and in $A/a$.

Denote the quotient map $A \to A' \overset{\Delta}{=} A/a$ by $a \mapsto a'$. Let $ht(p/a) = d$. Then there exist elements $a_1, \ldots, a_d$ in $A$ such that $p/a$ is a minimal prime ideal of $(a_1', \ldots, a_d')$. Let $b_1, \ldots, b_n$ generate $a$. Then $p$ is a minimal prime ideal of $(a_1, \ldots, a_d, b_1, \ldots, b_n)$, and hence has height $\leq d + n$. □

We now use dimension theory to prove a stronger version of “generic flatness”\(^{28}\).

Theorem 15.9 (Generic Freeness). Let $A$ be a noetherian integral domain, and let $B$ be a finitely generated $A$-algebra. For any finitely generated $B$-module $M$, there exists a nonzero element $a$ of $A$ such that $M_a$ is a free $A_a$-module.

Proof. Let $F$ be the field of fractions of $A$. We prove the theorem by induction on the Krull dimension of $F \otimes_A B$, starting with the case of Krull dimension $1$. Recall that this means that $F \otimes_A B = 0$, and so $a1_B = 0$ for some nonzero $a \in A$. Then $M_a = 0$, and so the theorem is trivially true ($M_a$ is the free $A_a$-module generated by the empty set).

In the general case, and argument as in (9.9) shows that, after replacing $A$, $B$, and $M$ with $A_a$, $B_a$, and $M_a$ for a suitable $a \in A$, we may suppose that the map $B \to F \otimes_A B$ is injective — we identify $B$ with its image. The Noether normalization shows that there exist algebraically independent elements $x_1, \ldots, x_m$ of $F \otimes_A B$ such that $F \otimes_A B$ is a finite $F[x_1, \ldots, x_m]$-algebra. As in the proof of (9.8), there exists a nonzero $a \in A$ such that $B_a$ is a finite $A_a[x_1, \ldots, x_m]$-algebra. Hence $M_a$ is a finitely generated $A_a[x_1, \ldots, x_m]$-module.

As any extension of free modules is free,\(^{19}\) Proposition 3.5 shows that it suffices to prove the theorem for $M_a = A_a[x_1, \ldots, x_m]/p$ for some prime ideal $p$ in $A_a[x_1, \ldots, x_m]$. If $p = 0$, then $M_a$ is free over $A_a$ (with basis the monomials in the $x_i$). Otherwise, $F \otimes_A (A_a[x_1, \ldots, x_m]/p)$ has Krull dimension less than that of $F \otimes_A B$, and so we can apply the induction hypothesis. □

16  Regular local rings

Throughout this section, $A$ is a noetherian local ring with maximal ideal $m$ and residue field $k$. The Krull dimension $d$ of $A$ is equal to the height of $m$, and

$ht(m) \overset{15.5}{\leq} \text{minimum number of generators of } m \overset{3.9}{=} \dim_k (m/m^2).

When equality holds, the ring $A$ is said to be regular. In other words, $\dim_k (m/m^2) \geq d$, and equality holds exactly when the ring is regular.

For example, when $A$ has dimension zero, it is regular if and only if its maximal ideal can be generated by the empty set, and so is zero. This means that $A$ is a field; in particular, it is an integral domain. The main result of this section is that all regular rings are integral domains.

Lemma 16.1. Let $A$ be a noetherian local ring with maximal ideal $m$, and let $c \in m \setminus m^2$. Denote the quotient map $A \to A'/\overset{\Delta}{=} A/(c)$ by $a \mapsto a'$. Then

$\dim_k m/m^2 = \dim_k m'/m'^2 + 1$

where $m' \overset{\Delta}{=} m/(c)$ is the maximal ideal of $A'$.

\(^{19}\)If $M'$ is a submodule of $M$ such that $M'' \overset{\Delta}{=} M/M'$ is free, then $M \overset{\Delta}{=} M' \oplus M''$. 
PROOF. Let \( e_1, \ldots, e_n \) be elements of \( \mathfrak{m} \) such that \( \{e_1', \ldots, e'_n\} \) is a \( k \)-linear basis for \( \mathfrak{m}'/\mathfrak{m}^2 \). We shall show that \( \{e_1, \ldots, e_n, c\} \) is a basis for \( \mathfrak{m}/\mathfrak{m}^2 \).

