

Commutative Algebra

HHH

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Part I

Commutative Ring and Modules

Chapter I

§1 Ideals quotient

Definition 1.1. If $\mathfrak{a}, \mathfrak{b}$ are ideals in a commutative ring R , their **ideal quotient** is

$$(\mathfrak{a} : \mathfrak{b}) = \{x \in R : x\mathfrak{b} \subseteq \mathfrak{a}\}$$

which is an ideal. If \mathfrak{b} is a principal ideal (x) , we shall write $(\mathfrak{a} : x)$ in place of $(\mathfrak{a} : (x))$.

Proposition 1.2. Let R be a commutative ring. Then

1. $\mathfrak{a} \subseteq (\mathfrak{a} : \mathfrak{b})$
2. $(\mathfrak{a} : \mathfrak{b})\mathfrak{b} \subseteq \mathfrak{a}$
3. $((\mathfrak{a} : \mathfrak{b}) : \mathfrak{c}) = (\mathfrak{a} : \mathfrak{b}\mathfrak{c}) = ((\mathfrak{a} : \mathfrak{c}) : \mathfrak{b})$
4. $(\bigcap_i \mathfrak{a}_i : \mathfrak{b}) = \bigcap_i (\mathfrak{a}_i : \mathfrak{b})$
5. $(\mathfrak{a} : \sum_i \mathfrak{b}_i) = \bigcap_i (\mathfrak{a} : \mathfrak{b}_i).$

§2 Primary Decomposition

Throughout this section, R be a commutative ring with identity

§2.1 Primary (Submodule) Ideals

Definition 2.1. Let A be a commutative ring with identity and M an A -module.

1. An ideal \mathfrak{q} in A is **primary** if $\mathfrak{q} \neq A$ and if

$$xy \in \mathfrak{q}, x \notin \mathfrak{q} \Rightarrow y^n \in \mathfrak{q} \text{ for some } n > 0.$$

In other words, \mathfrak{q} is primary $\Leftrightarrow R/\mathfrak{q} \neq 0$ and every zero-divisor in R/\mathfrak{q} is nilpotent.

2. A submodule Q of M is **primary** if $Q \neq M$ and if

$r \in R, m \in M - Q$ and $rm \in Q \Rightarrow r^n M \subset Q$ for some positive integer n

It is equivalent that

- $(Q : M) = \text{Ann}(M/Q)$ is a primary ideal in R
- principal homomorphism $a_{M/Q}$ is injective or nilpotent for each $a \in R$

Remark. If we view A as itself A -module, the two definition are equivalent for A .

Proposition 2.2. Let A be a commutative ring and M an A -module.

1. If \mathfrak{q} is a primary ideal in A , ideal $\mathfrak{p} = \text{Rad}(\mathfrak{q})$ is a prime ideal containing \mathfrak{q} . The radical \mathfrak{p} is called the **associated prime ideal of \mathfrak{q}** or that \mathfrak{q} is **\mathfrak{p} -primary**.
2. If N is a primary submodule of M , $(N : M) = \{r \in A \mid rM \subset N\}$ is a primary ideal in A . Thus $\mathfrak{p} = \text{Rad}(N : M) = \{r \in A \mid r^n M \subset N \text{ for some } n > 0\}$ is a prime ideal in A . The primary submodule N of a module M is said to **belong to a prime ideal \mathfrak{p}** or to be a **\mathfrak{p} -primary submodule** of M .

Theorem 2.3. Let A be a commutative ring, \mathfrak{q} and \mathfrak{p} be ideals in A . Then \mathfrak{q} is primary for \mathfrak{p} if and only if

- (i) $\mathfrak{q} \subset \mathfrak{p} \subset \text{Rad}(\mathfrak{q})$
- (ii) if $ab \in \mathfrak{q}$ and $a \notin \mathfrak{q}$, then $b \in \mathfrak{p}$.

Proof. Suppose (i) and (ii) hold. If $ab \in \mathfrak{q}$ with $a \notin \mathfrak{q}$, then $b \in \mathfrak{p} \subset \text{Rad } \mathfrak{q}$, whence $b^n \in \mathfrak{q}$ for some $n > 0$. Therefore \mathfrak{q} is primary.

To show that \mathfrak{q} is primary for \mathfrak{p} we need only show $\mathfrak{p} = \text{Rad } \mathfrak{q}$. By (i), $\mathfrak{p} \subset \text{Rad } \mathfrak{q}$. If $b \in \text{Rad } \mathfrak{q}$, let n be the least integer such that $b^n \in \mathfrak{q}$. If $n = 1$, $b \in \mathfrak{q} \subset \mathfrak{p}$. If $n > 1$, then $b^{n-1}b = b^n \in \mathfrak{q}$, with $b^{n-1} \notin \mathfrak{q}$ by the minimality of n . By (ii), $b \in \mathfrak{p}$. Thus $b \in \text{Rad } \mathfrak{q}$ implies $b \in \mathfrak{p}$, whence $\text{Rad } \mathfrak{q} \subset \mathfrak{p}$. \square

Corollary 2.4. Let A be a commutative ring with identity, if $\mathfrak{q}_1, \mathfrak{q}_2, \dots, \mathfrak{q}_n$ are \mathfrak{p} -primary, then $\bigcap_{i=1}^n \mathfrak{q}_i$ is also \mathfrak{p} -primary.

Proof. Let $\mathfrak{q} = \bigcap_{i=1}^n \mathfrak{q}_i$. Then by 1.2, $\text{Rad } \mathfrak{q} = \bigcap_{i=1}^n \text{Rad } \mathfrak{q}_i = \bigcap_{i=1}^n \mathfrak{p} = \mathfrak{p}$; in particular, $\mathfrak{q} \subset \mathfrak{p} \subset \text{Rad } \mathfrak{q}$. If $ab \in \mathfrak{q}$ and $a \notin \mathfrak{q}$, then $ab \in \mathfrak{q}_i$ and $a \notin \mathfrak{q}_i$ for some i . Since \mathfrak{q}_i is \mathfrak{p} -primary, $b \in \mathfrak{p}$ by 2.3. Consequently, \mathfrak{q} itself is \mathfrak{p} -primary by 2.3. \square

Proposition 2.5. Clearly every prime ideal is primary. Also the contraction of a primary ideal is primary, for if $f : A \rightarrow B$ and if \mathfrak{q} is a primary ideal in B , then A/\mathfrak{q}^c is isomorphic to a subring of B/\mathfrak{q} .

Proposition 2.6. If $\text{Rad}(\mathfrak{a})$ is maximal, then \mathfrak{a} is primary. In particular, the powers of a maximal ideal \mathfrak{m} are \mathfrak{m} -primary.

Proof. Let $\text{Rad}(\mathfrak{a}) = \mathfrak{m}$. The image of \mathfrak{m} in A/\mathfrak{a} is the nilradical of A/\mathfrak{a} , hence A/\mathfrak{a} has only one prime ideal $\pi(\mathfrak{m})$, by (1.8). Hence every element of A/\mathfrak{a} is either a unit or nilpotent, and so every zero-divisor in A/\mathfrak{a} is nilpotent. \square

§2.2 Primary Decomposition

Definition 2.7. Let R be a commutative ring with identity and M an unitary R -module.

1. An ideal \mathfrak{a} of R has a **primary decomposition** if

(i) $\mathfrak{a} = \mathfrak{q}_1 \cap \mathfrak{q}_2 \cap \cdots \cap \mathfrak{q}_n$ with each \mathfrak{q}_i primary

then the primary decomposition is said to be **reduced (or irredundant)** if

(ii) no \mathfrak{q}_i contains $\mathfrak{q}_1 \cap \cdots \cap \mathfrak{q}_{i-1} \cap \mathfrak{q}_{i+1} \cap \cdots \cap \mathfrak{q}_n$ and the $\mathfrak{p}_i = \text{Rad } \mathfrak{q}_i$ are all distinct,

2. A submodule N of M has a **primary decomposition** if

(i) $N = Q_1 \cap Q_2 \cap \cdots \cap Q_n$, with each Q_i a \mathfrak{p}_i -primary submodule of N for some prime ideal \mathfrak{p}_i of R .

then the primary decomposition is said to be **reduced**. if

(ii) no Q_i contains $Q_1 \cap \dots \cap Q_{i-1} \cap Q_{i+1} \cap \dots \cap Q_n$ and the ideals $\mathfrak{p}_i, \dots, \mathfrak{p}_i$ are all distinct,

If $\mathfrak{p}_j \not\subset \mathfrak{p}_i$ for all $j \neq i$, then \mathfrak{p}_i is said to be an **isolated prime** ideal of N . In other words, \mathfrak{p}_i is isolated if it is minimal in the set $\{\mathfrak{p}_1, \dots, \mathfrak{p}_n\}$. If \mathfrak{p}_i is not isolated it is said to be **embedded**.

Theorem 2.8. Let R be a commutative ring with identity and M a unitary module.

1. If an ideal \mathfrak{a} of R has a primary decomposition, then \mathfrak{a} has a reduced primary decomposition.
2. If a submodule N has a primary decomposition, then N has a reduced primary decomposition.

Proof. 1. If $\mathfrak{a} = \mathfrak{q}_1 \cap \dots \cap \mathfrak{q}_n$ (\mathfrak{q}_i primary) and some \mathfrak{q}_i contains $\mathfrak{q}_1 \cap \dots \cap \mathfrak{q}_{i-1} \cap \mathfrak{q}_{i+1} \cap \dots \cap \mathfrak{q}_n$, then $\mathfrak{a} = \mathfrak{q}_1 \cap \dots \cap \mathfrak{q}_{i-1} \cap \mathfrak{q}_{i+1} \cap \dots \cap \mathfrak{q}_n$ is also a primary decomposition. By thus eliminating the superfluous \mathfrak{q}_i (and reindexing) we have $\mathfrak{a} = \mathfrak{q}_1 \cap \dots \cap \mathfrak{q}_k$ with no \mathfrak{q}_i containing the intersection of the other \mathfrak{q}_j .

Let $\mathfrak{p}_1, \dots, \mathfrak{p}_r$ be the distinct prime ideals in the set $\{\text{Rad } \mathfrak{q}_1, \dots, \text{Rad } \mathfrak{q}_k\}$. Let \mathfrak{q}'_i ($1 \leq i \leq r$) be the intersection of all the \mathfrak{q} 's that belong to the prime \mathfrak{p}_i , that is,

$$\mathfrak{q}'_i = \bigcap_{\text{Rad } (\mathfrak{q}_j) = \mathfrak{p}_i} \mathfrak{q}_j$$

By 2.4 each \mathfrak{q}'_i is primary for \mathfrak{p}_i . Clearly no \mathfrak{q}'_i contains the intersection of all the other \mathfrak{q}'_i . Therefore, $\mathfrak{a} = \bigcap_{i=1}^k \mathfrak{q}_i = \bigcap_{i=1}^r \mathfrak{q}'_i$, whence \mathfrak{a} has a reduced primary decomposition.

2. It is similar to 1. Note that $(\bigcap Q_i : M) = \bigcap (Q_i : M)$. □

Theorem 2.9. *Let R be a commutative ring with identity. If M is an unitary R -module and N is a proper submodule of M with two reduced primary decompositions,*

$$Q_1 \cap Q_2 \cap \cdots \cap Q_k = N = Q'_1 \cap Q'_2 \cap \cdots \cap Q'_s$$

where Q_i is \mathfrak{p}_i -primary and Q'_j is \mathfrak{p}'_j -primary. Then $k = s$ and (after reordering if necessary) $\mathfrak{p}_i = \mathfrak{p}'_i$ for all $i = 1, 2, \dots, k$. Furthermore if Q_i and Q'_i both are \mathfrak{p}_i -primary and \mathfrak{p}_i is an isolated prime, then $Q_i = Q'_i$.

Theorem 2.10. *Let R be a commutative ring with identity and M an Noetherian unitary R -module. Then every submodule $N \neq M$ has a reduced primary decomposition.*

Proof. Let \mathcal{S} be the set of all submodules of M that do not have a primary decomposition. Clearly no primary submodule is in \mathcal{S} . We must show that \mathcal{S} is actually empty. If \mathcal{S} is nonempty, then \mathcal{S} contains a maximal element C by Theorem 1.4.

Since C is not primary, there exist $r \in R$ and $b \in M - C$ such that $rb \in C$ but $r^nM \not\subset C$ for all $n > 0$. Let $M_n = (C : r^n) = \{x \in M \mid r^n x \in C\}$. Then each M_n is a submodule of M and $M_1 \subset M_2 \subset M_3 \subset \cdots$. By hypothesis there exists $k > 0$ such that $M_i = M_k$ for $i \geq k$. Let D be the submodule $r^kM + C = \{x \in M \mid x = r^k y + c \text{ for some } y \in M, c \in C\}$. Clearly $C \subset M_k \cap D$.

