

M4P55 Commutative Algebra

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Autumn 2019

Syllabus

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0 Introduction

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The prerequisites are

- groups,
- rings,
- fields, and
- a solid linear algebra.

This course is good for

- algebraic geometry, and
- algebraic number theory.

The following are books.

- M Reid, Undergraduate commutative algebra, 1995
- M F Atiyah and I G Macdonald, Introduction to commutative algebra, 1969

The following is the structure of the course.

- Generalities on rings, such as ideals, and examples.
- Localisation of rings between a ring R and the fraction field K of R , such as \mathbb{Z} and \mathbb{Q} .
- Finiteness conditions of Noetherian rings and Artinian rings.
- Integral closure and normal rings, such as $\mathbb{Z}[i] \subset \mathbb{Q}(i)$ and $\mathbb{Z}[\sqrt{-3}] \subset \mathbb{Z}\left[\frac{1+\sqrt{-3}}{2}\right] \subset \mathbb{Q}(\sqrt{-3})$.
- Discrete valuation rings.
- Completion of rings with topology.

1 Rings and ideals

Definition 1.1. A **commutative ring** is a set $(A, +, \cdot, 0, 1)$ such that

1. $(A, +, 0)$ is an abelian group,
2. for all $x, y, z \in A$,
 - $(x \cdot y) \cdot z = x \cdot (y \cdot z)$,
 - $x \cdot y = y \cdot x$,
 - $x \cdot (y + z) = x \cdot y + x \cdot z$, and
3. for all $x \in A$, $x \cdot 1 = 1 \cdot x = x$.

Remark 1.2.

- One is uniquely determined by 3, since $1' = 1' \cdot 1 = 1$.
- If $1 = 0$, then $0 = x \cdot 0 = x \cdot 1 = x$, since

$$x \cdot 0 = x \cdot (0 + 0) = x \cdot 0 + x \cdot 0,$$

so $x \cdot 0 = 0$. So every element is zero. Hence $R = \{0\}$.

Definition 1.3. A **homomorphism of rings** $f : A \rightarrow B$ is a map such that for all $x, y \in A$,

$$f(x + y) = f(x) + f(y), \quad f(xy) = f(x)f(y), \quad f(1) = 1.$$

Example. If $A \subset B$ is closed under $+$ and \cdot , and $1 \in A$, then

$$\begin{array}{ccc} A & \longrightarrow & B \\ x & \longmapsto & x \end{array}$$

is a homomorphism.

Remark 1.4.

- A composition of homomorphisms is a homomorphism.
- An **isomorphism** is a bijective homomorphism.

Definition 1.5. A subset I of a ring A is an **ideal** if I is a subgroup of the additive group $(A, +)$ which is closed under multiplication by elements of A , so $xI \subset I$ for any $x \in A$. Sometimes this is written as $I \triangleleft A$. In this case the **quotient group** A/I is naturally a ring, where $(x + I)(y + I)$ is defined as $xy + I$.

Proposition 1.6. Let I be an ideal of a commutative ring A . Then there is a natural bijection between the ideals $J \subset A$ such that $I \subset J$ and the ideals of A/I .

Proof. Let

$$\begin{array}{ccc} A & \longrightarrow & A/I \\ x & \longmapsto & x + I \end{array}$$

be the natural surjective map. Send J to its image under this map. □

Definition 1.7. If $f : A \rightarrow B$ is a homomorphism, then

$$\text{Ker } f = \{x \in A \mid f(x) = 0\}$$

is an ideal in A , and

$$\text{Im } f = f(A) \cong A / \text{Ker } f \subset B.$$

2 Polynomials and formal power series

Definition 2.1. Let R be a ring. The **polynomial ring** with coefficients in R is

$$R[x] = \{a_0 + \cdots + a_n x^n \mid a_i \in R, n \in \mathbb{Z}_{\geq 0}\}.$$

The addition is coefficient-wise, and the multiplication is given by the formula

$$\left(\sum_{i \geq 0} a_i x^i\right) \left(\sum_{j \geq 0} b_j x^j\right) = \sum_{i \geq 0} \left(\sum_{j+k=i, j \geq 0, k \geq 0} a_j b_k\right) x^i,$$

where all but finitely many coefficients are zero. Define

$$R[x_1, \dots, x_n] = R[x_1] \cdots [x_n] = \left\{ \sum_{i_1, \dots, i_n \geq 0} a_{i_1, \dots, i_n} x_1^{i_1} \cdots x_n^{i_n} \mid a_{i_1, \dots, i_n} \in R \right\},$$

where all but finitely many coefficients a_{i_1, \dots, i_n} are equal to zero.

Definition 2.2. The **ring of formal power series** with coefficients in R is

$$R[[t]] = \{a_0 + a_1 t + \dots \mid a_i \in R\}.$$

The addition is coefficient-wise, and the multiplication is given by the formula

$$\left(\sum_{i \geq 0} a_i t^i\right) \left(\sum_{j \geq 0} b_j t^j\right) = \sum_{i \geq 0} \left(\sum_{j+k=i, j \geq 0, k \geq 0} a_j b_k\right) t^i.$$

Define

$$R[[t_1, \dots, t_n]] = R[[t_1]] \cdots [[t_n]].$$

In $R[[t]]$ many products equal one unlike in $R[t]$, for example $(1-t)(1+t+\dots) = 1$.

3 Zero-divisors, nilpotents, units

Definition 3.1. Let A be a ring. An element $x \in A$ is a **zero-divisor** if $x \neq 0$ but $xy = 0$ for some $y \neq 0$ in A . A ring without zero-divisors is called an **integral domain**. An element $x \in A$ is **nilpotent** if $x^n = 0$ for some $n \in \mathbb{Z}_{>0}$. A **unit** $x \in A$ is an element such that $xy = 1$ for some $y \in A$. The units of A form a group under multiplication, denoted by A^* , or A^\times .

Definition 3.2. Let $x \in A$. Then the set

$$\langle x \rangle = \{xy \mid y \in A\}$$

is an ideal. Such ideals are called **principal ideals**.

Remark. $x \in A^*$ if and only if $\langle x \rangle = A$, and R is a field if and only if $R^* = R \setminus \{0\}$.