As \( e_1', \ldots, e'_n \) span \( \mathfrak{m}'/\mathfrak{m}^2 \), they generate the ideal \( \mathfrak{m}' \) (see \( \text{[3.9]} \)), and so \( \mathfrak{m} = (e_1, \ldots, e_n) + (c) \), which implies that \( \{e_1, \ldots, e_n, c\} \) spans \( \mathfrak{m}/\mathfrak{m}^2 \).

Suppose that \( a_1, \ldots, a_{n+1} \) are elements of \( A \) such that
\[
a_1 e_1 + \cdots + a_n e_n + a_{n+1} c \equiv 0 \mod \mathfrak{m}^2.
\] (24)

Then
\[
a_1' e_1' + \cdots + a_n' e_n' \equiv 0 \mod \mathfrak{m}^2.
\]
and so \( a_1', \ldots, a_n' \in \mathfrak{m}' \). It follows that \( a_1, \ldots, a_n \in \mathfrak{m} \). Now (24) shows that \( a_{n+1} c \in \mathfrak{m}^2 \).

If \( a_{n+1} \notin \mathfrak{m} \), then it is a unit in \( A \), and \( c \in \mathfrak{m}^2 \), which contradicts its definition. Therefore, \( a_{n+1} \in \mathfrak{m} \), and the relation (24) is the trivial one.

\[ \Box \]

**Proposition 16.2.** If \( A \) is regular, then so also is \( A/(a) \) for any \( a \in \mathfrak{m} \setminus \mathfrak{m}^2 \); moreover, \( \dim A = \dim A/(a) + 1 \).

**Proof.** With the usual notations, \( \text{[15.8]} \) shows that
\[
\operatorname{ht}(\mathfrak{m}') \leq \operatorname{ht}(\mathfrak{m}) \leq \operatorname{ht}(\mathfrak{m}') + 1.
\]

Therefore
\[
\dim_k (\mathfrak{m}'/\mathfrak{m}^2) \geq \operatorname{ht}(\mathfrak{m}') \geq \operatorname{ht}(\mathfrak{m}) - 1 = \dim_k (\mathfrak{m}/\mathfrak{m}^2) - 1 = \dim_k (\mathfrak{m}'/\mathfrak{m}^2).
\]

Equalities must hold throughout, which proves that \( A' \) is regular with dimension \( \dim A - 1 \).

**Theorem 16.3.** Every regular noetherian local ring is an integral domain.

**Proof.** Let \( A \) be a regular local ring of dimension \( d \). We have already noted that the statement is true when \( d = 0 \).

We next prove that \( A \) is an integral domain if it contains distinct ideals \( \mathfrak{a} \supseteq \mathfrak{p} \) with \( \mathfrak{a} = (a) \) principal and \( \mathfrak{p} \) prime. Let \( b \in \mathfrak{p} \), and suppose \( b \in \mathfrak{a}^n = (a^n) \) for some \( n \geq 1 \). Then \( b = a^n c \) for some \( c \in A \). As \( a \) is not in the prime ideal \( \mathfrak{p} \), we must have that \( c \in \mathfrak{p} \subseteq \mathfrak{a} \), and so \( b \in \mathfrak{a}^{n+1} \). Continuing in this fashion, we see that \( b \in \bigcap_n \mathfrak{a}^n \cup \{0\} \). Therefore \( \mathfrak{p} = \{0\} \), and so \( A \) is an integral domain.