Conversely, if $x \in M_k \cap D$, then $x = r^k y + c$ and $r^k x \in C$, whence $r^{2k}v = r^k(r^k y) = r^k(x - c) = r^k x - r^k c \in C$. Therefore, $y \in M_{2k} = M_k$. Consequently, $r^k y \in C$ and hence $x = r^k y + c \in C$. Therefore $M_k \cap D \subset C$, whence $M_k \cap D = C$. Now $C \neq M_k \neq M$ and $C \neq D \neq M$ since $b \in M_k - C$ and $r^kM \not\subset C$. By the maximality of C in \mathcal{S} , M_k and D must have primary decompositions. Thus C has a primary decomposition, which is a contradiction. Therefore \mathcal{S} is empty and every submodule has a primary decomposition. Consequently, every submodule has a reduced primary decomposition by 2.8. \square

Corollary 2.11. *If R is a commutative Noetherian ring with identity and M is a finitely generated unitary R -module. Then every submodule $N (\neq M)$ of M has a reduced primary decomposition.*

Proof. This is an immediate consequence of 1.6 2.1 and 2.10 \square

§3 Contraction and extension of ideal

Definition 3.1. *Let R be a ring and $f : A \rightarrow B$ be a ring homomorphism,*

1. the **extension** of ideal \mathfrak{a} of A is the ideal generated by $f(\mathfrak{a})$ in B , denoted by \mathfrak{a}^e .
2. the **contraction** of \mathfrak{b} is $f^{-1}(\mathfrak{b})$, denoted by \mathfrak{b}^c .

Especially if A be a subring of B and $i : A \rightarrow B$, the contraction of ideal of \mathfrak{b} of B is $A \cap \mathfrak{b}$.

Proposition 3.2. .

1. $\mathfrak{a} \subseteq \mathfrak{a}^{ec}, \mathfrak{b} \supseteq \mathfrak{b}^{ce};$
2. $\mathfrak{b}^c = \mathfrak{b}^{cec}, \mathfrak{a}^e = \mathfrak{a}^{ece};$
3. If \mathcal{C} is the set of all contracted ideals in A and if \mathcal{E} is the set of all extended ideals in B , then $\mathcal{C} = \{\mathfrak{a} \mid \mathfrak{a}^{ec} = \mathfrak{a}\}, \mathcal{E} = \{\mathfrak{b} \mid \mathfrak{b}^{ce} = \mathfrak{b}\}$, and $\mathfrak{a} \mapsto \mathfrak{a}^e$ is a bijective map, whose inverse is $\mathfrak{b} \mapsto \mathfrak{b}^c$.

Proposition 3.3.

$$\begin{aligned} (\mathfrak{a}_1 + \mathfrak{a}_2)^e &= \mathfrak{a}_1^e + \mathfrak{a}_2^e & (\mathfrak{b}_1 + \mathfrak{b}_2)^c &\supseteq \mathfrak{b}_1^c + \mathfrak{b}_2^c, \\ (\mathfrak{a}_1 \cap \mathfrak{a}_2)^e &\subseteq \mathfrak{a}_1^e \cap \mathfrak{a}_2^e & (\mathfrak{b}_1 \cap \mathfrak{b}_2)^c &= \mathfrak{b}_1^c \cap \mathfrak{b}_2^c, \\ (\mathfrak{a}_1 \mathfrak{a}_2)^e &= \mathfrak{a}_1^e \mathfrak{a}_2^e & (\mathfrak{b}_1 \mathfrak{b}_2)^c &\supseteq \mathfrak{b}_1^c \mathfrak{b}_2^c, \\ (\mathfrak{a}_1 : \mathfrak{a}_2)^e &\subseteq (\mathfrak{a}_1^e : \mathfrak{a}_2^e) & (\mathfrak{b}_1 : \mathfrak{b}_2)^c &\subseteq (\mathfrak{b}_1^c : \mathfrak{b}_2^c) \\ \text{Rad}(\mathfrak{a})^e &\subseteq \text{Rad}(\mathfrak{a}^e) & \text{Rad}(\mathfrak{b})^c &= \text{Rad}(\mathfrak{b}^c) \end{aligned}$$

if \mathfrak{b} is a prime ideal in B , then so \mathfrak{b}^c .

The set \mathcal{C} is closed under the other three operations, and \mathcal{E} is closed under sum and product.

§4 Nil and nilpotent ideals

Definition 4.1. Let R be a ring and \mathfrak{a} be an (left, right, two-sided) ideal of R .

1. \mathfrak{a} of R is **nil** if every element of \mathfrak{a} is a nilpotent element;
2. \mathfrak{a} is **nilpotent** if $\mathfrak{a}^n = 0$ for some integer n .

Theorem 4.2. Let R be a ring.

1. If $a \in R$ is nilpotent, a is both left and right quasiregula with quasi inverse $r = -a + a^2 - a^3 + \cdots + (-1)^{n-1}a^{n-1}$
2. Every nil left ideal is contained in $J(R)$.
3. Thus every nil ring is a radical ring.

Proposition 4.3. If R is a left [resp. right] Noetherian ring, then every nil ideal is nilpotent (Exercise 16).

Chapter II

Radical Ideals

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R is a commutative ring (with identity) throughout this chapter unless otherwise stated.

§1 Radical and Nilradical

Definition 1.1. Let R be a commutative ring. If \mathfrak{a} is any ideal of R , the ideal

$$\text{Rad}(\mathfrak{a}) = \{x \in R : x^n \in \mathfrak{a} \text{ for some } n \in \mathbb{Z}_{\geq 1}\}$$

is called **radical** of \mathfrak{a} , sometimes denoted by $\sqrt{\mathfrak{a}}$. The radical of 0 (the set of all nilpotent elements in R) is called **nilradical** of R , denoted by $\text{Nil}(R)$.

Proposition 1.2. Let R be a commutative ring. Then

1. $\mathfrak{a} \subset r(\mathfrak{a})$
2. $r(r(\mathfrak{a})) = r(\mathfrak{a})$
3. $r(\mathfrak{a}\mathfrak{b}) = r(\mathfrak{a} \cap \mathfrak{b}) = r(\mathfrak{a}) \cap r(\mathfrak{b})$
4. thus $r(\mathfrak{a}_1\mathfrak{a}_2 \cdots \mathfrak{a}_n) = r(\bigcap \mathfrak{a}_i) = \bigcap r(\mathfrak{a}_i)$ and $r(\mathfrak{a}^n) = r(\mathfrak{a})$
5. $r(\mathfrak{a} + \mathfrak{b}) = r(r(\mathfrak{a}) + r(\mathfrak{b}))$
6. if \mathfrak{p} is prime in R , $r(\mathfrak{p}^n) = r(\mathfrak{p}) = \mathfrak{p}$ for all $n > 0$.
7. $r(\mathfrak{a}) = (1) \Leftrightarrow \mathfrak{a} = (1)$

Proposition 1.3. Let R be a commutative ring. If S is a multiplicative subset which is disjoint from an ideal \mathfrak{a} , then there exists a prime ideal \mathfrak{p} which is maximal in $\mathcal{S} = \{\mathfrak{b} : \mathfrak{a} \subset \mathfrak{b} \text{ and } \mathfrak{b} \cap S = \emptyset\}$.

Proof. Since $S \neq \emptyset$ and every ideal in \mathcal{S} is properly contained in R , set \mathcal{S} is partially ordered by inclusion. By Zorn's Lemma there is an ideal \mathfrak{p} which is maximal in \mathcal{S} .

Let $\mathfrak{a}_1, \mathfrak{a}_2$ be ideals of R such that $\mathfrak{a}_1 \mathfrak{a}_2 \subset \mathfrak{p}$. If $\mathfrak{a}_1 \not\subset \mathfrak{p}$ and $\mathfrak{a}_2 \not\subset \mathfrak{p}$, then each of the ideals $\mathfrak{p} + \mathfrak{a}_1$ and $\mathfrak{p} + \mathfrak{a}_2$ properly contains \mathfrak{p} and hence must meet S . Consequently, for some $p_i \in \mathfrak{p}, a_i \in \mathfrak{a}_i$.

$$p_1 + a_1 = s_1 \in S \quad \text{and} \quad p_2 + a_2 = s_2 \in S$$

Thus $s_1 s_2 = p_1 p_2 + p_1 a_2 + a_1 p_2 + a_1 a_2 \in \mathfrak{p} + \mathfrak{a}_1 \mathfrak{a}_2 \subset \mathfrak{p}$. This is a contradiction since $s_1 s_2 \in S$ and $S \cap \mathfrak{p} = \emptyset$. Therefore $\mathfrak{a}_1 \subset \mathfrak{p}$ or $\mathfrak{a}_2 \subset \mathfrak{p}$, whence \mathfrak{p} is prime. \square

Theorem 1.4. *Let R be a commutative rng and an ideal \mathfrak{a} .*

1. *If $\pi : R \rightarrow R/\mathfrak{a}$ is the canonical projection, then $\text{Rad}(\mathfrak{a}) = \pi^{-1}(\text{Nil}(R/\mathfrak{a}))$*
2. *The radical of an ideal \mathfrak{a} is the intersection of the prime ideals which contain \mathfrak{a} , that is,*

$$\text{Rad}(\mathfrak{a}) = \bigcap_{\substack{\mathfrak{a} \subset \mathfrak{p} \\ \mathfrak{p} \text{ is prime}}} \mathfrak{p}$$

Proof. It is clear that

$$\text{Rad}(\mathfrak{a}) \subset \bigcap_{\substack{\mathfrak{a} \subset \mathfrak{p} \\ \mathfrak{p} \text{ is prime}}} \mathfrak{p} := \tilde{\mathfrak{p}}$$

by ???. If $S = \tilde{\mathfrak{p}} - \text{Rad}(\mathfrak{a})$ is nonempty, whence is a multiplicative subset of R (verify that $x, y \in S \Rightarrow xy \in S$) and disjoint from $\text{Rad}(\mathfrak{a})$, there exist a prime ideal \mathfrak{p}' that contains $\text{Rad}(\mathfrak{a})$ and disjoint from S by 1.3. But $\tilde{\mathfrak{p}} \subset \mathfrak{p}'$ by the definition of $\tilde{\mathfrak{p}}$, this is a contradiction. \square

Proposition 1.5. *If R is a commutative ring with identity $\neq 0$, then $R^\times + \text{Nil}(R) \subset R^\times$.*

Chapter III

Fractions and Localization

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§1 Rings of Quotient

A is a commutative ring with identity throughout this section unless otherwise stated.

Definition 1.1. Let A be a commutative ring. A subset S called a **multiplicative subset** of A if S is a submonoid of (A, \times) .

Remark. In general, we always assume that $0 \notin S$.

Definition 1.2. Let S be a multiplicative subset of A and

1. The relation defined on the set $A \times S$ by

$$(a, s) \sim (a', s') \Leftrightarrow s_1 (as' - a's) = 0 \text{ for some } s_1 \in S$$

is an equivalence relation and the equivalence class containing the element (a, s) is denoted by a/s .

2. $S^{-1}R$ is a commutative ring with identity $1/1$, where addition and multiplication are defined by

$$r/s + r'/s' = (rs' + r's)/ss' \quad \text{and} \quad (r/s)(r'/s') = rr'/ss'$$

is called the **ring of fractions** of R by S .

Remark. The map $\varphi_S : A \rightarrow S^{-1}A$ given by $a \mapsto a/1$ is a well-defined homomorphism of rings and $\varphi(S) \subset (S^{-1}A)^\times$.

Theorem 1.3 (Universal property). Let \mathcal{C} be the category

- whose objects are ring-homomorphisms (commutative rings with identity)

$$f : A \rightarrow B$$

such that for every $s \in S$, the element $f(s)$ is invertible in B .

- If $f : A \rightarrow B$ and $f' : A \rightarrow B'$ are two objects of \mathcal{C} , a morphism g of f into f' is a homomorphism

$$g : B \rightarrow B'$$

making the diagram commutative:

We have that $\varphi_S : A \rightarrow S^{-1}A$ is a universal object in this category \mathcal{C} .

Theorem 1.4. Let S be a multiplicative subset of A .

1. If S contains no zero divisors, then φ_S is a monomorphism.
2. If A has no zero divisors and $0 \notin S$, then $S^{-1}A$ is an integral domain.
3. If $S \subset A^\times$, then φ_S is an isomorphism.

Definition 1.5. Let A be a commutative ring and S be the set of all nonzero elements of A that are not zero divisors, then $S^{-1}A$ is called the **complete ring of quotients** of the ring A .

The complete ring of quotients of an integral domain A is its **quotient field**, denoted by $\text{Frac}(A)$.

§2 Extensions and Contractions in ring of fractions

Let A be a commutative with identity 1_A and S be a multiplicative subset with $\varphi_S : A \rightarrow S^{-1}A$

Proposition 2.1. 1. If \mathfrak{a} is an ideal in A , then $S^{-1}\mathfrak{a} = \{a/s \mid a \in \mathfrak{a}; s \in S\} = \mathfrak{a}S^{-1}A = \mathfrak{a}^e$.

2. If \mathfrak{b} is an ideal in $S^{-1}A$, then $\varphi_S^{-1}(\mathfrak{b})$ coincides with \mathfrak{b}^c
3. let \mathfrak{a} be an ideal of A , then $S^{-1}\mathfrak{a} = S^{-1}A$ if and only if $S \cap \mathfrak{a} \neq \emptyset$.

Corollary 2.2.

$$S^{-1}(\mathfrak{a} + \mathfrak{b}) = S^{-1}\mathfrak{a} + S^{-1}\mathfrak{b}$$

$$S^{-1}(\mathfrak{a}\mathfrak{b}) = (S^{-1}\mathfrak{a})(S^{-1}\mathfrak{b})$$

$$S^{-1}(\mathfrak{a} \cap \mathfrak{b}) = S^{-1}\mathfrak{a} \cap S^{-1}\mathfrak{b}$$

$$S^{-1}\text{Rad}(\mathfrak{a}) = \text{Rad}(S^{-1}\mathfrak{a})$$

Theorem 2.3.