Proposition 3.3. Let A be a non-zero ring. Then the following are equivalent.

1. A is a field.
2. There are no ideals in A other than $\langle 0 \rangle$ and A .
3. Every non-zero homomorphism $f : A \rightarrow B$ is injective.

Proof.

1 \implies 2 Clear.

2 \implies 3 $\text{Ker } f \subset A$ is an ideal. Since $f \neq 0$, $\text{Ker } f \neq A$. Hence $\text{Ker } f = 0$.

3 \implies 1 Take any $x \neq 0$ in A . Look at $\langle x \rangle$. Define $B = A/\langle x \rangle$. Then take $f : A \rightarrow B$ to be the natural surjective map. If f is not identically zero, we get a contradiction with 3.

□

4 Prime ideals and maximal ideals

Definition 4.1. An ideal $I \subset A$ is called **prime** if $I \neq A$ and if whenever $xy \in I$, then $x \in I$ or $y \in I$. An ideal $J \subset A$ is called **maximal** if there is no ideal J' such that $J \subsetneq J' \subsetneq A$.

Notation. The set of prime ideals of A is called the **spectrum** of A and is denoted by $\text{Spec } A$.

Lemma 4.2. An ideal $I \subset A$ is prime if and only if A/I is an integral domain.

Proof. Obvious. □

Lemma 4.3. An ideal $J \subset A$ is maximal if and only if A/J is a field.

Proof. Obvious. □

Proposition 4.4. If $f : A \rightarrow B$ is a ring homomorphism and $I \subset B$ is a prime ideal, then $f^{-1}(I)$ is a prime ideal of A .

Proof. It is easy to see that $f^{-1}(I)$ is an ideal in A . Suppose $xy \in f^{-1}(I)$ for some $x, y \in A$. Then $f(x)f(y) = f(xy) \in I$. Since I is prime, $f(x) \in I$ or $f(y) \in I$, so $x \in f^{-1}(I)$ or $y \in f^{-1}(I)$. □

So we get a canonical map

$$\begin{aligned} f^* : \text{Spec } B &\longrightarrow \text{Spec } A \\ I \subset B &\longmapsto f^{-1}(I) \subset A \end{aligned}$$

Remark 4.5. If $f : A \rightarrow B$ is a ring homomorphism, then $f^{-1}(\mathfrak{p})$, where $\mathfrak{p} \subset B$ is a prime ideal, is a prime ideal. But this is false for maximal ideals. Let $A = \mathbb{Z}$, let $B = \mathbb{Q}$, and let $f(x) = x$. Then $\langle 0 \rangle \subset \mathbb{Q}$ is a maximal ideal and $f^{-1}(\langle 0 \rangle) = \langle 0 \rangle \subset \mathbb{Z}$ is not a maximal ideal. For example, $\langle 0 \rangle \subsetneq \langle 2 \rangle \subsetneq \mathbb{Z}$.

Theorem 4.6. Let A be a non-zero ring. Then A has at least one maximal ideal. In particular, $\text{Spec } A$ is not empty.

The proof is based on Zorn's lemma. Let S be a set. Then a **partial order** is a binary relation \leq such that

- $x \leq x$ for all $x \in S$,
- $x \leq y \leq z$ implies that $x \leq z$, and
- $x \leq y$ and $y \leq x$ imply that $x = y$,

where not all pairs are comparable. A **chain** $T \subset S$ is a subset in which every two elements are comparable.

Lemma 4.7 (Zorn). Suppose that S is a partially ordered set such that every chain $T \subset S$ has an upper bound, that is an element $t \in S$ such that $x \leq t$ for all $x \in T$. Then S has a maximal element, that is there exists $s \in S$ such that if $x \in S$ and $x \geq s$, then $x = s$.

Zorn's lemma is equivalent to the axiom of choice.

Proof of Theorem 4.6. Let Σ be the set of all ideals of A which are not equal to A . Then $\langle 0 \rangle \in \Sigma$, so $\Sigma \neq \emptyset$. Equip Σ with partial order given by inclusion. Enough to check the assumption of Zorn's lemma. Suppose T is a chain of ideals, so it is a collection of ideals J_i for $i \in T$. Consider instead

$$I = \bigcup_{i \in T} J_i.$$

Claim that T is a chain implies that I is an ideal. Then $x \in I$ implies that $x \in J_i$ for some i . Take any $x, y \in I$. Then $x \in J_i$ and $y \in J_k$ for some $i, k \in T$, so T is a chain, hence $i \leq k$ or $k \leq i$, so $J_i \subset J_k$ or $J_k \subset J_i$. Without loss of generality assume $J_i \subset J_k$. Then $x, y \in J_k$, so $x + y \in J_k \subset I$. Clearly, I is an upper bound. □

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Corollary 4.8. Any ideal of A is contained in a maximal ideal of A .

Proof. If $I \subset A$ is an ideal, apply Theorem 4.6 to A/I . □

Corollary 4.9. Any non-unit of A is contained in a maximal ideal.

Proof. Apply Corollary 4.8 to $\langle a \rangle$. □

Example. The maximal ideals of \mathbb{Z} are $\langle p \rangle$, where p is prime.

Definition 4.10. A ring A is **local** if A has exactly one maximal ideal.

Example. Any field is a local ring. If k is a field, then $k[[t]]$ is a local ring.