We now assume \( d \geq 1 \), and proceed by induction on \( d \). Let \( a \in \mathfrak{m} \setminus \mathfrak{m}^2 \). As \( A/(a) \) is regular of dimension \( d - 1 \), it is an integral domain, and so \( (a) \) is a prime ideal. If \( d \) has height \( 1 \), then the last paragraph shows that \( A \) is an integral domain. Thus, we may suppose that, for all \( a \in \mathfrak{m} \setminus \mathfrak{m}^2 \), the prime ideal \( (a) \) has height \( 0 \), and so is a minimal prime ideal of \( A \). Let \( S \) be the set of all minimal prime ideals of \( A \) — recall (13) that \( S \) is finite. We have shown that \( \mathfrak{m} \setminus \mathfrak{m}^2 \subset \bigcup \{ \mathfrak{p} \mid \mathfrak{p} \in S \} \), and so \( \mathfrak{m} \subset \mathfrak{m}^2 \cup \bigcup \{ \mathfrak{p} \mid \mathfrak{p} \in S \} \). It follows from Proposition \( \text{[2.9]} \) that either \( \mathfrak{m} \subset \mathfrak{m}^2 \) (and hence \( m = 0 \)) or \( m \) is a minimal prime ideal of \( A \), but both of these statements contradict the assumption that \( d \geq 1 \).

\[ \Box \]

**Corollary 16.4.** A regular noetherian local ring of dimension \( 1 \) is a principal ideal domain (with a single nonzero prime ideal).
PROOF. Let $A$ be a regular local ring of dimension 1 with maximal ideal $m$, and let $a$ be a nonzero proper ideal in $A$. The conditions imply that $m$ is principal, say $m = (t)$. The radical of $a$ is $m$ because $m$ is the only prime ideal containing $a$, and so $a = (t^r)$ for some $r$ (by 3.13). The ring $A/m^r$ is local and artinian, and so $a/(t^s) + m^r$ for some $s \geq 1$ (by 14.8). This implies that $a = (t^s)$ by Nakayama’s lemma (3.7).

THEOREM 16.5. Let $A$ be a regular noetherian local ring.
(a) For any prime ideal $p$ in $A$, the ring $A_p$ is regular.
(b) The ring $A$ is a unique factorization domain (hence is integrally closed).

PROOF. The best proofs use homological algebra, and are (at present) beyond this primer. For an account of the theorems in the same spirit as this primer, see [link to source]. See also [source] 19.3, 20.3.

17 Connections with geometry

Throughout this section, $k$ is a field.

AFFINE $k$-ALGEBRAS

Let $A$ be a finitely generated $k$-algebra. Recall (10.5) that the nilradical of $A$ is equal to the intersection of the maximal ideals of $A$.

PROPOSITION 17.1. Let $A$ be a finitely generated $k$-algebra over a perfect field $k$. If $A$ is reduced, then so also is $K \otimes_k A$ for every field $K \supseteq k$.

PROOF. Let $(e_i)$ be a basis for $K$ as a $k$-vector space, and suppose $a = \sum e_i \otimes a_i$ is a nonzero nilpotent element in $K \otimes_k A$. Because $A$ is reduced, there exists a maximal ideal $m$ in $A$ such that some $a_i$ do not belong to $m$. The image $\overline{a}$ of $a$ in $K \otimes_k (A/m)$ is a nonzero nilpotent, but $A/m$ is a finite separable field extension of $k$, and so this is impossible.

When $k$ is not perfect, Proposition 17.1 fails, because then $k$ has characteristic $p \neq 0$ and it contains an element $a$ that is not a $p$th power. The polynomial $X^p - a$ is irreducible in $k[X]$, but $X^p - a = (X - \alpha)^p$ in $k^a[X]$. Therefore, $A = k[X]/(X^p - a)$ is a field, but $k^a \otimes_k A = k^a[X]/(X - \alpha)^p$ is not reduced.

DEFINITION 17.2. An affine $k$-algebra is a finitely generated $k$-algebra $A$ such that $k^a \otimes_k A$ is reduced.

Let $A$ be a finitely generated $k$-algebra. If $A$ is affine, then $K \otimes_k A$ is reduced for every finite extension $K$ of $k$, because a $k$-homomorphism $K \to k^a$ defines an injective homomorphism $K \otimes_k A \to k^a \otimes_k A$. Conversely, if $A$ is reduced and $k$ is perfect, then (17.1) shows that $A$ is affine.

PROPOSITION 17.3. If $A$ is an affine $k$-algebra and $B$ is a reduced $k$-algebra, then $A \otimes_k B$ is reduced.

