

# Commutative Algebra 1

Labix

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**Abstract**

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# 1 Ideals Of a Commutative Ring

## 1.1 Operations on Ideals

### Proposition 1.1.1

Let  $R$  be a commutative ring. Let  $I_1, \dots, I_n$  be ideals of  $R$ . Let  $P_1, \dots, P_k$  be prime ideals of  $R$ .

- Let  $I$  be an ideal of  $R$ . If  $I \subseteq \bigcup_{i=1}^k P_i$ , then  $I \subseteq P_i$  for some  $i$ .
- Let  $P$  be an ideal of  $R$ . If  $P \subseteq \bigcap_{i=1}^n I_i$ , then  $I_i \subseteq P$  for some  $i$ .
- Let  $P$  be an ideal of  $R$ . If  $P = \bigcap_{i=1}^n I_i$ , then  $I_i = P$  for some  $i$ .

*Proof.*

- We prove the contrapositive by induction  $k$ . When  $k = 1$ , the case is clear. Suppose that  $I \not\subseteq P_i$  for  $1 \leq i \leq k-1$  implies  $I \not\subseteq \bigcup_{i=1}^{k-1} P_i$ . Suppose also that  $I \not\subseteq P_k$ .

□

### Proposition 1.1.2

Let  $R$  be a commutative ring. Let  $S, T \subseteq R$  be subsets of  $R$ . Then

$$\langle S \cup T \rangle = \langle S \rangle + \langle T \rangle$$

### Proposition 1.1.3

Let  $R$  be a commutative ring. Let  $I, J$  be ideals of  $R$ . Suppose that  $I \subseteq J$ . Let  $\bar{J}$  denote the ideal of  $R/I$  corresponding to  $J$  under the correspondence theorem. Then there is an isomorphism

$$\frac{R/I}{\bar{J}} \cong \frac{R}{I+J}$$

given by the formula  $(r + I) + \bar{J} \mapsto r + (I + J)$ .

### Example 1.1.4

There is an isomorphism given by

$$\frac{\mathbb{Z}[x]}{(x+1, x^2+2)} \cong \mathbb{Z}/3\mathbb{Z}$$

*Proof.* Using the above propositions, we have that

$$\begin{aligned} \frac{\mathbb{Z}[x]}{(x+1, x^2+2)} &= \frac{\mathbb{Z}[x]}{(x+1) + (x^2+2)} \\ &\cong \frac{\mathbb{Z}[x]/(x+1)}{(3)} \end{aligned}$$

Indeed, the ideal  $(x^2+2)$  corresponds to the ideal  $(3)$  in  $\frac{\mathbb{Z}[x]}{(x+1)}$  because the remainder of  $x^2+2$  divided by  $(x+1)$  is  $(3)$ . Now  $\mathbb{Z}[x]/(x+1) \cong \mathbb{Z}$  by the evaluation homomorphism. Thus quotienting by the ideal  $(3)$  gives the field  $\mathbb{Z}/3\mathbb{Z}$ . □

Some more important results from Groups and Rings and Rings and Modules include:

- If  $I$  and  $J$  are coprime, then  $IJ = I \cap J$

- Chinese Remainder Theorem: If  $I$  and  $J$  are coprime, then there is an isomorphism

$$\frac{R}{I \cap J} \cong \frac{R}{I} \times \frac{R}{J}$$

## 1.2 The Radical of an Ideal

The radical of an ideal is a very different notion from the radical of module.

### Definition 1.2.1: Radical of an Ideal

Let  $I$  be an ideal of a ring  $R$ . Define the radical of  $I$  to be

$$\sqrt{I} = \{r \in R \mid r^n \in I \text{ for some } n \in \mathbb{N}\}$$

### Proposition 1.2.2

Let  $R$  be a commutative ring. Let  $I$  be an ideal. Then the following are true.

- $I \subseteq \sqrt{I}$
- $\sqrt{\sqrt{I}} = \sqrt{I}$
- $\sqrt{I^m} = \sqrt{I}$  for all  $m \geq 1$
- $\sqrt{I} = R$  if and only if  $I = R$

*Proof.*

- Let  $r \in I$ . Then  $r^1 \in I$ . Thus by choosing  $n = 1$  we shows that  $r^n \in I$ . Thus  $r \in \sqrt{I}$ .
- By the above, we already know that  $\sqrt{I} \subseteq \sqrt{\sqrt{I}}$ . So let  $r \in \sqrt{\sqrt{I}}$ . Then there exists some  $n \in \mathbb{N}$  such that  $r^n \in \sqrt{I}$ . But  $r^n \in \sqrt{I}$  means that there exists some  $m \in \mathbb{N}$  such that  $(r^n)^m \in I$ . But  $nm \in \mathbb{N}$  is a natural number such that  $r^{nm} \in I$ . Hence  $r \in \sqrt{I}$  and so we conclude. □

### Proposition 1.2.3

Let  $R$  be a commutative ring. Let  $I, J$  be ideals of  $R$ . Then the following are true.