Lemma 4.11 (Prime avoidance). *Let A be a ring and let $\mathfrak{p} \subset A$ be a prime ideal. Suppose that I_1, \dots, I_n are ideals in A such that $\bigcap_{j=1}^n I_j \subset \mathfrak{p}$. Then $I_j \subset \mathfrak{p}$ for some j . If, moreover, $\bigcap_{j=1}^k I_j = \mathfrak{p}$, then $I_j = \mathfrak{p}$ for some j .*

Proof. Suppose that I_j is not a subset of \mathfrak{p} for any j . Then there exists $x_j \in I_j$ such that $x_j \notin \mathfrak{p}$. Hence

$$x_1, \dots, x_n \in I_1 \dots I_n \subset \bigcap_{j=1}^n I_j \subset \mathfrak{p},$$

so $x_1(x_2 \dots x_n) \in \mathfrak{p}$. Then $x_1 \notin \mathfrak{p}$ implies that $x_2 \dots x_n \in \mathfrak{p}$. Since \mathfrak{p} is prime we get a contradiction. For the second claim, we know that some $I_j \subset \mathfrak{p}$. But $\mathfrak{p} = \bigcap_{j=1}^k I_j \subset I_k$ for all k . Hence $\mathfrak{p} = I_j$. □

5 Nilradical and the Jacobson radical

Proposition 5.1. *The set $\mathcal{N}(A)$ consisting of all nilpotents of the ring A and zero is an ideal. Then $\mathcal{N}(A)$ is called the **nilradical** of A . The quotient $A/\mathcal{N}(A)$ has no nilpotents.*

Proof. Suppose $x \in A$ is nilpotent, so $x^n = 0$. For any $a \in A$, $(ax)^n = a^n x^n = 0$. Let x and y be nilpotents. Say $x^n = y^m = 0$. Then

$$(x+y)^{n+m} = \sum_{i,j \geq 0, i+j=n+m} a_{ij} x^i y^j, \quad a_{ij} \in A.$$

Clearly, either $i \geq n$ or $j \geq m$. Then $a_{ij} x^i y^j = 0$. Therefore, $(x+y)^{n+m} = 0$, hence $x+y \in \mathcal{N}(A)$. If $x + \mathcal{N}(A)$ is nilpotent in $A/\mathcal{N}(A)$, then $x^n + \mathcal{N}(A) = \mathcal{N}(A)$ is the trivial coset. Hence $x^n \in \mathcal{N}(A)$. Thus $(x^n)^m = 0$ for some m . □

Definition 5.2. A ring A such that $\mathcal{N}(A) = 0$ is called a **reduced ring**.

Proposition 5.3. $\mathcal{N}(A)$ is the intersection of all prime ideals of A .

Proof.

- ⊂ Let I be the intersection of all prime ideals of A . Let $f \in A$ be such that $f^n = 0$. Take any prime ideal $\mathfrak{p} \subset A$. We know that $f^n = 0 \in \mathfrak{p}$. Then $f(f \dots f) \in \mathfrak{p}$ and \mathfrak{p} prime implies that $f \in \mathfrak{p}$, so $f \in I$.
- ⊃ Let us prove the converse. Suppose f is not nilpotent, so $f^n \neq 0$ for all $n \geq 1$. We will show that there exists a prime ideal $\mathfrak{p} \subset A$ that does not contain f . Let us consider all ideals of A that do not contain f^m , where $m \in \mathbb{Z}_{>0}$. Let Σ be the set of ideals $J \subset A$ such that

$$J \cap \{f^m \mid m \geq 1\} = \emptyset.$$

The zero ideal $\langle 0 \rangle$ is in Σ . So $\Sigma \neq \emptyset$. Equip Σ with a partial order given by inclusion. Applying Zorn's lemma we obtain that Σ contains a maximal element. Call it \mathfrak{p} . By construction, $\mathfrak{p} \cap \{f^m \mid m \geq 1\} = \emptyset$, so $f \notin \mathfrak{p}$. It remains to prove that \mathfrak{p} is prime. Enough to prove that if $x \notin \mathfrak{p}$ and $y \notin \mathfrak{p}$, then $xy \notin \mathfrak{p}$. Consider the ideal $\mathfrak{p} + \langle x \rangle \supsetneq \mathfrak{p}$. Since \mathfrak{p} is maximal in Σ , thus $\mathfrak{p} + \langle x \rangle$ is not in Σ . By definition of Σ there exists $n \geq 1$ such that $f^n \in \mathfrak{p} + \langle x \rangle$. Similarly, there exists $m \geq 1$ such that $f^m \in \mathfrak{p} + \langle y \rangle$. Then $(\mathfrak{p} + \langle x \rangle)(\mathfrak{p} + \langle y \rangle) \subset \mathfrak{p} + \langle xy \rangle$. In particular, $f^{n+m} = f^n \cdot f^m \in \mathfrak{p} + \langle xy \rangle$. If $xy \in \mathfrak{p}$, then $f^{n+m} \in \mathfrak{p}$, which is not possible. Therefore, $xy \notin \mathfrak{p}$. So \mathfrak{p} is a prime ideal that does not contain f . □

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Definition 5.4. The **Jacobson radical** $\mathcal{J}(A)$ is the intersection of all maximal ideals of A .

Proposition 5.5. $x \in \mathcal{J}(A)$ if and only if $1 - xy \in A^*$ for all $y \in A$.

Proof.

\Rightarrow Let $x \in \mathcal{J}(A)$. Suppose there exists $y \in A$ such that $1 - xy$ is not a unit. By Corollary 4.9 every non-unit is contained in a maximal ideal. Say $M \subset A$ is a maximal ideal and $1 - xy \in M$. But $x \in \mathcal{J}(A) \subset M$. Then $1 = (1 - xy) + xy \in M$, but then $M \neq A$. A contradiction.

\Leftarrow Given $x \in A$ such that $1 - xy \in A^*$ for all $y \in A$, we must have $x \in \mathcal{J}(A)$. If $x \notin \mathcal{J}(A)$, then there exists a maximal ideal $M \subset A$ such that $x \notin M$. Then $M + \langle x \rangle = A \ni 1$. Thus $1 = m + xy$, where $y \in A$. But by assumption $1 - xy \in A^*$, so $m \in A^*$. But then $M = A$. A contradiction.

□

Definition 5.6. Let I be an ideal of A . The **radical** of I is the set

$$\text{rad } I = \{x \in A \mid \exists n \geq 1, x^n \in I\}.$$

Proposition 5.7. The radical of I is the intersection of all prime ideals of A that contain I .

Proof. Apply Proposition 5.3 to A/I .