20Every finite separable field extension of $k$ is of the form $k[X]/(f(X))$ with $f(X)$ separable and therefore without repeated factors in any extension field of $k$; hence $K \otimes_k k[X]/(f(X)) \simeq K[X]/(f(X))$ is a product of fields.
PROOF. Let \((e_i)\) be a basis for \(A\) as a \(k\)-vector space, and suppose \(\alpha = \sum e_i \otimes b_i\) is a nonzero nilpotent element of \(A \otimes_k B\). Let \(B'\) be the \(k\)-subalgebra of \(B\) generated by the (finitely many) nonzero \(b_i\). Because \(B'\) is reduced, there exists a maximal ideal \(m\) in \(B'\) such that some \(b_i\) do not belong to \(m\). Then the image \(\bar{\alpha}\) of \(\alpha\) in \(A \otimes_k (B'/m)\) is a nonzero nilpotent, but \(B'/m\) is a finite field extension of \(k\) (Zariski’s lemma, [10.1]), and so this is impossible.

COROLLARY 17.4. If \(A\) and \(B\) are affine \(k\)-algebras, then so also is \(A \otimes_k B\).

PROOF. By definition, \(k^\text{al} \otimes_k A\) is reduced, and \(k^\text{al} \otimes_k (A \otimes_k B) \simeq (k^\text{al} \otimes_k A) \otimes_k B\), which is reduced by [17.2].

LOCALLY RINGED SPACES

Let \(V\) be a topological space, and let \(k\) be a \(k\)-algebra. A presheaf \(\mathcal{O}\) of \(k\)-algebras on \(V\) assigns to each open subset \(U\) of \(V\) a \(k\)-algebra \(\mathcal{O}(U)\) and to each inclusion \(U' \subset U\) a “restriction” map

\[ f \mapsto f|U' : \mathcal{O}(U) \to \mathcal{O}(U') \]

when \(U = U'\) the restriction map is required to be the identity map, and if

\[ U'' \subset U' \subset U, \]

then the composite of the restriction maps

\[ \mathcal{O}(U) \to \mathcal{O}(U') \to \mathcal{O}(U'') \]

is required to be the restriction map \(\mathcal{O}(U) \to \mathcal{O}(U'')\). In other words, a presheaf is a contravariant functor to the category of \(k\)-algebras from the category whose objects are the open subsets of \(V\) and whose morphisms are the inclusions. A homomorphism of presheaves \(\alpha : \mathcal{O} \to \mathcal{O}'\) is a family of homomorphisms of \(k\)-algebras

\[ \alpha(U) : \mathcal{O}(U) \to \mathcal{O}'(U) \]

commuting with the restriction maps, i.e., a natural transformation.

A presheaf \(\mathcal{O}\) is a sheaf if for every open covering \(\{U_i\}\) of an open subset \(U\) of \(V\) and family of elements \(f_i \in \mathcal{O}(U_i)\) agreeing on overlaps (that is, such that \(f_i|U_i \cap U_j = f_j|U_i \cap U_j\) for all \(i, j\)), there is a unique element \(f \in \mathcal{O}(U)\) such that \(f_i = f|U_i\) for all \(i\). A homomorphism of sheaves on \(V\) is a homomorphism of presheaves.

For \(v \in V\), the stalk of a sheaf \(\mathcal{O}\) (or presheaf) at \(v\) is

\[ \mathcal{O}_v = \lim_{\rightarrow} \mathcal{O}(U) \] (limit over open neighbourhoods of \(v\)).

In other words, it is the set of equivalence classes of pairs \((U, f)\) with \(U\) an open neighbourhood of \(v\) and \(f \in \mathcal{O}(U)\); two pairs \((U, f)\) and \((U', f')\) are equivalent if \(f|U'' = f'|U''\) for some open neighbourhood \(U''\) of \(v\) contained in \(U \cap U'\).

A ringed space is a pair \((V, \mathcal{O})\) consisting of topological space \(V\) together with a sheaf of rings. If the stalk \(\mathcal{O}_v\) of \(\mathcal{O}\) at \(v\) is a local ring for all \(v \in V\), then \((V, \mathcal{O})\) is called a locally ringed space.