1. $\mathfrak{b}^{ce} = \mathfrak{b}$ for all ideals \mathfrak{b} of $S^{-1}A$. In other words every ideal in $S^{-1}A$ is of the form $S^{-1}\mathfrak{a} = \mathfrak{a}^e$ for some ideal \mathfrak{a} in A by [proposition 3.2](#).
2. $\mathfrak{a}^{ec} = \bigcup_{s \in S} (\mathfrak{a} : s)$
3. If \mathfrak{p} is a prime ideal in A and $S \cap \mathfrak{p} = \emptyset$, then $S^{-1}\mathfrak{p}$ is a prime ideal in $S^{-1}A$
4. there is a one-to-one correspondence between the set $\mathcal{U} = \{\mathfrak{p} : \mathfrak{p} \text{ is prime and disjoint from } S\}$ and the set $\mathcal{V} = \{S^{-1}\mathfrak{p} : S^{-1}\mathfrak{p} \text{ is prime in } S^{-1}R\}$, given by $\mathfrak{p} \mapsto S^{-1}\mathfrak{p}$.

Proof. Let $I = \varphi_S^{-1}(J)$, then $I^e = J^{ce} \subset J$, whence $S^{-1}I \subset J$. Conversely, if $r/s \in J$, then $\varphi_S(r) = rs/s = (r/s)(s^2/s) \in J$, whence $r \in \varphi_S^{-1}(J) = I$. Thus $r/s \in S^{-1}I$ and hence $J \subset S^{-1}I$. \square

§3 Fractions of modules

Let A be a commutative ring with identity, M be a A -module and S be a multiplicative subset of A .

Definition 3.1. The **module of fractions** of M with respect to S is the set

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

of equivalence classes of the relation on $M \times S$ defined by

$$(m, s) \sim (m', s') \Leftrightarrow s_1(s'm - sm') = 0 \text{ for some } s_1 \in S$$

with addition and scalar multiplication defined by

$$m/s + m'/s' = (s'm + sm')/ss' \quad \text{and} \quad (a/t)(m/s) = (am)/ts$$

for all $m, m' \in M, s, s', t \in S$ and $a \in A$.

Lemma 3.2. 1. $S^{-1}(N + P) = S^{-1}(N) + S^{-1}(P)$

$$2. S^{-1}(N \cap P) = S^{-1}(N) \cap S^{-1}(P)$$

Proposition 3.3.

1. The functor $S^{-1} : {}_A\mathbf{Mod} \rightarrow {}_{S^{-1}A}\mathbf{Mod}$ is exact
2. $S^{-1}\square$ is additive
3. $S^{-1}\square \cong S^{-1}A \otimes_A \square$ in $[{}_A\mathbf{Mod}, {}_{S^{-1}A}\mathbf{Mod}]$

Corollary 3.4.

1. $S^{-1}(M/N) \cong (S^{-1}M) / (S^{-1}N)$ in $S^{-1}A\mathbf{Mod}$
2. $S^{-1}M \otimes_{S^{-1}A} S^{-1}N \cong S^{-1}(M \oplus_A N)$ in $S^{-1}A\mathbf{Mod}$
3. $S^{-1}A$ is a flat A -module

§4 Localization and Local rings

Definition 4.1. Let A be a commutative ring with identity, \mathfrak{p} a prime ideal of A and multiplicative subset $S = A - \mathfrak{p}$. The ring of quotients $S^{-1}A$ is called the **localization of A at \mathfrak{p}** and is denoted $A_{\mathfrak{p}}$. If \mathfrak{a} is an ideal in A , then the ideal $\mathfrak{a}^e = S^{-1}\mathfrak{a}$ in $A_{\mathfrak{p}}$.

Remark. We always identify A with its image $\varphi_S(A)$ in $A_{\mathfrak{p}}$ thus A can be considered as a subring of $A_{\mathfrak{p}}$. In this case, the extension ideal $\mathfrak{a}^e = S^{-1}\mathfrak{a} = \mathfrak{a}A_{\mathfrak{p}}$.

Theorem 4.2. Let \mathfrak{p} be a prime ideal in a commutative ring A with identity and localization $A_{\mathfrak{p}}$.

1. There is a one-to-one correspondence between the set $\{\mathfrak{q} : \mathfrak{q}$ is prime and contained in $\mathfrak{p}\}$ and the set $\{S^{-1}\mathfrak{q} : S^{-1}\mathfrak{q}$ is prime in $A_{\mathfrak{p}}\}$, given by $\mathfrak{q} \mapsto S^{-1}\mathfrak{q}$;
2. The ideal $S^{-1}\mathfrak{p}$ is the unique maximal ideal of $A_{\mathfrak{p}}$.

Definition 4.3. A **local ring** is a commutative ring with identity which has a unique maximal ideal.

Theorem 4.4. The following conditions are equivalent.

1. R is a local ring;
2. all nonunits of R are contained in some ideal $M \neq R$;
3. the nonunits of R form an ideal.
4. for all $r, s \in R$, $r + s = 1_R$ implies r or s is a unit.

Proposition 4.5. Every nonzero homomorphic image of a local ring is local.

§5 Local properties

Definition 5.1. A property P of a ring A (or of an A -module M) is said to be a **local property** if the following is true: A (or M) has $P \Leftrightarrow A_{\mathfrak{p}}$ (or $M_{\mathfrak{p}}$) has P , for each prime ideal \mathfrak{p} of A .

Proposition 5.2. The following are local properties:

1. A -module M is zero
2. A -module homomorphism $\phi : M \rightarrow N$ is injective [resp. surjective, bijective]
3. A -module M is flat

Chapter IV

Chain Condition

§1

Definition 1.1. Let R be a ring.

1. A R -module M is said to satisfy the **ascending chain condition (ACC) on submodules** (or to be Noetherian) if for every chain $M_1 \subset M_2 \subset M_3 \subset \dots$ of submodules of M , there is an integer n such that $M_i = M_n$ for all $i \geq n$.
2. The ring R is **left [resp. right] Noetherian** if R satisfies ACC on submodules as a left [resp. right] R -module. It equivalent that R satisfies the ascending chain condition on left [resp. right] ideals. R is said to be **Noetherian** if R is both left and right Noetherian.
3. A module N is said to satisfy, the **descending chain condition (DCC) on submodules** (or to be Artinian) if for every chain $N_1 \supset N_2 \supset N_3 \supset \dots$ of submodules of N , there is an integer m such that $N_i = N_m$ for all $i \geq m$.
4. R is **left [resp. right] Artinian** if R satisfies DCC on submodules as a left [resp. right] R -module. It equivalent that R satisfies the descending chain condition on left [resp. right] ideals. R is said to be **Artinian** if R is both left and right Artinian.

Definition 1.2. Let R be a ring, A module M is said to satisfy the **maximum condition** [resp. minimum condition] on submodules if every nonempty set of submodules of M contains a maximal [resp. minimal] element (with respect to set theoretic inclusion).

§1.1 Equivalent Condition of Chain Condition

Theorem 1.3. A module A satisfies the ascending [resp. descending] chain condition on submodules if and only if A satisfies the maximal [resp. minimal] condition on submodules.

Theorem 1.4. Let R be a ring and $0 \rightarrow A \xrightarrow{f} B \xrightarrow{g} C \rightarrow 0$ be a short exact sequence of R -modules. Then B satisfies the ACC [resp. DCC] on submodules if and only if A and C satisfy it.

Proof. Sufficiency. If B satisfies the ascending chain condition, then so does its submodule $f(A)$. By exactness A is isomorphic to $f(A)$, whence A satisfies the ascending chain condition. If $C_1 \subset C_2 \subset \dots$ is a chain of submodules of C , then $g^{-1}(C_1) \subset g^{-1}(C_2) \subset \dots$ is a chain of submodules of B . Therefore, there is an n such that $g^{-1}(C_i) = g^{-1}(C_n)$ for all $i \geq n$. Since g is an epimorphism by exactness, it follows that $C_i = C_n$ for all $i \geq n$. Therefore, C satisfies the ascending chain condition.

Necessity. Suppose A and C satisfy the ascending chain condition and $B_1 \subset B_2 \subset \dots$ is a chain of submodules of B . For each i let

$$A_i = f^{-1}(f(A) \cap B_i) \quad \text{and} \quad C_i = g(B_i)$$

Let $f_i = f|_{A_i}$ and $g_i = g|_{B_i}$. Verify that for each i the following sequence is exact:

$$0 \rightarrow A_i \xrightarrow{f_i} B_i \xrightarrow{g_i} C_i \rightarrow 0.$$

Verify that $A_1 \subset A_2 \subset \dots$ and $C_1 \subset C_2 \subset \dots$. By hypothesis there exists an integer n such that $A_i = A_n$ and $C_i = C_n$ for all $i \geq n$. For each $i \geq n$ there is a commutative diagram with exact rows:

$$\begin{array}{ccccccc} 0 & \longrightarrow & A_n & \xrightarrow{f_n} & B_n & \xrightarrow{g_n} & C_n \longrightarrow 0 \\ & & \downarrow \text{id} & & \downarrow i & & \downarrow \text{id} \\ 0 & \longrightarrow & A_i & \xrightarrow{f_i} & B_i & \xrightarrow{g_i} & C_i \longrightarrow 0 \end{array}$$

The Short Five Lemma implies that the inclusion map i is a isomorphism, thus be the identity map, whence B satisfies the ascending chain condition. \square

Corollary 1.5. *Let R be a ring, we have*

1. *If M_1 is a submodule of a module M , then M satisfies the ascending [resp. descending] chain condition if and only if M_1 and M/M_1 satisfy it.*
2. *If M_1, \dots, M_n are modules, then the direct sum $M_1 \oplus M_2 \oplus \dots \oplus M_n$ satisfies the ascending [resp. descending] chain condition on submodules if and only if each A_i satisfies it.*

Theorem 1.6. *If R is a left [resp. right] Noetherian [resp. Artinian] ring, then every finitely generated left [resp. right] R -module M is Noetherian [resp. Artinian].*

Proof. If M is finitely generated, then by ?? there is a free unitary R -module F with a finite basis and an epimorphism $\pi : F \rightarrow M$. Since F is a direct sum of a finite number of copies of R by ??, F is left Noetherian [resp. Artinian], whence $M \cong F / \text{Ker } \pi$ is Noetherian [resp. Artinian] by 1.5. \square

§2 Normal series and Composition Series of Modules

Definition 2.1. Let R be a ring and a R -module A .

1. A **normal series** for A is a chain of submodules: $A = A_0 \supset A_1 \supset A_2 \supset \cdots \supset A_n$. The factors of the series are the quotient modules

$$A_i/A_{i+1} \quad (i = 0, 1, \dots, n-1).$$

The **length** of the normal series is the number of proper inclusions (= number of nontrivial factors).

2. A **refinement** of the normal series $A = A_0 \supset A_1 \supset \cdots \supset A_n$ is a normal series obtained by inserting a finite number of additional submodules between the given ones. A **proper refinement** is one which has length larger than the original series.
3. Two normal series are **equivalent** if there is a one-to-one correspondence between the nontrivial factors such that corresponding factors are isomorphic modules. Thus equivalent series necessarily have the same length.
4. A **composition series** for A is a normal series $A = A_0 \supset A_1 \supset A_2 \supset \cdots \supset A_n = 0$ such that each factor A_k/A_{k+1} ($k = 0, 1, \dots, n-1$) is a module with no proper nonempty submodules.

Theorem 2.2. Any two normal series of a module A have refinements that are equivalent. Any two composition series of A are equivalent.

Theorem 2.3. A nonzero module M has a composition series if and only if M satisfies both the ACC and DCC on submodules.

Proof. (\Rightarrow) Suppose A has a composition series S of length n . If either chain condition fails to hold, one can find submodules

$$A = A_0 \supsetneq A_1 \supsetneq A_2 \supsetneq \cdots \supsetneq A_n \supsetneq A_{n+1}$$

which form a normal series T of length $n+1$. By 2.2, S and T have refinements that are equivalent. This is a contradiction since equivalent series have equal length. For every refinement of the composition series S has the same length n as S , but every refinement of T necessarily has length at least $n+1$. Therefore, A satisfies both chain conditions.

(\Leftarrow) If B is a nonzero submodule of A , let $S(B)$ be the set of all proper submodules C of B . Also define $S(0) = \{0\}$. For each B there is a maximal element B' of $S(B)$ by 1.3. Let S be the set of all submodules of A and define a map $f : S \rightarrow S$ by $f(B) = B'$

Let $A_i = f^{(i)}(A)$, then $A \supset A_1 \supset A_2 \supset \cdots$ is a descending chain by construction, whence for some n , $A_i = A_n$ for all $i \geq n$. Since $A_{n+1} = f(A_n)$, the definition of f shows that $A_{n+1} = A_n$

only if $A_n = 0 = A_{n+1}$. Let m be the smallest integer such that $A_m = 0$. Then $m \leq n$ and $A_k \neq 0$ for all $k < m$. Furthermore for each $k < m$, A_{k+1} is a maximal submodule of A_k such that $A_k \supsetneq A_{k+1}$. Consequently, each A_k/A_{k+1} is nonzero and has no proper submodules by ??.