- If  $I \subseteq J$  then  $\sqrt{I} \subseteq \sqrt{J}$
- $\sqrt{IJ} = \sqrt{I \cap J}$
- $\sqrt{I + J} = \sqrt{\sqrt{I} + \sqrt{J}}$

*Proof.*

- Let  $x \in \sqrt{IJ}$ . Then  $x^n \in IJ$ . This means that there exists  $i \in I$  and  $j \in J$  such that  $x^n = ij$ . Since  $I$  and  $J$  are two sided ideals, we can conclude that  $x^n = ij \in I \cap J$ . Hence  $x^n = ij \in I \cap J$ . We conclude that  $x \in \sqrt{I \cap J}$ . Now let  $x \in \sqrt{I \cap J}$ . Then there exists  $n \in \mathbb{N}$  such that  $x^n \in I \cap J$ . Then  $x^n \in I$  and  $x^n \in J$  implies that  $x^{2n} = x^n \cdot x^n \in IJ$ . We conclude that  $x \in \sqrt{IJ}$ . □

### Proposition 1.2.4

Let  $R$  be a commutative ring. Let  $I$  be an ideal. Then

$$\sqrt{I} = \bigcap_{\substack{p \text{ a prime ideal} \\ I \subseteq p \subseteq R}} p$$

**Definition 1.2.5: Radical Ideals**

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . We say that  $I$  is radical if

$$\sqrt{I} = I$$

In particular, by the above lemma it follows that the radical of an ideal is a radical ideal.

**Lemma 1.2.6**

Let  $R$  be a ring. Let  $P$  be a prime ideal of  $R$ . Then  $P$  is radical.

We conclude that there is an inclusion of types of ideal in which each inclusion is strict:

$$\text{Maximal ideals} \subset \text{Prime ideals} \subset \text{Radical ideals}$$

**1.3 The Nilradical Ideal of Commutative Rings**

Let  $R$  be a ring. Recall that an element  $r \in R$  is nilpotent if  $r^n = 0_R$  for some  $n \in \mathbb{N}$ . When  $R$  is commutative, we can form an ideal out of nilpotent elements.

**Definition 1.3.1: Nilradicals**

Let  $R$  be a ring. Define the nilradical of  $R$  to be

$$N(R) = \{r \in R \mid r \text{ is nilpotent}\}$$

Note that this is different from nilpotent ideals, as nilpotency is a property of an ideal. However the Nilradical ideal is a nil ideal and every sub-ideal of the nilradical is a nil ideal.

**Proposition 1.3.2**

Let  $R$  be a ring and  $N(R)$  its nilradical. Then the following are true.

- $N(R)$  is an ideal of  $R$
- $N(R/N(R)) = 0$

*Proof.*

- Suppose that  $r, s$  are nilpotent, meaning that  $r^n = 0$  and  $s^m = 0$ . Then  $(r + s)^{n+m} = 0$ . Moreover, if  $t \in R$  then  $t \cdot r$  is also nilpotent
- Let  $r \notin N(R)$ . Every element  $r + N(R) \in R/N(R)$  has the property that  $r^n \neq 0$ . Consider  $(r + N(R))^n = r^n + N(R)$ . If  $r^n \in N(R)$  then  $r^n = u$  for some nilpotent  $u$ , which means that  $r^n$  is nilpotent and thus  $r$  is nilpotent, a contradiction. This means that  $r + N(R) \notin N(R/N(R))$  for all  $r \notin N(R)$  and thus  $N(R/N(R)) = 0$

□

**Proposition 1.3.3**

Let  $R$  be a commutative ring. Then we have

$$N(R) = \bigcap_{P \in \text{Spec}(R)} P$$

*Proof.* Let  $x \in N(R)$ . Let  $P$  be an arbitrary prime ideal. Since  $x$  is nilpotent,  $x^n = 0$  for some  $n \in \mathbb{N}$ . If  $x \notin P$ , then  $x^2 \notin P$  since  $P$  is a prime ideal. Recursively we see that  $x^k \notin P$  for all  $k \in \mathbb{N} \setminus \{0\}$ . But  $x^n = 0 \in P$  is a contradiction. Hence  $N(R) \subseteq \bigcap_{P \in \text{Spec}(R)} P$ .