\(^{21}\)This condition implies that \(\mathcal{O}(\emptyset) = 0\).
A morphism \((V, \mathcal{O}) \to (V', \mathcal{O}')\) of ringed spaces is a pair \((\varphi, \psi)\) with \(\varphi\) a continuous map \(V \to V'\) and \(\psi\) a family of maps
\[
\psi(U') : \mathcal{O}'(U') \to \mathcal{O}(\varphi^{-1}(U')), \quad U' \text{ open in } V',
\]
commuting with the restriction maps. Such a pair defines homomorphism of rings \(\psi_v : \mathcal{O}'_{\varphi(v)} \to \mathcal{O}_v\) for all \(v \in V\). A morphism of locally ringed spaces is a morphism of ringed space such that \(\psi_v\) is a local homomorphism for all \(v\).

Let \(B\) be a base for the topology on \(V\) that is closed under finite intersections. A sheaf on \(B\) can be defined in the obvious way, and such a sheaf \(\mathcal{O}\) extends to a sheaf \(\mathcal{O}'\) on \(V\): for any open subset \(U\) of \(V\), define \(\mathcal{O}'(U)\) to be the set of families \((f_{U'})_{U' \subset U, U' \in B}\) agreeing on overlaps. Then \(\mathcal{O}'\) is a sheaf of \(k\)-algebras on \(V\), and there is a canonical isomorphism \(\mathcal{O} \cong \mathcal{O}'|_{B}\).

**AFFINE ALGEBRAIC SPACES AND VARIETIES**

Let \(A\) be a finitely generated \(k\)-algebra, and let \(V = \text{spm}(A)\). Recall (§11) that the set of principal open subsets of \(V\)
\[B = \{D(f) \mid f \in A\}\]
is a base for the topology on \(V\) which is closed under finite intersections. If \(D(g) \subset D(f)\), then \(V(g) \supset V(f)\), and so some power of \(g\) lies in \((f)\) (by [10.4]), say, \(g^r = cf\) with \(c \in A\). Therefore \(f\) becomes a unit in \(A_g\), and so there is a well-defined “restriction” homomorphism \(A_f \to A_g\) of \(k\)-algebras. When \(D(g) = D(f)\) this homomorphism is an isomorphism. For each principal open subset \(D\) of \(\text{spm}(A)\), we choose an \(f_D\) such that \(D = D(f_D)\).

**PROPOSITION 17.5.** There exists a sheaf \(\mathcal{O}\) of \(k\)-algebras on \(\text{spm}(A)\) such that
(a) for all basic open subsets \(D\), the \(k\)-algebra \(\mathcal{O}(D) = A_{f_D}\), and
(b) for all inclusions \(D' \subset D\) of basic open subsets, the restriction map \(\mathcal{O}(D) \to \mathcal{O}(D')\) is the canonical map \(A_{f_D} \to A_{f_{D'}}\).

For any other sheaf \(\mathcal{O}'\) satisfying (a) and (b), there exists a unique isomorphism \(\mathcal{O} \cong \mathcal{O}'\) inducing the identity map \(\mathcal{O}(D) \to \mathcal{O}'(D)\) for every basic open subset.

**PROOF.** It suffices to check that \(D \to A_{f_D}\) is a sheaf on the base of basic open subsets. This is straightforward but tedious, and so is left as an exercise. \(\Box\)

We write \(\text{Spm}(A)\) for \(\text{spm}(A)\) endowed with this sheaf of \(k\)-algebras. It is independent of the choice of the elements \(f_D\) (up to a unique isomorphism).

**PROPOSITION 17.6.** For every \(m \in \text{spm}(A)\), the stalk \(\mathcal{O}_m\) is canonically isomorphic to \(\mathcal{O}_m\).

**PROOF.** Apply (7.3). \(\Box\)

Thus \(\text{Spm}(A)\) is a locally ringed space. An affine algebraic space is topological space \(V\) together with a sheaf of \(k\)-algebras \(\mathcal{O}\) such that \((V, \mathcal{O})\) is isomorphic to \(\text{Spm}(A)\) for some finitely generated \(k\)-algebra \(A\). A regular map of affine algebraic spaces is morphism of locally ringed spaces.
Example 17.7. Affine $n$-space $\mathbb{A}^n = \text{Spm}(k[X_1, \ldots, X_n])$. To give a regular map $V \to \mathbb{A}^1$ is the same as giving a homomorphism of $k$-algebras $k[X] \to \mathcal{O}(V)$, i.e., an element of $\mathcal{O}(V)$. For this reason, $\mathcal{O}(V)$ is often called the ring (or $k$-algebra) of regular functions on $V$.