Therefore, $A \supset A_1 \supset \cdots \supset A_m = 0$ is a composition series for A . \square

Chapter V

Noetherian Modules and Rings

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§1 Artinian Rings

§1.1

Theorem 1.1 (Hopkins-Levitzki). *Let R be a ring. Then*

$$\text{left Artinian} \Leftrightarrow \text{right Artinian} \Rightarrow \text{left Noetherian} + \text{right Noetherian}$$

§1.2

In this subsection we shall study commutative Artinian rings.

Theorem 1.2. *Let A be a commutative ring with identity. Then the following conditions are equivalent:*

1. A is Artinian
2. $\text{Spec}(A)$ is finite and $\dim A = 0$
3. A is Noetherian and $\dim A = 0$.
4. A is uniquely (up to isomorphism) a finite direct product of Artin local rings.

Corollary 1.3. *In a commutative Artin ring the nilradical is equal to the Jacobson radical.*

Proposition 1.4. *Let A be an Artin local ring. Then the following are equivalent:*

1. *every ideal in A is principal;*
2. *the maximal ideal \mathfrak{m} is principal;*
3. $\dim_k (\mathfrak{m}/\mathfrak{m}^2) \leq 1$.

§2 Noetherian Modules and Rings

Theorem 2.1. *A module M is Noetherian if and only if every submodule of M is finitely generated.*

Theorem 2.2. *Recall that a module M is Noetherian.*

1.3 *A module M satisfies the ascending [resp. descending] chain condition on submodules if and only if M satisfies the maximal [resp. minimal] condition on submodules.*

2.1 *A module M satisfies the ACC on submodules if and only if every submodule of M is finitely generated. In particular, a commutative ring R is Noetherian if and only if every ideal of R is finitely generated.*

1.6 *If R is a left [resp. right] Noetherian [resp. Artinian] ring with identity, then every finitely generated unitary left [resp. right] R -module A satisfies the ACC [resp. DCC] on submodules.*

Proposition 2.3. *Let A be Noetherian ring*

Proposition 2.4. *If A is Noetherian and ϕ is a homomorphism, then $B = \phi(A)$ is Noetherian.*

Proposition 2.5. *Let A be a subring of B ; suppose that A is Noetherian and that B is finitely generated as an A -module. Then B is Noetherian (as a ring).*

Proposition 2.6. *If A is Noetherian and S is any multiplicatively closed subset of A , then $S^{-1}A$ is Noetherian.*

Theorem 2.7. *If R is a commutative Noetherian ring with identity, then so is $R[x_1, \dots, x_n]$ and $R[[x]]$.*

Proposition 2.8. *If R is a commutative ring with identity and \mathfrak{p} is an ideal which is maximal in the set of all ideals of R which are not finitely generated, then \mathfrak{p} is prime.*

Proof. Suppose $ab \in \mathfrak{p}$ but $a \notin \mathfrak{p}$ and $b \notin \mathfrak{p}$. Then $\mathfrak{p} + (a)$ and $\mathfrak{p} + (b)$ are ideals properly containing \mathfrak{p} and therefore finitely generated by maximality of \mathfrak{p} . Consequently $\mathfrak{p} + (a) = (p_1 + r_1a, \dots, p_n + r_na)$ and $\mathfrak{p} + (b) = (p'_1 + r'_1b, \dots, p'_m + r'_mb)$ for some $p_i, p'_i \in \mathfrak{p}$ and $r_i, r'_i \in R$.

If $J = (\mathfrak{p} : a) = \{r \in R \mid ra \in \mathfrak{p}\}$, then J is an ideal. Since $ab \in \mathfrak{p}$, $(p'_i + r'_i b)a = p'_i a + r'_i ab \in \mathfrak{p}$ for all i , whence $\mathfrak{p} \subset \mathfrak{p} + (b) \subset J$. By maximality, J is finitely generated, say $J = (j_1, \dots, j_k)$.

If $x \in \mathfrak{p}$, then $x \in \mathfrak{p} + (a)$ and hence for some $s_i \in R$, $x = \sum_{i=1}^n s_i(p_i + r_i a) = \sum_{i=1}^n s_i p_i + \sum_{i=1}^n s_i r_i a$. Consequently, $(\sum_i s_i r_i)a = x - \sum_i s_i p_i \in \mathfrak{p}$, whence $\sum_i s_i r_i \in J$. Thus for some $t_i \in R$, $\sum_{i=1}^n s_i r_i = \sum_{i=1}^k t_i j_i$ and $x = \sum_{i=1}^n s_i p_i + \sum_{i=1}^k t_i j_i a$. Therefore, \mathfrak{p} is generated by $p_1, \dots, p_n, j_1 a, \dots, j_k a$, which is a contradiction. Thus $a \in \mathfrak{p}$ or $b \in \mathfrak{p}$ and \mathfrak{p} is prime by ?? \square

Theorem 2.9 (I.S.Cohen). *A commutative ring R with identity is Noetherian if and only if every prime ideal of R is finitely generated.*

Proof. Let \mathcal{S} be the set of all ideals of R which are not finitely generated. If \mathcal{S} is nonempty, then use Zorn's Lemma to find a maximal element P of \mathcal{S} . P is prime by Proposition 2.4 and hence finitely generated by hypothesis.

This is a contradiction unless $\delta = \emptyset$. Therefore, R is Noetherian by Theorem 1.9. \square

Chapter VI

Integral

§1 Rings Extensions

Definition 1.1. Let S be a commutative ring with identity and R a subring of S containing 1_S .

1. Then S is said to be an **extension ring** of R .
2. An element $s \in S$ is said to be **integral** over R if s is a root of a monic polynomial in $R[x]$.
3. If every element of S is integral over R , S is said to be an **integral extension** of R .
4. The **integral closure** of R in S is the set of elements of S that are integral over R .
5. The ring R is said to be **integrally closed** in S if R is equal to its integral closure in S .

The integral closure of an integral domain R in its field of fractions is called the **normalization** of R . An integral domain is called integrally closed or normal if it is integrally closed in its field of fractions.

Remark. It follows from [corollary 1.3](#) that the integral closure of R in S is a subring of S containing R .

Theorem 1.2. Let S be an extension ring of R and $s \in S$. Then the following conditions are equivalent.

1. s is integral over R
2. Subring $R[s]$ is a finitely generated R -module
3. There is a subring T that $R[s] \subset T \subset S$, which is finitely generated as an R -module;
4. There is a faithful $R[s]$ -submodule M which is finitely generated as an R -module.

Corollary 1.3. Let S be an extension ring of R . Then

1. If S is finitely generated as an R -module, then S is an integral extension of R .

2. If $s_1, \dots, s_t \in S$ are integral over R , then $R[s_1, \dots, s_t]$ is a finitely generated R -module and an integral extension ring of R .
3. If T is an integral extension ring of S and S is an integral extension ring of R , then T is an integral extension ring of R .

Proof. It immediately follows from 1.2 □

Proof. We have a tower of extension rings:

$$R \subset R[s_1] \subset R[s_1, s_2] \subset \cdots \subset R[s_1, \dots, s_t]$$

For each i , s_i is integral over R and hence integral over $R[s_1, \dots, s_{i-1}]$. Since $R[s_1, \dots, s_i] = R[s_1, \dots, s_{i-1}][s_i]$, $R[s_1, \dots, s_i]$ is a finitely generated module over $R[s_1, \dots, s_{i-1}]$ by 1.2. Thus $R[s_1, \dots, s_n]$ is a finitely generated R -module, then $R[s_1, \dots, s_n]$ is an integral extension ring of R by 1. □

Proof. T is obviously an extension ring of R . If $t \in T$, then t is integral over S and therefore the root of some monic polynomial $f \in S[x]$, say $f = \sum_{i=0}^n s_i x^i$. Since f is also a polynomial over the ring $R[s_0, s_1, \dots, s_{n-1}]$, t is integral over $R[s_0, \dots, s_{n-1}]$.

By 1.2 $R[s_0, \dots, s_{n-1}][t]$ is a finitely generated $R[s_0, \dots, s_{n-1}]$ -module. But since S is integral over R , $R[s_0, \dots, s_{n-1}]$ is a finitely generated R -module by 2. Then

$$R[s_0, \dots, s_{n-1}][t] = R[s_0, \dots, s_{n-1}, t]$$

is a finitely generated R -module. Since $R[t] \subset R[s_0, \dots, s_{n-1}, t]$, t is integral over R by 1.2. □

Proposition 1.4. 1. Every unique factorization domain is integrally closed.

2. In particular, the polynomial ring $F[x_1, \dots, x_n]$ (F a field) is integrally closed in its quotient field $F(x_1, \dots, x_n)$.

§1.1 integral extension

Theorem 1.5. Let T be a multiplicative subset of an integral domain R such that $0 \notin T$. If R is integrally closed, then $T^{-1}R$ is an integrally closed integral domain.

Proof. $T^{-1}R$ is an integral domain and R may be identified with a subring of $T^{-1}R$ by 1.2. Extending this identification, the quotient field $Q(R)$ of R may be considered as a subfield of the quotient field $Q(T^{-1}R)$ of $T^{-1}R$. Verify that $Q(R) = Q(T^{-1}R)$.

Let $u \in Q(T^{-1}R)$ be integral over $T^{-1}R$; then for some $r_i \in R$ and $s_i \in T$,

$$u^n + (r_{n-1}/s_{n-1}) u^{n-1} + \cdots + (r_1/s_1) u + (r_0/s_0) = 0.$$

Multiply through this equation by s^n , where $s = s_0s_1 \cdots s_{n-1} \in T$, and conclude that su is integral over R . Since $su \in Q(T^{-1}R) = Q(R)$ and R is integrally closed, $su \in R$. Therefore, $u = su/s \in T^{-1}R$, whence $T^{-1}R$ is integrally closed. \square

Theorem 1.6. *Let S be an integral extension ring of R . Then the following statements hold.*

1. *Assume that S is an integral domain. Then R is a field if and only if S is a field.*
2. *Let \mathfrak{p} be a prime ideal in R . Then there is a prime ideal \mathfrak{q} in S with $\mathfrak{p} = \mathfrak{q} \cap R$.*

Moreover, \mathfrak{p} is maximal if and only if \mathfrak{q} is maximal.

3. *(The Going-up Theorem) Let $\mathfrak{p}_1 \subseteq \mathfrak{p}_2 \subseteq \cdots \subseteq \mathfrak{p}_n$ be a chain of prime ideals in R and suppose there are prime ideals $\mathfrak{q}_1 \subseteq \mathfrak{q}_2 \subseteq \cdots \subseteq \mathfrak{q}_m$ of S with $\mathfrak{p}_i = \mathfrak{q}_i \cap R$, $1 \leq i \leq m$ and $m < n$. Then the ascending chain of ideals can be completed: there are prime ideals $\mathfrak{q}_{m+1} \subseteq \cdots \subseteq \mathfrak{q}_n$ in S such that $\mathfrak{p}_i = \mathfrak{q}_i \cap R$ for all i .*

Theorem 1.7 (The Going-down Theorem). *Assume that S is an integral domain and R is integrally closed in S . Let $\mathfrak{p}_1 \supseteq \mathfrak{p}_2 \supseteq \cdots \supseteq \mathfrak{p}_n$ be a chain of prime ideals in R and suppose there are prime ideals $\mathfrak{q}_1 \supseteq \mathfrak{q}_2 \supseteq \cdots \supseteq \mathfrak{q}_m$ of S with $\mathfrak{p}_i = \mathfrak{q}_i \cap R$, $1 \leq i \leq m$ and $m < n$. Then the descending chain of ideals can be completed: there are prime ideals $\mathfrak{q}_{m+1} \supseteq \cdots \supseteq \mathfrak{q}_n$ in S such that $\mathfrak{p}_i = \mathfrak{q}_i \cap R$ for all i .*

Theorem 1.8. *Let S be an integral extension ring of R and let \mathfrak{q} be a prime ideal in S which lies over a prime ideal \mathfrak{p} in R . Then \mathfrak{q} is maximal in S if and only if \mathfrak{p} is maximal in R .*

Proof. Suppose \mathfrak{q} is maximal in S . By ?? there is a maximal ideal \mathfrak{m} of R that contains \mathfrak{p} and \mathfrak{m} is prime by ??. By ?? there is a prime ideal \mathfrak{q}' in S such that $\mathfrak{q} \subset \mathfrak{q}'$ and \mathfrak{q}' lies over \mathfrak{m} . Since \mathfrak{q}' is prime, $\mathfrak{q}' \neq S$. The maximality of \mathfrak{q} implies that $\mathfrak{q} = \mathfrak{q}'$, whence $\mathfrak{p} = \mathfrak{q} \cap R = \mathfrak{q}' \cap R = \mathfrak{m}$. Therefore, \mathfrak{p} is maximal in R .