□

Definition 5.8. Let I be an indexing set. For each $i \in I$ we are given a ring R_i . Consider the product set $\prod_{i \in I} R_i$. This is $(x_i)_{i \in I}$ for $x_i \in R_i$. Define

$$0 = (0)_{i \in I} \in \prod_{i \in I} R_i, \quad 1 = (1)_{i \in I} \in \prod_{i \in I} R_i.$$

Define addition and multiplication coordinate-wise, so

$$(a_i)_{i \in I} + (b_i)_{i \in I} = (a_i + b_i)_{i \in I}, \quad (a_i)_{i \in I} \cdot (b_i)_{i \in I} = (a_i \cdot b_i)_{i \in I}, \quad (a_i)_{i \in I}, (b_i)_{i \in I} \in \prod_{i \in I} R_i.$$

Then $\prod_{i \in I} R_i$ is a ring, the **product of rings**.

A warning is if I has at least two elements, then $\prod_{i \in I} R_i$ has zero-divisors.

Example. $R_1 \times R_2$ has $(1, 0) \cdot (0, 1) = (0, 0) = 0$.

If $h_i : R \rightarrow R_i$ is a ring homomorphism for $i \in I$, then $(h_i)_{i \in I}$ is a ring homomorphism $R \rightarrow \prod_{i \in I} R_i$.

Remark 5.9. Let \mathfrak{p}_i for $i \in I$ be all prime ideals of R . Let $h_i : R \rightarrow R/\mathfrak{p}_i$. Then

$$h = (h_i)_{i \in I} : R \rightarrow \prod_{i \in I} R/\mathfrak{p}_i$$

is a homomorphism, and

$$\text{Ker } h = \bigcap_{i \in I} \text{Ker } h_i = \bigcap_{i \in I} \mathfrak{p}_i = \mathcal{N}(R).$$

So there is an injective map

$$R/\mathcal{N}(R) \hookrightarrow \prod_{i \in I} R/\mathfrak{p}_i,$$

a product of integral domains. Now take $f_j : R \rightarrow R/M_j$, so if we take the indexing set J to be the set of all maximal ideals of R , then we obtain an injective map

$$R/\mathcal{J}(R) \hookrightarrow \prod_{j \in J} R/M_j,$$

a product of fields.

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6 Localisation of rings

Example. Fix a prime p . Then

$$\mathbb{Z} \subset \left\{ \frac{m}{p^k} \mid m \in \mathbb{Z}, k \in \mathbb{Z}_{\geq 0} \right\} \subset \mathbb{Q}.$$

Definition 6.1. A subset S of a ring A is called a **multiplicative set** if $1 \in S$ and $0 \notin S$, and S is closed under multiplication.

Example 6.2.

- Let $a \in A$ be a non-nilpotent. Then $\{1, a, \dots\}$ is a multiplicative set.
- Let $\mathfrak{p} \subsetneq A$ be a prime ideal. Then $A \setminus \mathfrak{p}$ is a multiplicative set. Indeed, if $x \notin \mathfrak{p}$ and $y \notin \mathfrak{p}$ then $xy \notin \mathfrak{p}$ by the definition of a prime ideal.
- If we have a family \mathfrak{p}_i for $i \in I$ of prime ideals, then $A \setminus \bigcup_{i \in I} \mathfrak{p}_i$ is a multiplicative set.
- A^* is a multiplicative set.
- All non-zero-divisors in A form a multiplicative set.
- Let $I \subsetneq A$ be an ideal. Then $1 + I = \{1 + x \mid x \in I\}$ is a multiplicative set.

Definition 6.3. Consider $A \times S$ and the equivalence relation on $A \times S$ defined as

$$(a, s) \sim (b, t) \iff \exists u \in S, u(at - bs) = 0.$$

Check that this is indeed an equivalence relation.¹ The following is some notation.

- The equivalence class of (a, s) is written as a/s . For example, if $t \in S$, then $a/s = at/st$.
- The set of equivalence classes is denoted by $S^{-1}A$.

Define

$$\frac{a}{s} + \frac{b}{t} = \frac{at + bs}{st}, \quad \frac{a}{s} \cdot \frac{b}{t} = \frac{ab}{st}.$$

Need to check that these operations are well-defined.² Define $\frac{0}{1}$ as the zero of $S^{-1}A$, and $\frac{1}{1}$ as the one of $S^{-1}A$. Then $S^{-1}A$ is a ring, the **localisation of A with respect to a multiplicative set S** .

Lemma 6.4. *There is a ring homomorphism*

$$\begin{aligned} f : A &\longrightarrow S^{-1}A \\ x &\longmapsto \frac{x}{1} \end{aligned}.$$

This f is injective if and only if S has no zero-divisors.

Proof. If S contains a zero-divisor, say u , then there exists $a \in A$ for $a \neq 0$ such that $ua = 0$. Then

$$f(a) = \frac{a}{1} = \frac{au}{u} = \frac{0}{u} = 0.$$

So $\text{Ker } f$ contains a , hence f is not injective. If f has no zero-divisors, then $u \cdot a = u(a - 0) \neq 0$ if $a \neq 0$ and any $u \in S$. Hence $f(a) \neq 0$. \square

If A is an integral domain, then $\text{Ker } f = 0$. So $A \hookrightarrow S^{-1}A$.

¹Exercise

²Exercise

Example. Let $R = \mathbb{Z}$.

- If $S = \{1, a, \dots\}$, then

$$S^{-1}\mathbb{Z} = \left\{ \frac{n}{a^m} \mid n \in \mathbb{Z}, m \in \mathbb{Z}_{\geq 0} \right\}.$$

- If $S = \mathbb{Z} \setminus p\mathbb{Z}$, then

$$S^{-1}\mathbb{Z} = \left\{ \frac{n}{m} \mid p \nmid m \right\}.$$

- If $S = \mathbb{Z} \setminus \bigcup_{p_i \text{ prime}} p_i \mathbb{Z}$, then

$$S^{-1}\mathbb{Z} = \left\{ \frac{n}{m} \mid p_i \nmid m \right\}.$$

- If $S = \mathbb{Z}^* = \{\pm 1\}$, then $S^{-1}\mathbb{Z} = \mathbb{Z}$.
- If $S = \{\text{all non-zero elements}\}$, then $S^{-1}\mathbb{Z} = \mathbb{Q}$.
- If $S = \{1 + I \mid I \subset \mathbb{Z} \text{ ideal}\} = \{1 + nk \mid k \in \mathbb{Z}\}$, then

$$S^{-1}\mathbb{Z} = \left\{ \frac{m}{1 + nk} \mid m, k \in \mathbb{Z} \right\},$$

where n is fixed.