Proposition 17.8. For any affine algebraic space $(V, \mathcal{O}_V)$ and locally ringed space $(W, \mathcal{O}_W)$, the canonical map

$$\text{Hom}(V, W) \to \text{Hom}_{k\text{-alg}}(\mathcal{O}_W(W), \mathcal{O}_V(V))$$

is an isomorphism.

Proof. Exercise for the reader.

An affine algebraic space $V$ defines a functor

$$R \mapsto V(R) \overset{\text{def}}{=} \text{Hom}_{k\text{-alg}}(\mathcal{O}(V), R).$$

from $k$-algebras to sets. For example, $\mathbb{A}^n(R) \simeq R^n$ for all $k$-algebras $R$.

An affine algebraic variety is an affine algebraic space $V$ such that $\mathcal{O}_V(V)$ is an affine algebra.

Tangent Spaces; Nonsingular Points; Regular Points

Let $k[\varepsilon]$ be the ring of dual numbers (so $\varepsilon^2 = 0$). For an affine algebraic space $V$ over $k$, the map $\varepsilon \mapsto 0: k[\varepsilon] \to k$ defines a map

$$V(k[\varepsilon]) \to V(k).$$

For any $a \in V(k)$, we define the tangent space to $V$ at $a$, $\text{Tgt}_a(V)$, to be the inverse image of $a$ under this map.

Proposition 17.9. There is a canonical isomorphism

$$\text{Tgt}_a(V) \simeq \text{Hom}_{k\text{-lin}}(m_a/m_a^2, k).$$

This follows from the next two lemmas.

Let $V = V(a) \subset \mathbb{A}^n$, and assume that the origin $o$ lies on $V$. Let $a_\ell$ be the ideal generated by the linear terms $f_\ell$ of the $f \in \mathfrak{a}$. By definition, $T_0(V) = V(a_\ell)$. Let $A_\ell = k[X_1, \ldots, X_n]/a_\ell$, and let $m$ be the maximal ideal in $k[V]$ consisting of the functions zero at $o$; thus $m = (x_1, \ldots, x_n)$.

Lemma 17.10. There is a canonical isomorphism

$$\text{Hom}_{k\text{-lin}}(m/m^2, k) \overset{\sim}{\to} \text{Hom}_{k\text{-alg}}(A_\ell, k).$$

Proof. Let $n = (X_1, \ldots, X_n)$ be the maximal ideal at the origin in $k[X_1, \ldots, X_n]$. Then $m/m^2 \simeq n/(n^2 + a)$, and as $f - f_\ell \in n^2$ for every $f \in \mathfrak{a}$, it follows that $m/m^2 \simeq n/(n^2 + a_\ell)$. Let $f_{1, \ell}, \ldots, f_{r, \ell}$ be a basis for the vector space $a_\ell$. From linear algebra we know that there are $n - r$ linear forms $X_{i_1}, \ldots, X_{i_{n-r}}$ forming with the $f_{i, \ell}$ a basis for the linear forms on $k^n$. Then $X_{i_1} + m^2, \ldots, X_{i_{n-r}} + m^2$ form a basis for $m/m^2$ as a $k$-vector space, and the lemma shows that $A_\ell \simeq k[X_{i_1}, \ldots, X_{i_{n-r}}]$. A homomorphism $\alpha: A_\ell \to k$ of $k$-algebras is determined by its values $\alpha(X_{i_1}), \ldots, \alpha(X_{i_{n-r}})$, and they can be arbitrarily given. Since the $k$-linear maps $m/m^2 \to k$ have a similar description, the first isomorphism is now obvious.
17 CONNECTIONS WITH GEOMETRY

**Lemma 17.11.** There is a canonical isomorphism

\[ \text{Hom}_{\text{alg}}(A, k) \cong \mathcal{T}_o(V). \]

**Proof.** To give a $k$-algebra homomorphism $A \to k$ is the same as to give an element $(a_1, \ldots, a_n) \in k^n$ such that $f(a_1, \ldots, a_n) = 0$ for all $f \in A$, which is the same as to give an element of $T_P(V)$.