Conversely suppose \mathfrak{p} is maximal in R . Since \mathfrak{q} is prime in S , $\mathfrak{q} \neq S$ and there is a maximal ideal N of S containing \mathfrak{q} and N is prime, whence $1_R = 1_S \notin N$. Since $\mathfrak{p} = R \cap \mathfrak{q} \subset R \cap N \subset R$, we must have $\mathfrak{p} = R \cap N$ by maximality. Thus \mathfrak{q} and N both lie over \mathfrak{p} and $\mathfrak{q} \subset N$. Therefore, $\mathfrak{q} = N$ by 1.8. \square

§2 Discrete Valuation Ring

Definition 2.1. *The following conditions on a principal ideal domain are equivalent:*

1. *A has exactly one nonzero prime ideal;*
2. *up to associates, A has exactly one prime element;*
3. *A is local and is not a field.*

*A ring satisfying these conditions is called a **discrete valuation ring**.*

Theorem 2.2. *An integral domain A is a discrete valuation ring if and only if*

- (i) A is noetherian,
- (ii) A is integrally closed, and
- (iii) A has exactly one nonzero prime ideal.

§3 Dedekind Domain

Definition 3.1. *A **Dedekind domain** is an integral domain R satisfying the following equivalent conditions:*

1. *R is Noetherian, integrally closed and has Krull dimension one (Every nonzero prime ideal of R is maximal).*
2. *Every nonzero ideal of R is invertible*
3. *Every finitely generated torsion-free R -module is free.*
4. *the localization $R_{\mathfrak{p}}$ at each prime ideal \mathfrak{p} of R is a discrete valuation ring.*
5. *Every nonzero proper ideal of R can be written as a product of prime ideals of R , and this factorization is unique up to the order of the factors.*

Proposition 3.2. *Let A be an integral domain, and let S be a multiplicative subset of A .*

1. *If A is noetherian, then so also is $S^{-1}A$.*
2. *If A is integrally closed, then so also is $S^{-1}A$.*
3. *If A has Krull dimension one, then so also does $S^{-1}A$.*
4. *If A is a Dedekind domain, then so also is $S^{-1}A$.*

Proposition 3.3. *A noetherian integral domain A is a Dedekind domain if and only if, for every nonzero prime ideal \mathfrak{p} in A , the localization $A_{\mathfrak{p}}$ is a discrete valuation ring.*

§3.1 Unique factorization of ideals

Theorem 3.4. *Let A be a Dedekind domain. Every proper nonzero ideal \mathfrak{a} of A can be written in the form*

$$\mathfrak{a} = \mathfrak{p}_1^{r_1} \cdots \mathfrak{p}_n^{r_n}$$

with the \mathfrak{p}_i distinct prime ideals and the $r_i > 0$; the \mathfrak{p}_i and the r_i are uniquely determined.

§3.2 The ideal class group

Definition 3.5. Let R be an integral domain with quotient field K . A **fractional ideal** of R is

- (i) a nonzero R -submodule I of K
- (ii) there exists a nonzero $d \in R$ such that $dI \subset R$, i.e., $(R : I) \cap R \neq \emptyset$

Definition 3.6. If R is an integral domain with quotient field K , then the set of all fractional ideals of R forms a commutative monoid, with identity R and multiplication given by

$$IJ = \left\{ \sum_{i=1}^n a_i b_i \mid a_i \in I; b_i \in J; n \in \mathbb{Z}_{\geq 1} \right\}$$

A fractional ideal I of an integral domain R is said to be **invertible** if $IJ = R$ for some fractional ideal J of R .

Theorem 3.7. Let A be a Dedekind domain. The set $\text{Id}(A)$ of fractional ideals is a group; in fact, it is the free abelian group on the set of nonzero prime ideals.

Definition 3.8. We define the **ideal class group** $\text{Cl}(A)$ of A to be the quotient $\text{Cl}(A) = \text{Id}(A)/\text{P}(A)$ of $\text{Id}(A)$ by the subgroup of principal ideals. The **class number** of A is the order of $\text{Cl}(A)$ (when finite).

In the case that A is the ring of integers \mathcal{O}_K in a number field K , we often refer to $\text{Cl}(\mathcal{O}_K)$ as the **ideal class group** of K , and its order as the **class number** of K .

Proposition 3.9. Let R be an integral domain with quotient field K .

1. Indeed for any fractional ideal I the set $I^{-1} = \{a \in K \mid aI \subset R\}$ is easily seen to be a fractional ideal such that $I^{-1}I = II^{-1} \subset R$.
2. The inverse of an invertible fractional ideal I is unique and is $I^{-1} = \{a \in K \mid aI \subset R\}$. If I is invertible and $IJ = JI = R$, then clearly $J \subset I^{-1}$. Conversely, since I^{-1} and J are R -submodules of K , $I^{-1} = RI^{-1} = (JI)I^{-1} = J(II^{-1}) \subset JR = RJ \subset J$, whence $J = I^{-1}$.
3. If I, A, B are fractional ideals of R such that $IA = IB$ and I is invertible, then $A = RA = (I^{-1}I)A = I^{-1}(IB) = RB = B$.
4. If I is an ordinary ideal in R , then $R \subset I^{-1}$.

Lemma 3.10. Let I, I_1, I_2, \dots, I_n be ideals in an integral domain R .

1. The ideal $I_1 I_2 \cdots I_n$ is invertible if and only if each I_j is invertible.
2. If $\mathfrak{p}_1 \cdots \mathfrak{p}_m = I = \mathfrak{q}_1 \cdots \mathfrak{q}_n$, where the \mathfrak{p}_i and \mathfrak{q}_j are prime ideals in R and every \mathfrak{p}_i is invertible, then $m = n$ and (after reindexing) $\mathfrak{p}_i = \mathfrak{q}_i$ for each $i = 1, \dots, m$.

Lemma 3.11. *If I is a fractional ideal of an integral domain R with quotient field K and $f \in \text{Hom}_R(I, R)$, then for all $a, b \in I : af(b) = bf(a)$.*

Lemma 3.12. *Every invertible fractional ideal of an integral domain R with quotient field K is a finitely generated R -module.*

Theorem 3.13. *Let R be an integral domain and I a fractional ideal of R . Then I is invertible if and only if I is a projective R -module.*

§4 Discrete valuations

Definition 4.1. *Let K be a field. A **discrete valuation** on K is a nonzero homomorphism $v : K^\times \rightarrow \mathbb{Z}$ such that $v(a + b) \geq \min(v(a), v(b))$.*

*As v is not the zero homomorphism, its image is a nonzero subgroup of \mathbb{Z} , and is therefore of the form $m\mathbb{Z}$ for some $m \in \mathbb{Z}$. If $m = 1$, then $v : K^\times \rightarrow \mathbb{Z}$ is surjective, and v is said to be **normalized**; otherwise, $x \mapsto m^{-1} \cdot v(x)$ will be a normalized discrete valuation.*

We extend v to a map $K \rightarrow \mathbb{Z} \cup \{\infty\}$ by setting $v(0) = \infty$, where ∞ is a symbol $\geq n$ for all $n \in \mathbb{Z}$.

Remark. We have

1. $v(\zeta) = 0$ for some $\zeta \in K^\times$
2. $v(-a) = v(a)$ for all $a \in K$;
3. $v(a + b) = \max \{v(a), v(b)\}$ if $v(a) \neq v(b)$.

We often use "ord" rather than "v" to denote a discrete valuation.

Proposition 4.2. *Let v be a discrete valuation on K , then*

$$A := \{a \in K \mid v(a) \geq 0\}$$

is a principal ideal domain with maximal ideal

$$\mathfrak{m} = \{a \in K \mid v(a) > 0\}$$

If $v(K^\times) = m\mathbb{Z}$, then the ideal \mathfrak{m} is generated by every element of $v^{-1}(m)$.

Definition 4.3. *Let A be a Dedekind domain and let \mathfrak{p} be a prime ideal in A . For any $c \in K^\times$, let $v(c)$ be the exponent of \mathfrak{p} in the factorization of (c) . Then v is a normalized discrete valuation on K , called the **discrete valuation associated to \mathfrak{p}** , denoted by $\text{ord}_{\mathfrak{p}}$.*

Proposition 4.4. *Let x_1, \dots, x_m be elements of a Dedekind domain A , and let $\mathfrak{p}_1, \dots, \mathfrak{p}_m$ be distinct prime ideals of A . For every integer n , there is an $x \in A$ such that*

$$\text{ord}_{\mathfrak{p}_i}(x - x_i) > n, \quad i = 1, 2, \dots, m.$$

§5 Integral closures of Dedekind domains

Theorem 5.1. *Let A be a Dedekind domain with field of fractions K and L/K be a finite separable extension, then the integral closure of A in L is Dedekind domain.*

Definition 5.2. *Let A be a Dedekind domain with field of fractions K , and let B be the integral closure of A in a finite separable extension L of K . A prime ideal \mathfrak{p} of A will factor in B ,*

$$\mathfrak{p}B = \mathfrak{P}_1^{e_1} \cdots \mathfrak{P}_g^{e_g}$$

where \mathfrak{P} are distinct prime ideals in B and $e_i \geq 1$,

1. If any of the numbers $e_i > 1$, then we say that \mathfrak{p} is **ramified** in B (or L). The number e_i is called the **ramification index**.
2. We say \mathfrak{P} divides \mathfrak{p} , written $\mathfrak{P} \mid \mathfrak{p}$, if \mathfrak{P} occurs in the factorization of \mathfrak{p} in B .

We then write $e(\mathfrak{P}/\mathfrak{p})$ for the ramification index and $f(\mathfrak{P}/\mathfrak{p})$ for the degree of the field extension $[B/\mathfrak{P} : A/\mathfrak{p}]$ (called the **residue class degree**).

3. \mathfrak{p} is said to **split** (or split completely) in L if $e_i = f_i = 1$ for all i
4. \mathfrak{p} is said to be **inert** in L if $\mathfrak{p}B$ is a prime ideal (so $g = 1 = e$).

Theorem 5.3. *Let m be the degree of L over K , and let $\mathfrak{P}_1, \dots, \mathfrak{P}_g$ be the prime ideals dividing \mathfrak{p} ; then*

$$\sum_{i=1}^g e_i f_i = m$$

where $e_i = e(\mathfrak{P}_i/\mathfrak{p})$ and $f_i = f(\mathfrak{P}_i/\mathfrak{p})$. If L is Galois over K , then all the ramification numbers are equal, and all the residue class degrees are equal, and so

$$efg = m.$$

Chapter VII

Completions

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§1 Basic Definitions

§1.1 Graded

Definition 1.1. A **graded ring** is a ring A together with a family $\{A_n\}_{n \geq 0}$ of subgroups of A , such that

(i) $A = \bigoplus_{n=0}^{\infty} A_n$ in **Ab**

(ii) and $A_m A_n \subseteq A_{m+n}$ for all $m, n \geq 0$.

Thus A_0 must be a subring of A containing 1_A , and A is a A_0 -algebra. A is said to be **standard graded ring** if

(iii) $A = A_0[A_1]$ as a A_0 -algebra.

Definition 1.2. Let $A = \bigoplus_{n \geq 0} A_n$ be a graded ring. A **graded A -module** is an A -module M together with a family $\{M_n\}_{n \geq 0}$ of subgroups of M such that

(i) $M = \bigoplus_{n=0}^{\infty} M_n$ as an abelian group

(ii) $A_m M_n \subseteq M_{m+n}$ for all $m, n \geq 0$.

Elements of M_n are called **homogeneous elements of degree n** .

Remark. Thus each M_n is an A_0 -module.

Definition 1.3. Let A be a graded ring and M, N graded A -modules. A **graded A -homomorphism** from M to N is an A -module homomorphism $f : M \rightarrow N$ such that $f(M_n) \subseteq N_n$ for all $n \geq 0$.

Definition 1.4. Let k be a commutative ring (usually a field). A **graded k -algebra** is k -algebra A such that

- (i) $A = \bigoplus_{n \geq 0} A_n$ is a graded ring.
- (ii) the structure morphism $\varphi : k \rightarrow A$ with $\text{Im}(\varphi) \subset A_0$ (scalar action preserves degrees).

Remark. In this case, A_0 is naturally a k -algebra, and A may be viewed as a graded A_0 -algebra with base ring A_0 instead of k .

In many situations one further assumes that $A_0 = k$. In this case, A_0 coincides with the base ring, and A may equivalently be viewed as a graded A_0 -algebra.

Proposition 1.5. Let $A = \bigoplus_{n \geq 0} A_n$ be a graded ring. Then the following statements are equivalent:

1. A is a Noetherian ring.
2. A_0 is Noetherian and A is finitely generated as A_0 -algebra (A_0 -ring)

We give a graded ring of particular importance in commutative algebra.

Definition 1.6. Let k be commutative ring (usually a field). A **standard graded k -algebra** is a graded k -algebra $A = \bigoplus_{n \geq 0} A_n$ such that A is generated by A_1 as a k -algebra.

§1.2 Increasing filtration

Definition 1.7. Let A be a ring. A **increasing filtration** of A is a sequence of subgroups $\{F_i A\}$ of A such that

- (i) $F_0 A \subset F_1 A \subset F_2 A \subset \dots \subset F_n A \subset \dots \subset A$
- (ii) $\bigcup_{i \geq 0} F_i A = A$.
- (iii) $F_i A \cdot F_j A \subseteq F_{i+j} A$ for all i, j .

A is called a **filtered ring** if it has an increasing filtration.

Proposition 1.8. Let A be a ring.

1. If $A = \bigoplus_{i \geq 0} A_i$ is a graded ring, then the sequence of subgroups $\{F_k A := \bigoplus_{i=0}^k A_i\}$ is an increasing filtration of A .