Example. Let $R = k[x]$, where k is a field.

- If $S = k[x]^* = k^*$, then $S^{-1}k[x] = k[x]$.
- If $S = \{\text{all non-zero elements}\}$, then

$$S^{-1}k[x] = k(x) = \left\{ \frac{f(x)}{g(x)} \mid g(x) \text{ arbitrary non-zero polynomial} \right\}.$$

Example 6.5. Let k be a field, and let $A = k[x, y] / \langle xy \rangle$. Note that A has zero-divisors, since $xy = 0$ in A , but $x \neq 0$ in A and $y \neq 0$ in A . Then $S = \{1, x, \dots\}$ is a multiplicative set, since $x^n \neq 0$ in A for $n = 1, 2, \dots$, because no power of the polynomial x is in $\langle xy \rangle$. What is $S^{-1}A$? Let $f : A \rightarrow S^{-1}A$. Then $a \in \text{Ker } f$ if and only if $a/1 = 0/1$, if and only if $u \cdot (a \cdot 1 - 0 \cdot 1) = 0$ for some $u \in S$, if and only if $ua = 0$. Let $a \neq 0$. Then $u = 1$ is not interesting. Take $u = x$ and $a = y$, then $xy = 0$, hence $y \in \text{Ker } f$. Then f is a homomorphism, hence $\text{Ker } f$ is an ideal. So $\langle y \rangle = yA \subset \text{Ker } f$. In general,

$$a = \sum_{i,j \geq 0} a_{ij} x^i y^j \equiv a_{00} + \sum_{i \geq 1} a_{i0} x^i + \sum_{j \geq 1} a_{0j} y^j \pmod{\langle xy \rangle}.$$

Then $\text{Ker } f = yA = \langle y \rangle$, since $\sum_{j \geq 1} a_{0j} y^j$ goes to zero, since it is annihilated by x , and $x^n \cdot \sum_{i \geq 0} a_i x^i$ is never zero in A . Thus $f(A) = k[x]$, and

$$S^{-1}A = \left\{ \frac{f(x)}{x^n} \mid f(x) \in k[x], n \geq 0 \right\} = k[x, x^{-1}] = \left\{ \sum_{i \in \mathbb{Z}, a_i = 0 \text{ for almost all } i} a_i x^i \mid a_i \in k \right\}.$$

Lemma 6.6 (Universal property of localisation). *Let A be a ring, and $S \subset A$ a multiplicative set. Let $g : A \rightarrow B$ be a ring homomorphism such that $g(s)$ is a unit in B for all $s \in S$. Then there exists a unique ring homomorphism $h : S^{-1}A \rightarrow B$ such that $g = h \circ f$ where $f : A \rightarrow S^{-1}A$ is the canonical map, so*

$$\begin{array}{ccc} A & & \\ f \downarrow & \searrow g & \\ S^{-1}A & \xrightarrow{\exists! h} & B \end{array}.$$

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Proof. Define

$$\begin{aligned} h &: S^{-1}A \longrightarrow B \\ \frac{a}{s} &\longmapsto \frac{g(a)}{g(s)}, \quad a \in A, \quad s \in S. \end{aligned}$$

This is well-defined, that is if $a/s = b/t$ then $g(a)g(s)^{-1} = g(b)g(t)^{-1}$.³ This is a ring homomorphism.⁴ Now easy to check that

$$(h \circ f)(a) = h\left(\frac{a}{1}\right) = \frac{g(a)}{g(1)} = \frac{g(a)}{1} = g(a), \quad a \in A.$$

Moreover, if $h' : S^{-1}A \rightarrow B$ and $g = h' \circ f$ then for all $a \in A$ we have $(h' \circ f)(a) = g(a)$. Since h' is a ring homomorphism, for all $s \in S$, $h'(1/s) = 1/h'(s/1) = 1/g(s)$. Hence

$$h'\left(\frac{a}{s}\right) = h'\left(\frac{a}{1}\right)h'\left(\frac{1}{s}\right) = \frac{h'(f(a))}{h'(f(s))} = \frac{g(a)}{g(s)} = h\left(\frac{a}{s}\right).$$

□

For all ideal $I \subseteq A$, set

$$S^{-1}I = \left\{ \frac{i}{s} \in S^{-1}A \mid i \in I, s \in S \right\},$$

the ideal of $S^{-1}A$ generated by $f(I)$.

Proposition 6.7. *Let $S \subset A$ be a multiplicative subset, and let I_1, \dots, I_n be ideals of A . Then*

1. $S^{-1}(I_1 + \dots + I_n) = S^{-1}I_1 + \dots + S^{-1}I_n$,
2. $S^{-1}(I_1 \dots I_n) = S^{-1}I_1 \dots S^{-1}I_n$,
3. $S^{-1}(\bigcap_{i=1}^n I_i) = \bigcap_{j=1}^n S^{-1}I_j$, and
4. $S^{-1}(\text{rad } I) = \text{rad } S^{-1}I$ for every ideal I .

Proof. Exercise.⁵

□

There is a map

$$\{\text{ideals } I \text{ of } A\} \rightarrow \{\text{ideals } S^{-1}I \text{ of } S^{-1}A\}.$$

Proposition 6.8. *Every ideal of $S^{-1}A$ is of the form $S^{-1}I$ for some ideal $I \subseteq A$.*

Proof. Let J be any ideal of $S^{-1}A$. Define $I = f^{-1}J$. Know I is an ideal of A . Claim that $J = S^{-1}I$. Say $a/s \in J$. Since J is an ideal, $s(a/s) \in J$, so $a/1 \in J$, so $a \in I$. Hence $a/s \in S^{-1}I$. So $J \subseteq S^{-1}I$. Conversely, $f(I) = f(f^{-1}(J)) \subseteq J$. Thus $S^{-1}I \subseteq J$. □

Theorem 6.9. *The only prime ideals of $S^{-1}A$ are of the form $S^{-1}\mathfrak{p}$ where \mathfrak{p} is a prime ideal of A such that $\mathfrak{p} \cap S = \emptyset$. Hence there is a bijection*

$$\{ \text{prime ideals of } S^{-1}A \} \quad \longleftrightarrow \quad \{ \text{prime ideals of } A \text{ that do not intersect } S \}.$$