**Remark 17.12.** Let $V = \text{Spec} k[X_1, \ldots, X_n]/(f_1, \ldots, f_m)$, and let $(a_1, \ldots, a_n) \in V(k)$. Then $T_{g_A}(V)$ is canonically isomorphic to the subspace of $k^n$ defined by the equations

\[ \frac{\partial f_i}{\partial X_1} a_1 + \cdots + \frac{\partial f_i}{\partial X_n} a_n, \quad i = 1, \ldots, m. \]

When $a$ is the origin, this is a restatement of (17.11), and the general case can be deduced from this case by a translation.

The **dimension** of an affine algebraic space $V$ is the Krull dimension of $\mathcal{O}(V)$. If $V$ is irreducible, then $\mathcal{O}(V)/\mathfrak{N}$ is an integral domain, and the dimension of $V$ is equal to the transcendence degree over $k$ of the field of fractions of $\mathcal{O}(V)/\mathfrak{N}$; moreover, all maximal ideals have height $\dim V$. (12.11).

**Proposition 17.13.** Let $V$ be an affine algebraic space over $k$, and let $a \in V(k)$. Then $\dim T_{g_A}(V) \geq \dim V$, and equality holds if and only if $\mathcal{O}(V)_{m_a}$ is regular.

**Proof.** Let $n$ be the maximal ideal of the local ring $A = \mathcal{O}(V)_{m_a}$. Then $A/n = k$, and $\dim_k n/n^2 \geq \text{ht}(n)$, with equality if and only if $A$ is regular. As $m_a/m_a^2 \simeq n/n^2$ (6.7), Proposition 17.9 implies that $\dim T_{g_A}(V) = \dim_k n/n^2$, from which the statement follows.

An $a \in V(k)$ is **nonsingular** if $\dim T_{g_A}(V) = \dim V$; otherwise it is **singular**. An affine algebraic space $V$ is **regular** if all of its local rings $\mathcal{O}(V)_{m_a}$ are regular, and it is **smooth** if $V_{k^a}$ is regular. Thus an algebraic space over an algebraically closed field is smooth if and only if all $a \in V(k)$ are nonsingular. A smooth algebraic space is regular, but the converse is false. For example, let $k'$ be a finite inseparable extension of $k$, and let $V$ be a smooth algebraic space over $k'$; when we regard $V$ as an algebraic space over $k$, it is regular, but not smooth.

**Proposition 17.14.** A smooth affine algebraic space $V$ is a regular affine algebraic variety; in particular, $\mathcal{O}(V)$ is an integral domain. Conversely, if $k$ is perfect, then every regular affine algebraic space over $k$ is smooth.

**Proof.** Let $A = \mathcal{O}(V)$. If $V$ is smooth, then all the local the local rings of $k^a \otimes_k A$ are regular; in particular, they are integral domains (16.3). This implies that $k^a \otimes_k A$ is reduced, because it implies that the annihilator of any nilpotent element is not contained in any maximal ideal, and so is the whole ring. Therefore $A$ is an affine algebra, and so $V$ is an affine algebraic variety. Let $m$ be a maximal ideal in $A$, and let $n = m(k^a \otimes_k A)$. Then $n$ is a maximal ideal of $k^a \otimes_k A$, and

\[ n/n^2 \simeq k^a \otimes (m/m^2), \]

and so $\dim_k (m/m^2) = \dim_k(n/n^2)$. This implies that $A_m$ is regular. In particular, $A_m$ is an integral domain for all maximal ideals of $A$, which implies that $A$ is integral domain,
because it implies that the annihilator of any zero-divisor is not contained in any maximal
domain. Conversely, if \( V \) is regular, \( A \) is an integral domain, and hence an affine \( k \)-algebra if
\( k \) is perfect.

**Proposition 17.15.** Let \( V \) be an irreducible affine algebraic space over an algebraically
closed field \( k \), and identify \( V \) with \( V(k) \). The set of nonsingular points of \( V \) is open, and it
is nonempty if \( V \) is an algebraic variety.