2. If $\mathcal{F} = \{F_i A\}$ is a filtration of A , then

$$\text{gr}_{\mathcal{F}} A := \bigoplus_{i \geq 0} F_{i+1} A / F_i A$$

is a graded ring (multiplication follows from A), called the **associated graded ring of A associated with the filtration \mathcal{F}** .

Remark. Noted that the associated graded ring $\text{gr}_{\mathcal{F}} A$ depends on the filtration \mathcal{F} and not isomorphic to A in general.

Definition 1.9. Let A be a filtered ring with increasing filtration $\mathcal{F} = \{F_i A\}$. A left A -module M is called a **filtered left A -module** if it has a sequence of subgroups $\Gamma = \{\Gamma_i M\}$ such that

$$(i) \quad \Gamma_0 M \subset \Gamma_1 M \subset \Gamma_2 M \subset \cdots \subset \Gamma_n M \subset \cdots \subset M$$

$$(ii) \quad \bigcup_{i \geq 0} \Gamma_i M = M$$

$$(iii) \quad F_i A \cdot \Gamma_j M \subseteq \Gamma_{i+j} M \text{ for all } i, j.$$

Proposition 1.10. The **graded module of M associated with the filtration Γ** is defined by

$$\text{gr}_{\Gamma} M = \bigoplus_{i \geq 0} \Gamma_{i+1} M / \Gamma_i M$$

which is a graded $\text{gr}_{\mathcal{F}} A$ -module.

Definition 1.11. Let A be a ring, \mathfrak{a} an ideal of A and M an A -module.

1. A **(increasing) filtration** of M one means an sequence of submodules $\mathcal{F} = \{F_i M\}$

$$\cdots \subset F_{n+1} M \subset F_n M \subset F_{n-1} M \subset \cdots \subset M$$

Remark. A descending filtration of M one means a sequence of submodules

$$M = F^0 M \supset F^1 M \supset F^2 M \supset \cdots \supset F^n M \supset \cdots$$

A increasing filtration of M one means a sequence of submodules

$$F_0 M \subset F_1 M \subset F_2 M \subset \cdots \subset F_n M \subset \cdots \subset M$$

with union $\bigcup_{n=0}^{\infty} F_n M = M$.

In this chapter, we shall only consider descending filtrations.

2. We say that it is an **\mathfrak{a} -filtration** if $\mathfrak{a} F^n M \subset F^{n+1} M$ for all n .

3. We say that an \mathfrak{a} -filtration is **\mathfrak{a} -stable** if we have $\mathfrak{a} F^n M = F^{n+1} M$ for all n sufficiently large.

Lemma 1.12. *If $(M_n), (M'_n)$ are stable \mathfrak{a} -filtrations of M , then they have bounded difference: that is, there exists an integer n_0 such that $M_{n+n_0} \subseteq M'_n$ and $M'_{n+n_0} \subseteq M_n$ for all $n \geq 0$.*

Proof. Enough to take $M'_n = \mathfrak{a}^n M$. Since $\mathfrak{a}M_n \subseteq M_{n+1}$ for all n , we have $\mathfrak{a}^n M \subseteq M_n$; also $\mathfrak{a}M_n = M_{n+1}$ for all $n \geq n_0$ say, hence $M_{n+n_0} = \mathfrak{a}^n M_{n_0} \subseteq \mathfrak{a}^n M$. \square

§2 First associated graded ring

Definition 2.1. *Let A be a ring, ideal \mathfrak{a} and A -module M filtered by \mathfrak{a} -filtration $\{M_n\}$.*

1. *We can form a first associated graded ring*

$$S = S_{\mathfrak{a}}(A) = \bigoplus_{n=0}^{\infty} \mathfrak{a}^n$$

$$\mathfrak{a}^0 = A.$$

Remark. *It is also a A -algebra called **Rees algebra**, with the homomorphism $A \rightarrow S_{\mathfrak{a}}(A)$ defined by $a \mapsto (a, 0, 0, \dots)$.*

2. *Then $M_S = \bigoplus_n M_n$ is a graded $S_{\mathfrak{a}}(A)$ -module.*

Remark. *If A is Noetherian, \mathfrak{a} is generated by x_1, \dots, x_r ; then $S_{\mathfrak{a}}(A) = A[x_1, \dots, x_r]$ and is Noetherian.*

Lemma 2.2. *Let A be a Noetherian ring, ideal \mathfrak{a} , and M a finitely generated module, with an \mathfrak{a} -filtration. Then M_S is finite over $S_{\mathfrak{a}}(A)$ if and only if the filtration of M is \mathfrak{a} -stable.*

Theorem 2.3 (Artin-Rees). *Let A be a Noetherian ring, \mathfrak{a} an ideal, M a finite A -module with a stable \mathfrak{a} -filtration. Let N be a submodule, and let $N_n = N \cap M_n$. Then $\{N_n\}$ is a stable \mathfrak{a} -filtration of N .*

Corollary 2.4. *Let A be a Noetherian ring, M a finite A -module, and N a submodule. Let \mathfrak{a} be an ideal. There exists an integer s such that for all integers $n \geq s$ we have*

$$\mathfrak{a}^n M \cap N = \mathfrak{a}^{n-s} (\mathfrak{a}^s M \cap N)$$

§3 Second associated graded ring

Definition 3.1. *Let A be a ring, \mathfrak{a} an ideal and M an A -module with an \mathfrak{a} -filtration $\{M_n\}$.*

1. *We define the second associated graded ring*

$$\text{gr}_{\mathfrak{a}}(A) = \bigoplus_{n=0}^{\infty} \mathfrak{a}^n / \mathfrak{a}^{n+1}.$$

$$\text{where } \mathfrak{a}^0 = A.$$

2. We define

$$\text{gr}(M) = \bigoplus_{n=0}^{\infty} M_n / M_{n+1}$$

then $\text{gr}(M)$ is a graded $\text{gr}_{\mathfrak{a}}(A)$ -module.

Proposition 3.2. Let A be a Noetherian ring and \mathfrak{a} an ideal. Then

1. $\text{gr}_{\mathfrak{a}}(A)$ is Noetherian.
2. If M is a finitely generated A -module with a stable \mathfrak{a} -filtration, then $\text{gr}(M)$ is a finitely generated graded $\text{gr}_{\mathfrak{a}}(A)$ -module.

Chapter VIII

Dimension

§1 Hilbert Functions

Definition 1.1. Let \mathcal{A} be a abelian category. A **additive function** $\lambda : \mathcal{A} \rightarrow \mathbf{Ab}$ is a covariant functor such that for every short exact sequence

$$0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$$

in \mathcal{A} , we have

$$\lambda(M) = \lambda(M') + \lambda(M'')$$

In the following, $\lambda(N)$ is a finitely generated abelian group and we always view $\lambda(N)$ as the rank of $\lambda(N)$.

Definition 1.2. Let $R = \bigoplus_{n \geq 0} R_n$ be a commutative Noetherian graded ring, $M = \bigoplus_{n \geq 0} M_n$ a finitely generated graded R -module and assume that each M_n is a finitely generated R_0 -module with a additive function λ .

1. The **Hilbert function** of M with respect to λ is the function defined by

$$h_M^\lambda(n) := \lambda(M_n) : \mathbb{N} \rightarrow \mathbb{N}$$

2. the **Hilbert-Poincare series** of M

$$P_M^\lambda(t) := \sum_{n=0}^{\infty} h_M^\lambda(n) t^n$$

Remark. If R_0 is Artinian ring, $\lambda(N) = \ell_{R_0}(N)$. If R_0 is a field, $\lambda(N) = \dim_{R_0}(N)$.

Theorem 1.3 (Hilbert-Serre). The Poincare series $P_M^\lambda(t)$ is a rational function of the form

$$\frac{f(t)}{\prod_{i=1}^s (1 - t^{k_i})}$$

, where $f(t) \in \mathbb{Z}[t]$ and s be the number of generators of $R_0 R$ and k_i are the degrees of the homogeneous generators x_i respectively.

Proof. By induction on s , the number of generators of R over R_0 . Start with $s = 0$; this means that $R_n = 0$ for all $n > 0$, so that $R = R_0$ and M is a finitely generated R_0 module, hence $M_n = 0$ for all large n . Thus $P_M^\lambda(t)$ is a polynomial in this case.

Now suppose $s > 0$ and the theorem true for $s - 1$. Multiplication by x_s is an R -module homomorphism of M_n into M_{n+k_s} , hence it gives an exact sequence, say

$$0 \rightarrow K_n \rightarrow M_n \xrightarrow{x_s} M_{n+k_s} \rightarrow L_{n+k_s} \rightarrow 0.$$

Let $K = \bigoplus_n K_n, L = \bigoplus_n L_n$; these are both finitely-generated A -modules (because K is a submodule and L a quotient module of M), and both are annihilated by x_s , hence they are $A_0[x_1, \dots, x_{s-1}]$ -modules. Applying λ to (1) we have, by (2.11)

$$\lambda(K_n) - \lambda(M_n) + \lambda(M_{n+k_s}) - \lambda(L_{n+k_s}) = 0;$$

multiplying by t^{n+k_s} and summing with respect to n we get

$$(1 - t^{k_s}) P(M, t) = P(L, t) - t^{k_s} P(K, t) + g(t)$$

where $g(t)$ is a polynomial. Applying the inductive hypothesis the result now follows. \square

Corollary 1.4 (Existence of the Hilbert polynomial). *Then there exists a polynomial $H(t) \in \mathbb{Q}[t]$ of degree $\dim M$ such that $H(n) = h_M^\lambda(n)$ for all sufficiently large integers n .*

*This polynomial is called the **Hilbert polynomial** of M with respect to λ .*

Corollary 1.5. *There exists a $\chi(t, R, M) \in \mathbb{Q}[t]$ of degree $\dim M$ such that*

$$\sum_{i=0}^n \lambda(M_i) = \chi(n)$$

for all sufficiently large integers n .

Definition 1.6. *The **multiplicity** of M with respect to λ is defined to be*

$$e(M, \lambda) := d! \cdot a_{d(M)}$$

where $a_{d(M)}$ is the leading coefficient of the Hilbert polynomial $\chi(t)$.

§2 Krull Dimension

In this section, all rings A are commutative Noetherian ring with identity and modules M are finitely generated A -module. Although some definitions and results hold in greater generality, the most of useful properties stay in this case.

Definition 2.1. Let A -module M .

1. The **Krull dimension** of A is defined to be the supremum of the lengths n of all chains of prime ideals

$$\mathfrak{p}_0 \subsetneq \mathfrak{p}_1 \subsetneq \cdots \subsetneq \mathfrak{p}_n$$

say $\dim(A) = n$ if the supremum is attained, and $\dim(A) = \infty$ otherwise.

2. The **Krull dimension** of A -module M is defined to be the dimension of the quotient ring $A/\text{Ann}(M)$, that is,

$$\dim(M) := \dim(A/\text{Ann}(M))$$

Proposition 2.2.

1. $\dim A = \dim \text{Spec } A$
2. If A is a local ring with maximal ideal \mathfrak{m} , then $\dim A = \sup \{n : \mathfrak{p}_0 \subsetneq \mathfrak{p}_1 \subsetneq \cdots \subsetneq \mathfrak{p}_n = \mathfrak{m}\}$
3. if S is a multiplicatively closed subset of A , then $\dim S^{-1}A \leq \dim A$

Definition 2.3. Let A be a commutative ring and \mathfrak{p} a prime ideal of A . The **height** of \mathfrak{p} is defined to be

$$\text{ht}(\mathfrak{p}) := \sup \{n : \mathfrak{p}_0 \subsetneq \mathfrak{p}_1 \subsetneq \cdots \subsetneq \mathfrak{p}_n = \mathfrak{p}\}$$

Thus $\dim A = \sup_{\mathfrak{p} \in \text{Spec } A} \text{ht}(\mathfrak{p})$.

Theorem 2.4 (Krull Principal Ideal Theorem). Let A be a Noetherian commutative ring and a ideal $\mathfrak{a} = (f_1, \dots, f_r)$. If \mathfrak{p} is a minimal element of $\{\mathfrak{q} \in \text{Spec } A : \mathfrak{a} \subset \mathfrak{q}\}$. Then $\text{ht}(\mathfrak{p}) \leq r$.

Part II

The Structure of Rings

Chapter IX

The Structure of Rings

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§1 Simplicity and Primitivity

Definition 1.1. A ring R is said to be **simple** if R has no proper two-sided ideals.

Definition 1.2. A left module M over a ring R is said to be **simple** (or **irreducible**) if M has no proper submodules.

Remark. A left ideal \mathfrak{a} of R is a simple left R -module if and only if \mathfrak{a} is a minimal left ideal of R . In this case, we call \mathfrak{a} the **simple left ideal** of R .

Proposition 1.3. Let R be a ring and M be a simple R -module, then

1. $M = Rm$ for every $0 \neq m \in M$.
2. If $0 \neq u \in M$, then $M \cong R/\text{Ann}(u)$, thus $\text{Ann}(u)$ is a left maximal ideal.

Conversely, if \mathfrak{m} is left maximal in R , then R/\mathfrak{m} is a simple R -module with $\text{Ann}(R/\mathfrak{m}) = \mathfrak{m}$

3. If R is not a division ring, then M is a torsion module.

Lemma 1.4 (Schur). Let M be a simple module over a ring R and let N_i be any R -module.