Proof. Prove $S^{-1}\mathfrak{p}$ is prime if \mathfrak{p} is prime and $\mathfrak{p} \cap S = \emptyset$. Say $a/s \cdot b/t \in S^{-1}\mathfrak{p}$ for $a/s, b/t \in S^{-1}A$. This implies $v(abu - cst) = 0$ for some $u, v \in S$ and $c \in \mathfrak{p}$. Hence $abuv = cstv \in \mathfrak{p}$, so $ab \in \mathfrak{p}$, as u and v are units, so $a \in \mathfrak{p}$ or $b \in \mathfrak{p}$. Hence $S^{-1}\mathfrak{p}$ is prime. Next note that $f^{-1}(S^{-1}\mathfrak{p}) = \mathfrak{p}$, assuming $\mathfrak{p} \cap S = \emptyset$. For if $a \in A$ lies in $S^{-1}\mathfrak{p}$ then by definition there exists $s \in S$ such that $sa \in \mathfrak{p}$. Then s is a unit and so $a \in \mathfrak{p}$. Hence \mathfrak{p} is uniquely determined by $S^{-1}\mathfrak{p}$. Now let \mathfrak{q} be an arbitrary prime ideal of $S^{-1}A$. Then certainly $\mathfrak{q} = S^{-1}I$ for $I = f^{-1}(\mathfrak{q})$. But the preimage of a prime ideal is prime. So I is prime. Moreover, $I \cap S = \emptyset$ as no $s \in S$ is in \mathfrak{q} , since \mathfrak{q} is prime, so \mathfrak{q} contains no units. □

³Exercise

⁴Exercise

⁵Exercise

7 Spec R as a topological space

Lecture 8
Tuesday
22/10/19

A set X with a collection \mathcal{U} of subsets $U \subset X$ is called a **topological space** if the following properties hold.

1. \mathcal{U} contains \emptyset and X .
2. If U and U' are in \mathcal{U} , then $U \cap U'$ is in \mathcal{U} .
3. If U_i are in \mathcal{U} , where i is an element of an indexing set S , then $\bigcup_{i \in S} U_i$ is in \mathcal{U} .

Then the elements of \mathcal{U} are called **open subsets** of X . The following is an equivalent definition. A set X with a family \mathcal{V} of subsets $V \subset X$ is called a **topological space** if the following properties hold.

1. \mathcal{V} contains \emptyset and X .
2. If V and V' are in \mathcal{V} , then $V \cup V'$ is in \mathcal{V} .
3. If V_i are in \mathcal{V} , where i is an element of an indexing set S , then $\bigcap_{i \in S} V_i$ is in \mathcal{V} .

Then the elements of \mathcal{U} are called **closed subsets** of X . For the equivalence, if U is in \mathcal{U} , then define the closed subsets as $X \setminus U$ for U in \mathcal{U} , and vice versa. Let R be a ring with unity. Let $I \subset R$ be an ideal. Let V_I be the set of all prime ideals in R that contain I . Define $U_I = \text{Spec } R \setminus V_I$.

Proposition 7.1. *The collection of subsets $V_I \subset \text{Spec } R$, for all ideals $I \subset R$, satisfies 1, 2, 3 of closed subsets, hence defines a topology on $\text{Spec } R$.*

Proof.

1. If $I = 0$ is the zero ideal, then $V_0 = \text{Spec } R$, all prime ideals of R . If $I = R$, then no prime ideals of R contain R , so $V_R = \emptyset$, so 1 holds.
2. It is enough to check that $V_I \cup V_J = V_{IJ} = V_{I \cap J}$. Note that $IJ \subset I \cap J$. An element of V_I is a prime ideal $\mathfrak{p} \supset I$, so $\mathfrak{p} \supset IJ$. Conversely, let \mathfrak{p} be a prime ideal such that $IJ \subset \mathfrak{p}$. Claim that $I \subset \mathfrak{p}$ or $J \subset \mathfrak{p}$. Suppose not. Then there exists $x \in I$ such that $x \notin \mathfrak{p}$ and there exists $y \in J$ such that $y \notin \mathfrak{p}$. Then $xy \in IJ \subset \mathfrak{p}$. This contradicts the definition of prime ideals. So the claim is proved. Thus 2 holds.
3. J_i for $i \in S$ is a collection of ideals. Claim that $\bigcap_{i \in S} V_{J_i} = V_J$, where $J = \sum_{i \in S} J_i$ is the smallest ideal of R containing all J_i for $i \in S$. The elements of J are finite sums, where each summand is in some J_i . If $\mathfrak{p} \supset J_i$ for $i \in S$, then $\mathfrak{p} \supset J$. Conversely, if $\mathfrak{p} \supset J \supset J_i$, then $\mathfrak{p} \supset J_i$ for all $i \in S$.

□

Recall that if $f : A \rightarrow B$ is a homomorphism of rings, then $f^* : \text{Spec } B \rightarrow \text{Spec } A$ sends any prime ideal $\mathfrak{p} \subset B$ to the inverse image $f^{-1}(\mathfrak{p})$, which is a prime ideal in A . This breaks down for maximal ideals.

Example. Take $f : \mathbb{Z} \rightarrow \mathbb{Q}$, then $f^{-1}(0) = 0$, which is not maximal in \mathbb{Z} .

A map of topological spaces is **continuous** if the inverse image of any open set is open. Equivalently, the inverse images of closed sets are closed.

Proposition 7.2. *f^* is a continuous map.*

Proof. Let I be an ideal in A . We need to show that $(f^*)^{-1}(V_I) = V_J$ for some ideal J in B . Let J be the smallest ideal in B containing $f(I)$.