Now suppose that  $x \in R$  is not nilpotent. Consider the set

$$\Sigma = \{I \leq R \mid x^k \notin I \text{ for all } k \geq 1\}$$

Notice that  $(0) \in \Sigma$  and hence it is non-empty. Let  $I_1 \subseteq I_2 \subseteq \dots$  be a chain in  $\Sigma$ . Define  $I = \bigcup_{k=1}^{\infty} I_k$ . I claim that  $I \in \Sigma$ . First of all if  $a, b \in I$  and  $r \in R$ , then  $a \in I_m$  and  $b \in I_n$  for some  $m, n \geq 1$ . Then  $a, b \in I_{\max\{m, n\}}$  so that  $a + b \in I_{\max\{m, n\}} \subseteq I$ . Also  $ra \in I_m \subseteq I$  since  $I_m$  is an ideal. Hence  $I$  itself is an ideal of  $R$ . Suppose for a contradiction that  $x^n \in I$  for some  $n$ . Then  $x^n \in I_k$  for some  $k$ . This is a contradiction since  $I_k \in \Sigma$ . Thus we know that  $I \in \Sigma$ . In particular,  $I$  is an upper bound of  $I_1 \subseteq I_2 \subseteq \dots$ . By Zorn's lemma, we conclude that  $\Sigma$  has a maximal element, say  $P$ .

Suppose for a contradiction that  $P$  is not a prime ideal. Let  $ab \in P$  and  $a, b \notin P$ . Then  $P \subset P + (a), P + (b)$ . Since  $P$  is maximal in  $\Sigma$ ,  $P + (a)$  and  $P + (b)$  cannot be in  $\Sigma$ , and there exists  $x^m \in P + (a)$  and  $x^n \in P + (b)$  for some  $m, n$ . Then

$$x^{m+n} = x^m \cdot x^n \in (P + (a))(P + (b)) = P + (ab)$$

Hence  $P + (ab) \notin \Sigma$ . But  $ab \in P$  implies that  $P + (ab) = P$ . We have reached a contradiction. Thus  $P$  is a prime ideal that does not contain  $x$ . We show that  $x \notin N(R)$  implies  $x \notin P$  for some prime ideal  $P$ . The contrapositive of this statement is  $x \in P$  for all prime ideals  $P$  implies  $x \in N(R)$ . Hence we are done.  $\square$

#### Example 1.3.4

Consider the ring

$$R = \frac{\mathbb{C}[x, y]}{(x^2 - y, xy)}$$

Then its nilradical is given by  $N(R) = (x, y)$ .

*Proof.* Notice that in the ring  $R$ ,  $x^3 = x(x^2) = xy = 0$  and  $y^3 = x^6 = (x^3)^2 = 0$  and hence  $x$  and  $y$  are both nilpotent elements of  $R$ . By definition of the nilradical, we conclude that  $(x, y) \subseteq N(R)$ . Now  $(x, y)$  is a maximal ideal of  $\mathbb{C}[x, y]$  because  $\mathbb{C}[x, y]/(x, y) \cong \mathbb{C}$ . Also notice that  $(x, y) \supseteq (x^2 - y, xy)$  because for any element  $f(x)(x^2 - y) + g(x)(xy) \in (x^2 - y, xy)$ , we have that

$$\begin{aligned} f(x)(x^2 - y) + g(x)(xy) &\in (x^2 - y, xy) = (xf(x))x - f(x)y + (g(x)x)y \\ &= (xf(x))x + (xg(x) - f(x))y \in (x, y) \end{aligned}$$

By the correspondence theorem,  $(x, y)/(x^2 - y)$  is an maximal ideal of  $R$ . In particular,  $(x, y)$  is also a prime ideal. But the  $N(R)$  is the intersection of all prime ideals and hence  $N(R) \subseteq (x, y)$ . We conclude that  $N(R) = (x, y)$ .  $\square$

#### Definition 1.3.5: Reduced Rings

Let  $R$  be a commutative ring. We say that  $R$  is reduced if  $N(R) = 0$ .