1. Every nonzero R -module homomorphism $f : M \rightarrow N_1$ is a monomorphism;
2. Every nonzero R -module homomorphism $g : N_2 \rightarrow M$ is an epimorphism;
3. The endomorphism ring $D = \text{Hom}_R(M, M)$ is a division ring, then M is a vector space over $\text{Hom}_R(M, M)$ with $fa = f(a)$

§1.1 Primitivity

Definition 1.5. Let R be a ring.

1. A ring R is said to be **left** [resp. **right**] **primitive** if there exists a simple faithful left [resp. right] R -module.
2. An ideal \mathfrak{a} of a ring R is said to be **left** [resp. **right**] **primitive** if the quotient ring R/\mathfrak{a} is a left [resp. right] primitive ring.

Remark. If M is a simple left R -module, then $R/\text{Ann}(M)$ is left primitive with faithful simple left $R/\text{Ann}(M)$ -module M .

Proposition 1.6. Let R be a ring.

1. A simple ring R is primitive.
2. A commutative ring R is primitive if and only if R is a field.

Proof. 1. Since R has an identity, R contains a maximal left ideal \mathfrak{m} by ??, whence R/\mathfrak{m} is a simple R -module. Since $\text{Ann}(R/\mathfrak{m})$ is an ideal of R that does not contain 1_R , $\text{Ann}(R/\mathfrak{m}) = 0$ by simplicity of R . Therefore R/\mathfrak{m} is a faithful R -module.

2. Conversely, let M be a faithful simple left R -module. Then $M \cong R/I$ for some maximal ideal I of R . Therefore, $0 = \text{Ann}(M) = \text{Ann}(R/I) \supset I$. Then $I = 0$ is a maximal ideal of R , thus R is a field. \square

§1.2 Jacobson Density Theorem

Definition 1.7. Let V be a vector space over a division ring D . A subring R of $\text{Hom}_D(V, V)$ is called a **dense ring of endomorphisms** of V if for every positive integer n , every linearly independent subset $\{u_1, \dots, u_n\}$ of V and every arbitrary subset $\{v_1, \dots, v_n\}$ of V , there exists $f \in R$ such that $f(u_i) = v_i$, $(i = 1, 2, \dots, n)$.

Theorem 1.8. Let R be a dense ring of endomorphisms of a vector space V over a division ring D . Then R is Artinian if and only if $\dim_D V$ is finite, in which case $R = \text{Hom}_D(V, V) \cong M_n(D)$.

Proof. If R is Artinian and $\dim_D V$ is infinite, then there exists an infinite linearly independent subset $\{u_1, u_2, \dots\}$ of V . By V is a left $\text{Hom}_D(V, V)$ -module and hence a left R -module. For each n let $I_n = \text{Ann}\{u_1, \dots, u_n\}$. Then $I_1 \supset I_2 \supset \dots$ is a descending chain of left ideals of R and hence $I_1 \supsetneq I_2 \supsetneq \dots$ is a properly descending chain, which is a contradiction. Hence $\dim_D V$ is finite.

Conversely if $\dim_D V$ is finite, then V has a finite basis $\{v_1, \dots, v_m\}$. Then $R = \text{Hom}_D(V, V) \cong M_n(D)$ is Artinian. \square

Lemma 1.9. Let M be a simple module over a ring R . Consider M as a vector space over the division ring $D = \text{Hom}_R(M, M)$ by 1.4. If V is a finite dimensional D -subspace of M and $a \in M - V$, then there exists $r \in R$ such that $ra \neq 0$ and $rV = 0$.

Remark. In other words, the element $r \in \text{Ann}_R(V)$ only annihilates D -subspace V .

Proof. The proof is by induction on $n = \dim_D V$. If $n = 0$, then $V = 0$ and $a \neq 0$. Since M is simple, $M = Ra$. Consequently, there exists $r \in R$ such that $ra = a \neq 0$ and $rV = r0 = 0$.

Suppose now $\dim_D V = n > 0$ and the theorem is true for dimensions less than n . Let $\{u_1, \dots, u_{n-1}, u\}$ be a D -basis of V and let $W = \text{span}\{u_1, \dots, u_{n-1}\}$ ($W = 0$ if $n = 1$). Then $V = W \oplus Du$ (vector space direct sum, W may not be an R -submodule of M) the left annihilator $I = \text{Ann}_R(W)$ is a left ideal of R .

Consequently, Iu is an R -submodule of M . Since $u \in M - W$, the induction hypothesis implies that there exists $r \in R$ such that $ru \neq 0$ and $rW = 0$. Consequently $r \in I$ and $0 \neq ru \in Iu$, whence $Iu \neq 0$. Therefore $M = Iu$ by simplicity.

We must find $r \in R$ such that $ra \neq 0$ and $rV = 0$. If no such r exists, $\text{Ann}(a) \subset \text{Ann}(V)$, then we can define a map $\theta : M \rightarrow M$ as follows. For $ru \in Iu = M$ let $\theta(ru) = ra \in M$. We claim that θ is well defined. If $r_1u = r_2u$ ($r_i \in I$), then $(r_1 - r_2)u = 0$, whence $(r_1 - r_2)V = (r_1 - r_2)(W \oplus Du) = 0$. Consequently by hypothesis $(r_1 - r_2)a = 0$. Therefore, $\theta(r_1u) = r_1a = r_2a = \theta(r_2u)$. Verify that $\theta \in \text{Hom}_R(M, M) = D$. Then for every $r \in I$,

$$0 = \theta(ru) - ra = r\theta(u) - ra = r(\theta(u) - a)$$

Therefore $\theta(u) - a \in W$ by induction hypothesis. Consequently

$$a = \theta u - (\theta u - a) \in Du + W = V,$$

which contradicts the fact that $a \notin V$. Therefore, there exists $r \in R$ such that $ra \neq 0$ and $rV = 0$. \square

Theorem 1.10 (Classic Jacobson Density Theorem). *Let R be a primitive ring with a faithful simple R -module M and division ring $D = \text{End}_R(M)$. Then R is a dense ring of endomorphisms of the D -vector space M (viewed $\alpha : R \hookrightarrow \text{Hom}_R(M, M)$ by $r \mapsto \alpha_r$ where $\alpha_r : m \mapsto rm$ in M).*

Remark. If R is not primitive, then R is not a subring of $\text{Hom}_R(M, M)$. But $R/\text{Ann}(M)$ is primitive with faithful simple left $R/\text{Ann}(M)$ -module M with the action of \bar{r} on M which is same as that of r on M , so we also can say that R acts on simple M densely i.e. for every positive integer n , every linearly independent subset $\{u_1, \dots, u_n\}$ and every arbitrary subset $\{v_1, \dots, v_n\}$, there exists $r \in R$ such that $ru_i = v_i$, ($i = 1, 2, \dots, n$).

Proof. It clear that $\alpha : R \rightarrow \text{Hom}_D(M, M)$ is a ring monomorphism since M is faithful. Let $\{u_1, u_2, \dots, u_n\}$ be a D -linearly independent subset and $\{v_1, v_2, \dots, v_n\}$ be an arbitrary subset. For each i let

$$V_i = \text{span}\{u_1, \dots, u_{i-1}, u_{i+1}, \dots, u_n\}.$$

Since U is D -linearly independent, $u_i \notin V_i$. Consequently, by 1.9 there exists $r_i \in R$ such that

$$r_i u_i \neq 0 \text{ and } r_i V_i = 0$$

whence $Rr_i u_i = M$ by simplicity. Therefore exists $t_i \in R$ such that $t_i r_i u_i = v_i$. Let

$$r = t_1 r_1 + t_2 r_2 + \cdots + t_n r_n \in R.$$

Consequently for each $i = 1, 2, \dots, n$

$$\alpha_r(u_i) = (t_1 r_1 + \cdots + t_n r_n) u_i = v_i$$

Therefore $\text{Im } \alpha$ is a dense ring of endomorphisms of the D -vector space M . \square

§2 Simple ring

Corollary 2.1. *If R is a nonzero simple ring, then*

$$R \cong \alpha(R) \subseteq \text{End}_D(V)$$

for some faithful simple R -module V and division ring $D = \text{End}_R(V)$.

Corollary 2.2. *If R is a primitive ring, then for some division ring D either R is isomorphic to the endomorphism ring of a finite dimensional vector space over D or for every positive integer m there is a subring R_m of R and an epimorphism of rings $R_m \rightarrow \text{Hom}_D(V_m, V_m)$, where V_m is an m -dimensional vector space over D .*

Proof. In the notation of 1.10,

$$\alpha : R \rightarrow \text{Hom}_D(M, M)$$

is a monomorphism such that $R \cong \text{Im } \alpha$ and $\text{Im } \alpha$ is dense in $\text{Hom}_D(M, M)$. If $\dim_D M = n$ is finite, then $R \cong \text{Im } \alpha = \text{Hom}_D(M, M)$ by 1.8. If $\dim_D A$ is infinite and $\{u_1, u_2, \dots\}$ is an infinite linearly independent set, let V_m be the m -dimensional D -subspace of A spanned by $\{u_1, \dots, u_m\}$. Verify that $R_m = \{r \in R \mid rV_m \subset V_m\}$ is a subring of R . Use the density of $R \cong \text{Im } \alpha$ in $\text{Hom}_D(M, M)$ to show that the map $R_m \rightarrow \text{Hom}_D(V_m, V_m)$ given by $r \mapsto \alpha_r|_{V_m}$ is a well-defined ring epimorphism. \square

Theorem 2.3 (Wedderburn-Artin). *The following conditions on a ring R are equivalent.*

1. R is simple Artinian.
2. R is primitive Artinian.
3. R is isomorphic to $M_n(D)$ for some positive integer n and some division ring D .

In this case, D is isomorphic to $\text{Hom}_R(M, M)$ for any simple left R -module M and $n = \dim_D M$.

Proof. (1) \Rightarrow (2) This is clear since a simple ring is primitive.

(2) \Rightarrow (3) Let M be a faithful simple left R -module. By theorem 1.10, R is isomorphic to a dense ring of endomorphisms of the D -vector space M , where $D = \text{Hom}_R(M, M)$. Since R is left Artinian, $\dim_D M$ is finite by theorem 1.8. Therefore $R \cong \text{Hom}_D(M, M) \cong M_n(D)$, where $n = \dim_D M$.

(3) \Rightarrow (1) Since $M_n(D)$ is left Artinian, it suffices to show that $M_n(D)$ is simple. Let \mathfrak{a} be a nonzero two-sided ideal of $M_n(D)$ and let $0 \neq A = (a_{ij}) \in \mathfrak{a}$. Then there exist indices p, q such that $a_{pq} \neq 0$. For any indices i, j , let E_{ij} be the matrix unit whose (i, j) -entry is 1 and all other entries are 0. Then

$$E_{ip}AE_{qj} = a_{pq}E_{ij} \in \mathfrak{a}$$

□

Lemma 2.4. *Let V be a nonzero vector space over a division ring D . If $g : V \rightarrow V$ is a homomorphism of additive groups such that $gf = fg$ for all $f \in \text{Hom}_D(V, V)$, then there exists $\lambda \in D$ such that $g(x) = \lambda x$ for all $x \in V$.*

Lemma 2.5. *Let V be a finite dimensional vector space over a division ring D . If M and N are simple faithful modules over $R = \text{Hom}_D(V, V)$, then M and N are isomorphic R -modules.*

Proof. Since M and N are simple and faithful, we have $\text{Ann}(M) = 0$ and $\text{Ann}(N) = 0$. By lemma 1.4, we have $\text{Hom}_R(M, N) \cong \text{Hom}_D(V, V)$, which is a division ring. Thus M and N are isomorphic as R -modules. □

Proposition 2.6. *For $i = 1, 2$ let V_i be a vector space of finite dimension n_i over the division ring D_i .*

1. *If there is an isomorphism of rings $\text{Hom}_{D_1}(V_1, V_1) \cong \text{Hom}_{D_2}(V_2, V_2)$, then $\dim_{D_1} V_1 = \dim_{D_2} V_2$ and D_1 is isomorphic to D_2 .*
2. *If there is an isomorphism of rings $M_{n_1}(D_1) \cong M_{n_2}(D_2)$, then $n_1 = n_2$ and D_1 is isomorphic to D_2 .*

Chapter X

Semisimplicity

§1 Definitions

Theorem 1.1. *Let R be a ring and M a left R -module. The following conditions on M are equivalent:*

1. *M is the sum of a family of simple submodules.*
2. *M is the direct sum of a family of simple submodules.*
3. *Every submodule N is a direct summand of M .*

Proof. (1) \Rightarrow (2) Let \mathcal{S} be the set of all families \mathcal{F} of simple submodules of M such that the sum of the members of \mathcal{F} is direct. Since M is the sum of a family of simple submodules, \mathcal{S} is nonempty. Partially order \mathcal{S} by inclusion and let \mathcal{C} be a chain in \mathcal{S} . Then $\mathcal{U} = \bigcup_{\mathcal{F} \in \mathcal{C}} \mathcal{F}$ is an upper bound for \mathcal{C} in \mathcal{S} . By Zorn's lemma there exists a maximal element \mathcal{F}_0 in \mathcal{S} . We claim that $M = \bigoplus_{N \in \mathcal{F}_0} N$. If not, there exists a simple submodule K of M such that

$$K \cap \left(\bigoplus_{N \in \mathcal{F}_0} N \right) = 0.$$

Consequently, $\mathcal{F}_0 \cup \{K\} \in \mathcal{S}$, contradicting the maximality of \mathcal{F}_0 .