- ⊂ Fix \mathfrak{p} in V_I , a prime ideal in A such that $\mathfrak{p} \supset I$. The elements of the left hand side that are mapped to \mathfrak{p} by f^* are the prime ideals $\mathfrak{q} \subset B$ such that $\mathfrak{p} = f^{-1}(\mathfrak{q})$. We have $I \subset \mathfrak{p}$, so $f(I) \subset f(\mathfrak{p}) \subset \mathfrak{q}$, so $J \subset \mathfrak{q}$, by definition of J .
- ⊃ Take any prime ideal $\mathfrak{q} \subset B$ such that $J \subset \mathfrak{q}$. We have $I \subset f^{-1}(f(I)) \subset f^{-1}(J) \subset f^{-1}(\mathfrak{q})$, so $f^{-1}(\mathfrak{q})$ is a prime ideal in A containing I . This ideal is exactly $f^*(\mathfrak{q})$, so $f^*(\mathfrak{q})$ is in V_I . Since $\mathfrak{q} \in (f^*)^{-1}(f^*(\mathfrak{q})) \subset (f^*)^{-1}(V_I)$, so we are done.

□

The following are particular cases.

- Assume f is surjective. Then $B \cong A/\text{Ker } f$. Then

$$\begin{aligned} \{\text{prime ideals in } B\} &\longrightarrow \{\text{prime ideals in } A \text{ containing } \text{Ker } f\} \\ \mathfrak{p} \subset B &\longmapsto f^{-1}(\mathfrak{p}) \end{aligned} .$$

So in this case f^* is injective and its image is $V_{\text{Ker } f}$.

- Let S be a multiplicative set in A . Let $f : A \rightarrow S^{-1}A$ be the associated canonical map. By Theorem 6.9 the prime ideals of $S^{-1}A$ are $S^{-1}\mathfrak{p}$, where \mathfrak{p} is a prime ideal in A such that $\mathfrak{p} \cap S = \emptyset$. Thus $f^* : \text{Spec } S^{-1}A \rightarrow \text{Spec } A$ is injective and its image consists of $\mathfrak{p} \subset A$ such that $\mathfrak{p} \cap S = \emptyset$.

Example.

- Let k be a field. Then $\text{Spec } k$ is one point.
- Let $R = k[x]$, an integral domain. This is a PID, so every ideal is $\langle p(x) \rangle$, where $p(x) \in k[x]$ is monic. Then $\langle p(x) \rangle$ is prime if and only if $p(x)$ is irreducible, so

$$\text{Spec } k[x] = \{\langle 0 \rangle\} \cup \{\langle p(x) \rangle \mid p(x) \text{ is monic and irreducible}\} .$$

In particular, if k is algebraically closed, such as $k = \mathbb{C}$, then

$$\text{Spec } k[x] = \{\langle 0 \rangle\} \cup \{\langle x - a \rangle \mid a \in k\} .$$

- Let $R = \mathbb{Z}$, a PID. Then

$$\text{Spec } \mathbb{Z} = \{\langle 0 \rangle\} \cup \{\langle p \rangle \mid p \text{ is a prime number}\} .$$

- Let $R = \mathbb{Z}[i]$ be the Gaussian integers, a PID. The tautological map $f : \mathbb{Z} \rightarrow \mathbb{Z}[i]$ gives rise to $f^* : \text{Spec } \mathbb{Z}[i] \rightarrow \text{Spec } \mathbb{Z}$. Take a usual prime p and decompose p into a product of primes in $\mathbb{Z}[i]$.
 - $2 = (1+i)(1-i) = -i(1+i)^2$, where $1+i$ is a prime in $\mathbb{Z}[i]$.
 - If $p \equiv 1 \pmod{4}$, then $p = (a+bi)(a-bi)$. In this case $a+bi$ and $a-bi$ are not associated primes.
 - If $p \equiv 3 \pmod{4}$, then p stays prime in $\mathbb{Z}[i]$.

Then

$$\begin{array}{ccc} \text{Spec } \mathbb{Z}[i] & \longrightarrow & \text{Spec } \mathbb{Z} \\ \langle 0 \rangle & \longmapsto & \langle 0 \rangle \\ \langle 1+i \rangle & \longmapsto & \langle 2 \rangle \quad \text{ramified} \\ \langle 3 \rangle & \longmapsto & \langle 3 \rangle \quad \text{inert} \\ \langle 1+2i \rangle, \langle 1-2i \rangle & \longmapsto & \langle 5 \rangle \quad \text{split} \end{array} .$$

- Let R be an integral domain and let k be the fraction field of R , so $f : R \hookrightarrow k$. Then $\text{Spec } k = \{\langle 0 \rangle\}$ and $f^* : \text{Spec } k \rightarrow \text{Spec } R$.
- Let k be a field, so $f : k \hookrightarrow k[x]$. Then $f^* : \text{Spec } k[x] \rightarrow \text{Spec } k$. If $\mathfrak{p} \subset k[x]$, then $\mathfrak{p} \cap k = \{\langle 0 \rangle\}$, otherwise if \mathfrak{p} contains a unit of $k[x]$ then $\mathfrak{p} = k[x]$, a contradiction.

Usually, every point of a topological space is a closed subset. But this is not always true. Recall that if Y is a subset of a topological space X , then the **closure** of Y is the smallest closed subset of X containing Y . It is the same as the intersection of all closed subsets containing Y . Claim that if $\mathfrak{p} \subseteq R$ is a prime ideal, then the closure of \mathfrak{p} is $V_{\mathfrak{p}}$. Any closed subset of $\text{Spec } R$ containing \mathfrak{p} is V_J , where $J \subset \mathfrak{p}$. This V_J visibly contains $V_{\mathfrak{p}}$. Hence $V_{\mathfrak{p}}$ is the intersection of all such V_J .

Example. In $\text{Spec } \mathbb{Z}$, the point $\langle p \rangle$ is closed, because $V_{\langle p \rangle} = \{\langle p \rangle\}$. The point $\langle 0 \rangle$ is not closed, as $V_{\langle 0 \rangle} = \text{Spec } \mathbb{Z}$. The closure of $\langle 0 \rangle$ is all of $\text{Spec } \mathbb{Z}$.

Example. Let $R = k[[t]] = \{a_0 + a_1 t + \dots \mid a_i \in k\}$, a local ring. Its unique maximal ideal is $\langle t \rangle$. This is also a unique non-zero prime ideal.⁶ All ideals are $\langle 0 \rangle$ and $\langle t^n \rangle$. Then $\text{Spec } k[[t]] = \{\langle 0 \rangle, \langle t \rangle\}$. Similarly, $\langle 0 \rangle$ is not a closed point, since its closure is $\text{Spec } k[[t]]$, and $\langle t \rangle$ is a closed point.