**Proof.** We may suppose \( V = \text{Spec} k[X_1, \ldots, X_n]/(f_1, \ldots, f_m) \). Let \( d = \dim V \). According
to Remark 17.12, the set of singular points of \( V \) is the zero-set of the ideal generated by
the \((n - d)/2\) minors of the matrix

\[
\text{Jac}(f_1, \ldots, f_m)(a) = \begin{pmatrix}
\frac{\partial f_1}{\partial X_1}(a) & \cdots & \frac{\partial f_1}{\partial X_n}(a) \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m}{\partial X_1}(a) & \cdots & \frac{\partial f_m}{\partial X_n}(a)
\end{pmatrix},
\]

which is closed. Therefore the set of nonsingular points is open.

Now suppose that \( V \) is an algebraic variety. The next two lemmas allow us to sup-
pose that \( V = k[X_1, \ldots, X_n]/(f) \) where \( f \) is a nonconstant irreducible polynomial. Then
\( \dim V = n - 1 \), and so we have to show that the equations

\[
f = 0, \quad \frac{\partial f}{\partial X_1} = 0, \quad \ldots, \quad \frac{\partial f}{\partial X_n} = 0
\]

have no common zero. If \( \frac{\partial f}{\partial X_i} \) is identically zero on \( V(f) \), then \( f \) divides it. But \( \frac{\partial f}{\partial X_i} \) has
degree less than that of \( f \) and \( f \) is irreducible, and so this implies that \( \frac{\partial f}{\partial X_i} = 0 \). Therefore
\( f \) is a polynomial in \( X_2, \ldots, X_n \) (characteristic zero) or \( X_1^p, X_2, \ldots, X_n \) (characteristic \( p \)).
Continuing in this fashion, we find that either \( f \) is constant (characteristic zero) or a \( p \)th
power (characteristic \( p \)), which contradict the hypothesis.

Let \( V \) be an irreducible affine algebraic variety. Then \( \mathcal{O}(V) \) is an integral domain, and
we let \( k(V) \) denote its field of fractions. Two irreducible affine algebraic varieties \( V \) and
\( W \) are said to be **birationally equivalent** if \( k(V) \approx k(W) \).

**Lemma 17.16.** Two irreducible varieties \( V \) and \( W \) are birationally equivalent if and only
if there are open subsets \( U \) and \( U' \) of \( V \) and \( W \) respectively such that \( U \approx U' \).

**Proof.** Assume that \( V \) and \( W \) are birationally equivalent. We may suppose that \( A = \mathcal{O}(V) \)
and \( B = \mathcal{O}(W) \) have a common field of fractions \( K \). Write \( B = k[x_1, \ldots, x_n] \). Then
\( x_i = a_i/b_i, a_i, b_i \in A, \) and \( B \subset A_{b_1 \ldots b_r} \). Since \( \text{Spec}(A_{b_1 \ldots b_r}) \) is a basic open subvariety
of \( V \), we may replace \( A \) with \( A_{b_1 \ldots b_r} \), and suppose that \( B \subset A \). The same argument shows
that there exists a \( d \in B \subset A \) such \( A \subset B_d \). Now

\[
B \subset A \subset B_d \implies B_d \subset A_d \subset (B_d)_d = B_d,
\]

and so \( A_d = B_d \). This shows that the open subvarieties \( D(b) \subset V \) and \( D(b) \subset W \) are
isomorphic. This proves the “only if” part, and the “if” part is obvious.

**Lemma 17.17.** Every irreducible algebraic variety of dimension \( d \) is birationally equiva-
lent to a hypersurface in \( k^{d+1} \).
Proof. Let \( V \) be an irreducible variety of dimension \( d \). According to FT 8.21, there exist algebraically independent elements \( x_1, \ldots, x_d \in k(V) \) such that \( k(V) \) is finite and separable over \( k(x_1, \ldots, x_d) \). By the primitive element theorem (FT 5.1), \( k(V) = k(x_1, \ldots, x_d, x_{d+1}) \) for some \( x_{d+1} \). Let \( f \in k[X_1, \ldots, X_{d+1}] \) be an irreducible polynomial satisfied by the \( x_i \), and let \( H \) be the hypersurface \( f = 0 \). Then \( k(V) \approx k(H) \).
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