(2) \Rightarrow (3) Let $M = \bigoplus_{i \in I} N_i$, where each N_i is a simple submodule of M , and let N be a submodule of M . For each $i \in I$, either $N_i \subset N$ or $N_i \cap N = 0$ by simplicity. Let $J = \{i \in I \mid N_i \subset N\}$ and $K = I - J$. Then

$$M = N \oplus \left(\bigoplus_{i \in K} N_i \right).$$

(3) \Rightarrow (1) Let N be the sum of all simple submodules of M . By hypothesis, $M = N \oplus P$ for some submodule P . \square

Remark. A left R -module M satisfying the three conditions is said to be **semisimple**. Similarly one defines a right semisimple module.

Proposition 1.2. *Every submodule and every factor module of a left semisimple module is left semisimple.*

§2 Structure of semisimple rings

Definition 2.1. *A ring R is called **semisimple** if $1 \neq 0$, and if R is semisimple as a left R -module.*

Proposition 2.2. *If R is a semisimple ring, then R is Artinian.*

Proof. Since $_R R$ is semisimple module, there exist simple left ideals L_j of R such that

$${}_R R \cong \bigoplus_{j \in J} L_j$$

with projection maps $\pi_j : R \rightarrow L_j$ for each $j \in J$. Since the sum is direct, $\{j_k : \pi_{j_k}(1_R) \neq 0\}$ is finite. Then $J = \{j_k : \pi_{j_k}(1_R) \neq 0\}$ is finite and

$${}_R R \cong L_1 \oplus L_2 \oplus \cdots \oplus L_n$$

Therefore ring R is Artinian. □

Remark. *It is clear that any simple ideal L of R is isomorphic to some L_j , thus R has finitely many minimal left ideals up to isomorphism.*

Lemma 2.3. *If L and L' are minimal left ideals in a ring R , then each of the following statements implies the one below it:*

1. $LL' \neq (0)$.
2. $\text{Hom}_R(L, L') \neq \{0\}$ and there exists $b' \in L'$ with $L' = Lb'$.
3. $L \cong L'$ as left R -modules.

If also $L^2 \neq (0)$, then (iii) implies (i) and the three statements are equivalent.

Theorem 2.4 (Wedderburn-Artin). *If R is a semisimple ring, then we have ring isomorphisms*

$$R \cong \prod_{i=1}^t R_i \cong \prod_{i=1}^t M_{n_i}(D_i)$$

where $R_i \cong M_{n_i}(D_i)$ is a simple ring for each $i \in I$.

Proof. Let $\{L_{j_i}\}_{i=1}^t$ be all distinct simple left ideals of R up to isomorphism and define R_i be the sum

$${}_R R_i := \bigoplus_{L_j \cong L_i} L_j$$

Thus, as left R -modules,

$${}_R R \cong \bigoplus_{i=1}^t {}_R R_i.$$

Then R_i is a two-sided ideal of R by [lemma 2.3](#) and hence a ring with identity element $e_i = \pi_i(1_R)$ (π_i the projection from R to R_i). The projection from R to R_i induce a ring homomorphism

$$R \cong \prod_{i=1}^t R_i$$

It remains to show that each R_i is simple. Let I be a nonzero two-sided ideal of R_i , then I is a left ideal of R . Since R is semisimple, there exists a left ideal J of R such that

$$R = I \oplus J$$

Then

$$R_i = e_i R = e_i I + e_i J \subset I$$

Thus R_i is simple. □

§3 Structure of modules over semisimple rings

§3.1 Modules over $M_n(D)$

Proposition 3.1. *Let $R = M_n(D)$ for some division ring D and positive integer n .*

1. *If S is a left R -module, then*

$${}_R S \cong {}_R D^n$$

2. *every left R -module is isomorphic to $({}_R D^n)^{(I)}$ for some index set I .*

Corollary 3.2. *There is, up to isomorphism, only one simple left module over a Artinian simple ring R ; namely, the left R -module Re , where e is any primitive idempotent of R .*

§3.2 Modules over semisimple rings

Theorem 3.3. *Let semisimple ring*

$$R \cong \prod_{i=1}^t R_i$$

where each $R_i \cong M_{n_i}(D_i)$. Then every left R -module M is isomorphic to

$$\bigoplus_{i=1}^t e_i M \cong \bigoplus_{i=1}^t S_i^{(\kappa_i)}$$

where $e_i M \cong S_i$ is the unique simple left R_i -module and κ_i is a cardinal number. And the decomposition is unique in the sense that if

$$M \cong \bigoplus_{i=1}^t S_i^{(\kappa_i)} \cong \bigoplus_{i=1}^t S_i^{(\kappa'_i)}$$

then $\kappa_i = \kappa'_i$ for each i

Remark. If M is finitely generated, then each κ_i is finite.

§4 Jacobson Radical

Definition 4.1. Let R be a ring. A element $x \in R$ is said to be **right quasi-regular** if there exists $y \in R$ such that $x + y - xy = 0$, y is called a **right quasi-inverse** of x .

Remark. That is, $1 - x$ has a right inverse $1 - y$.

Definition 4.2. A element $a \in R$ is said **right quasi-nilpotent element** if for every $r \in R$, ra is right quasi-regular.

Remark. That is, $1 - ra$ has a right inverse for every $r \in R$.

§4.1 Jacobson radical

Theorem 4.3. Let R be a ring, then the following sets are equal:

1. the intersection of all maximal left ideals of R
- 1' the intersection of all maximal right ideals of R
2. the intersection of all the annihilators of simple left R -modules;
- 2' the intersection of all the annihilators of simple right R -modules;
3. $\{x \in R : x \text{ is right quasi-nilpotent element}\}$
- 3' $\{x \in R : x \text{ is left quasi-nilpotent element}\}$
4. Nakayama's $\{x \in R : \text{for any finitely generated module } M, xM = M \Rightarrow M = 0\}$
5. the ideal J such that R/J is semisimple.

the two-sided ideal is called the **Jacobson radical** of R and is denoted by $J(R)$.

Corollary 4.4. 1. $J(\prod_{i \in I} R_i) = \prod_{i \in I} J(R_i)$.

2. $J(J(R)) = J(R)$.

3. $R/J(R)$ is semisimple.

Proposition 4.5. If R is a Artinian ring, then the radical $J(R)$ is a nilpotent ideal. Thus $J(R) = \text{Rad}(R)$

Proof. Since R is Artinian, the descending chain of ideals

$$J(R) \supseteq J(R)^2 \supseteq J(R)^3 \supseteq \dots$$

stabilizes, say $J(R)^n = J(R)^{n+1}$ for some positive integer n . On the other hand, $_R R$ is Noetherian thus $J(R)^n$ is finitely generated submodule of $_R R$ and $J(R)^n = 0$ by Nakayama's lemma. \square

Proposition 4.6. Let R be a ring. $J(M_n R) = M_n(J(R))$.

Proof. (a) If A is a left R -module, consider the elements of $A^n = A \oplus A \oplus \dots \oplus A$ (n summands) as column vectors; then A^n is a left $(\text{Mat}_n R)$ -module (under ordinary matrix multiplication).

(b) If A is a simple R -module, A^n is a simple $(\text{Mat}_n R)$ -module.

(c) $J(\text{Mat}_n R) \subset \text{Mat}_n J(R)$.

(d) $\text{Mat}_n J(R) \subset J(\text{Mat}_n R)$. [Hint: prove that $\text{Mat}_n J(R)$ is a left quasi-regular ideal of $\text{Mat}_n R$ as follows. For each $k = 1, 2, \dots, n$ let K_k consist of all matrices (a_{ij}) such that $a_{ij} \in J(R)$ and $a_{ij} = 0$ if $j \neq k$. Show that K_k is a left quasi-regular left ideal of $\text{Mat}_n R$ and observe that $K_1 + K_2 + \dots + K_n = \text{Mat}_n J(R)$.] \square

Corollary 4.7. Let R be a ring. If matrix $A \in M_n(J(R))$, then $I - A$ is invertible in $M_n(R)$.

§4.2 Nakayama's Lemma

Theorem 4.8 (Nakayama's lemma). Let M be a finitely generated left R -module and a subset $X \subset J(R)$. Then $\mathfrak{a}M = M$ implies $M = 0$.

Corollary 4.9. Let M be a finitely generated left R -module, N a submodule of M , left ideal $\mathfrak{a} \subset J(R)$. Then $M = \mathfrak{a}M + N \Rightarrow M = N$.

Corollary 4.10. If R is a Noetherian local ring with maximal ideal \mathfrak{m} , then $\bigcap_{n=1}^{\infty} \mathfrak{m}^n = 0$.

Proposition 4.11. If R is a local ring, then every finitely generated projective R -module is free.

Proof. If P is a finitely generated projective R -module, then by ?? there exists a free R -module F with a finite basis and an epimorphism $\pi : F \rightarrow P$. Among all the free R -modules F with this property choose one with a basis $\{x_1, x_2, \dots, x_n\}$ that has a minimal number of elements. Since π is an epimorphism $\{\pi(x_1), \dots, \pi(x_n)\}$ necessarily generate P .

We shall first show that $K = \text{Ker } \pi$ is contained in $\mathfrak{m}F$, where \mathfrak{m} is the unique maximal ideal of R .

If $K \not\subset \mathfrak{m}F$, then there exists $k \in K$ with $k \notin \mathfrak{m}F$. Now $k = r_1x_1 + r_2x_2 + \dots + r_nx_n$ with $r_i \in R$ uniquely determined. Since $k \notin \mathfrak{m}F$, some r_i , say r_1 , is not an element of \mathfrak{m} , thus r_1 is a unit, whence $x_1 - r_1^{-1}k = -r_1^{-1}r_2x_2 - \dots - r_1^{-1}r_nx_n$.

Consequently, since $k \in \text{Ker } \pi$, $\pi(x_1) = \pi(x_1 - r_1^{-1}k) = \sum_{i=2}^n -r_1 r_i \pi(x_i)$. Therefore, $\{\pi(x_2), \dots, \pi(x_n)\}$ generates P . Thus if F' is the free submodule of F with basis $\{x_2, \dots, x_n\}$ and $\pi' : F' \rightarrow P$ the restriction of π to F' , then π' is an epimorphism. This contradicts the choice of F as having a basis of minimal cardinality. Hence $K \subset \mathfrak{m}F$.

Since $0 \rightarrow K \hookrightarrow F \xrightarrow{\pi} P \rightarrow 0$ is exact and P is projective $K \oplus P \cong F$ by ???. Under this isomorphism $(k, 0) \mapsto k$ for all $k \in K$ (see the proof of Theorem IV.1.18), whence F is the internal direct sum $F = K \oplus P'$ with $P' \cong P$. Thus $F = K + P' \subset \mathfrak{m}F + P'$. If $u \in F$, then $u = \sum_i m_i v_i + p_i$ with $m_i \in \mathfrak{m}$, $v_i \in F$, $p_i \in P'$. Consequently, in the R -module F/P' ,

$$u + P' = \sum_i m_i v_i + P' = \sum_i m_i (v_i + P') \in \mathfrak{m}(F/P')$$

whence $\mathfrak{m}(F/P') = F/P'$. Since F is finitely generated, so is F/P' . Therefore $K \cong F/P' = 0$ by ???. Thus $P \cong P' = F$ and P is free. \square

§5 Characterizations of semisimple rings

Theorem 5.1. *The following conditions on a ring R are equivalent:*

1. *R is a semisimple ring.*
2. *Every left R -module is a semisimple module.*
3. *Every left R -module is injective.*
4. *Every left R -module is projective.*
5. *Every short exact sequence of left R -modules splits.*
6. *R is Artinian and $J(R) = 0$.*

§6 Algebra

Definition 6.1. *Let A be an algebra over a commutative ring K with identity.*

1. *A **left algebra A -module** is a left K -module M such that M is a left module over the ring A and $k(am) = (ka)m = a(km)$ for all $k \in K$, $a \in A$, $m \in M$. Indeed,*

$$\begin{cases} (k_1 a_1 + k_2 a_2)(m_1 + m_2) = k_1 a_1 m_1 + k_1 a_1 m_2 + k_2 a_2 m_1 + k_2 a_2 m_2 \\ k(am) = (ka)m = a(km) \\ 1_K m = m, 1_K a = a \end{cases}$$

for all $k \in K$, $a \in A$, $m \in M$

2. *A left algebra A -submodule of M is a subset of M which is itself an left algebra A -module.*

3. A left algebra A -module M is **simple** (or **irreducible**) if M has no proper A -submodules.
4. A homomorphism $f : M \rightarrow N$ of algebra A -modules is a map that is both a K -module and an A -module homomorphism.

Remark.

Theorem 6.2. Let A be a K -algebra. The Jacobson radical of the ring A coincides with the Jacobson radical of the algebra A . In particular A is a semisimple ring if and only if A is a semisimple algebra.

Theorem 6.3. Let A be a K -algebra.

- (1) Every simple algebra A -module is a simple module over the ring A .
- (2) Every simple module M over the ring A can be given a unique K -module structure in such a way that M is a simple algebra A -module.