⁶Exercise

8 Determinants

Lecture 10
Thursday
24/10/19

Let R be a commutative ring with unity. Let A be a matrix $A = (a_{ij})_{i,j=1}^n$ for $a_{ij} \in R$. Then

$$\det A = \sum_{\pi \in \mathcal{S}_n} \operatorname{sgn} \pi \cdot a_{1\pi(1)} \cdots a_{n\pi(n)} \in R,$$

where $\operatorname{sgn} : \mathcal{S}_n \rightarrow \{\pm 1\}$. Let

$$M_{ij} = \det(A \text{ without } j\text{-th column and } i\text{-th row}) \in R.$$

Then

$$(-1)^{j+1} a_{i1} M_{j1} + \cdots + (-1)^{j+n} a_{in} M_{jn} = \begin{cases} \det A & i = j \\ 0 & i \neq j \end{cases}.$$

Define the **adjoint matrix** of A as the $n \times n$ matrix A^\vee with entries $(A^\vee)_{ij} = (-1)^{i+j} M_{ji}$, so

$$A^\vee = \left((-1)^{i+j} M_{ji} \right)^\top.$$

Then $A \cdot A^\vee = A^\vee \cdot A = \det A \cdot I_n$, where I_n is the identity matrix.

9 Modules

Definition 9.1. Let A be a commutative ring with unity. An **A -module** M is an abelian group with an additional structure $A \times M \rightarrow M$ such that

$$\lambda(x + y) = \lambda x + \lambda y, \quad (\mu + \lambda)x = \mu x + \lambda x, \quad \mu(\lambda x) = (\mu\lambda)x, \quad 1x = x, \quad \lambda, \mu \in R, \quad x, y \in M.$$

Example 9.2.

- If R is a field, then an R -module is the same as a vector space.
- If $R = \mathbb{Z}$, then an R -module is the same as an abelian group. Remark that if G is an abelian group then $n \cdot g = g + \cdots + g$.
- If R is any ring, then subgroups of R that are R -modules are the same as ideals.
- If k is a field, then $k[x]$ -modules are vector spaces V over k equipped with a linear transformation $L : V \rightarrow V$. Here x acts on V as L .

Definition 9.3. If M and N are R -modules, then a **homomorphism of R -modules** $f : M \rightarrow N$ is a homomorphism of abelian groups such that $f(rx) = rf(x)$ for all $x \in M$ and all $r \in R$.

Definition 9.4. Let $\operatorname{Hom}_R(M, N)$ be the set of R -module homomorphisms $M \rightarrow N$.

This is an abelian group. Moreover, it is an R -module. If $r \in R$ and $f \in \operatorname{Hom}_R(M, N)$ then $r \cdot f$ sends $x \in M$ to $rf(x) \in N$. Warning that if R is not commutative $\operatorname{Hom}_R(M, N)$ is just an abelian group.

Definition 9.5. Let M and N be submodules of an R -module. Define

$$(N : M) = \{r \in R \mid rM \subset N\}.$$

This is an ideal in R .

Example. The **annihilator** of M is

$$(0 : M) = \{r \in R \mid rM = 0\} = \operatorname{Ann} M.$$

Definition 9.6. An R -module M is **finitely generated** if there are elements $x_1, \dots, x_n \in M$ such that for any $m \in M$ there are $r_1, \dots, r_n \in R$ such that $m = r_1x_1 + \dots + r_nx_n$.

Example. There is a **free** finitely generated module

$$R^{\oplus n} = \{(t_1, \dots, t_n) \mid t_i \in R\},$$

with coordinate-wise addition and multiplication.

Remark. Any finitely generated R -module is a quotient of a free finitely generated R -module. Indeed, define

$$\begin{aligned} f_i : R^{\oplus n} &\longrightarrow M \\ (t_1, \dots, t_n) &\longmapsto t_1x_1 + \dots + t_nx_n. \end{aligned}$$

Comment that JM is the smallest submodule of M containing all elements rm for $r \in J$ and $m \in M$, so

$$JM = \{\text{finite sums } r_1m_1 + \dots + r_nm_n\} \subset M.$$

Lemma 9.7. Let A be a ring. Let M be a finitely generated A -module. Let $J \subset A$ be an ideal such that $JM = M$. Then there is an $a \in J$ such that $(1 - a)M = 0$.

Proof. If $M = 0$, then it is fine. Suppose $M \neq 0$ and m_1, \dots, m_n are generators of M . Then $m_i \in M = JM$, so

$$\begin{aligned} m_1 &= x_{11}m_1 + \dots + x_{1n}m_n \\ &\vdots \\ m_n &= x_{n1}m_1 + \dots + x_{nn}m_n, \end{aligned}$$

for $x_{ij} \in J$. Define $X = (x_{ij})_{i,j=1}^n$. Then

$$\begin{pmatrix} m_1 \\ \vdots \\ m_n \end{pmatrix} = X \begin{pmatrix} m_1 \\ \vdots \\ m_n \end{pmatrix} \iff (\mathbf{I}_n - X) \begin{pmatrix} m_1 \\ \vdots \\ m_n \end{pmatrix} = 0.$$

Consider the adjoint matrix $(\mathbf{I}_n - X)^\vee$. Then

$$(\mathbf{I}_n - X)^\vee (\mathbf{I}_n - X) \begin{pmatrix} m_1 \\ \vdots \\ m_n \end{pmatrix} = 0 \iff \det(\mathbf{I}_n - X) \begin{pmatrix} m_1 \\ \vdots \\ m_n \end{pmatrix} = 0.$$

We have $\det(\mathbf{I}_n - X) \in A$. Then $\det(\mathbf{I}_n - X)$ is a product of diagonal entries $\prod_{i=1}^n (1 - x_{ii})$, plus other terms but every non-diagonal term contains at least one factor in J , so is in J . Finally, $\det(\mathbf{I}_n - X) = 1 - a$, where $a \in J$. Now, $(1 - a)m_i = 0$ for $i = 1, \dots, n$. Hence $(1 - a)M = 0$. \square