#### Proposition 1.3.6

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Then  $R/I$  is reduced if and only if  $I$  is a radical ideal.

So radical, prime and maximal ideals all have characterizations using the quotient ring:

- $I$  is maximal if and only if  $R/I$  is a field.
- $I$  is prime if and only if  $R/I$  is an integral domain.

- $I$  is radical if and only if  $R/I$  is reduced.

## 1.4 The Correspondence between Ideals and the Quotient

### Definition 1.4.1: Max Spectrum of a Ring

Let  $A$  be a commutative ring. Define the max spectrum of  $A$  to be

$$\max\text{Spec}(A) = \{m \subseteq A \mid m \text{ is a maximal ideal of } A\}$$

### Definition 1.4.2: Spectrum of a Ring

Let  $A$  be a commutative ring. Define the spectrum of  $A$  to be

$$\text{Spec}(A) = \{p \subseteq A \mid p \text{ is a prime ideal of } A\}$$

### Example 1.4.3

Consider the following commutative rings.

- $\text{Spec}(\mathbb{Z}/6\mathbb{Z}) = \{(2 + 6\mathbb{Z}), (3 + 6\mathbb{Z})\}$
- $\text{Spec}(\mathbb{Z}/8\mathbb{Z}) = \{(2 + 8\mathbb{Z})\}$
- $\text{Spec}(\mathbb{Z}/24\mathbb{Z}) = \{(2 + 24\mathbb{Z}), (3 + 24\mathbb{Z})\}$
- $\text{Spec}(\mathbb{R}[x]) = \{(f) \mid f \text{ is irreducible}\}$

*Proof.*

- The only ideals of  $\mathbb{Z}/6\mathbb{Z}$  are  $(2 + 6\mathbb{Z})$  and  $(3 + 6\mathbb{Z})$ . We need to find which ones are prime ideals. Now  $\mathbb{Z}/6\mathbb{Z} \setminus (2 + 6\mathbb{Z})$  consists of  $1 + 6\mathbb{Z}$ ,  $3 + 6\mathbb{Z}$  and  $5 + 6\mathbb{Z}$ . No multiplication of these elements give an element of  $(2 + 6\mathbb{Z})$ . So any two elements in  $\mathbb{Z}/6\mathbb{Z}$  which multiply to an element of  $(2 + 6\mathbb{Z})$  must contain one element that lie in  $(2 + 6\mathbb{Z})$ . Hence  $(2 + 6\mathbb{Z})$  is prime. This is similar for  $(3 + 6\mathbb{Z})$ . Hence  $\text{Spec}(\mathbb{Z}/6\mathbb{Z}) = \{(2 + 6\mathbb{Z}), (3 + 6\mathbb{Z})\}$ .
- The only ideals of  $\mathbb{Z}/8\mathbb{Z}$  are  $(2 + 8\mathbb{Z})$  and  $(4 + 8\mathbb{Z})$ . A similar argument as above shows that  $(2 + 8\mathbb{Z})$  is a prime ideal. However,  $6 + 8\mathbb{Z} \notin (4 + 8\mathbb{Z})$  while  $(6 + 8\mathbb{Z})^2 = 4 + 8\mathbb{Z} \in (4 + 8\mathbb{Z})$  which shows that  $(4 + 8\mathbb{Z})$  is not a prime ideal.
- A similar proof as above ensues.
- Recall that  $\mathbb{R}[x]$  is a principal ideal domain. Let  $I = (f)$  be a prime ideal of  $\mathbb{R}[x]$ . Then  $f$  is irreducible. Thus every prime ideal of  $\mathbb{R}[x]$  is of the form  $(f)$  for  $f$  an irreducible polynomial. □

### Lemma 1.4.4

Let  $R, S$  be commutative rings. Let  $f_1 : R \times S \rightarrow R$  and  $f_2 : R \times S \rightarrow S$  denote the projection maps. Then the map

$$f_1^* \amalg f_2^* : \text{Spec}(R) \amalg \text{Spec}(S) \rightarrow \text{Spec}(R \times S)$$

is a bijection.

*Proof.* The core of the proof is the fact that  $P$  is a prime ideal of  $R \times S$  if and only if  $P = R \times Q$  or  $P = V \times S$  for either a prime ideal  $Q$  of  $R$  or a prime ideal  $V$  of  $S$ . It is clear that if  $Q$  is a prime ideal of  $R$  and  $V$  is a prime ideal of  $S$ , then  $R \times Q$  and  $V \times S$  are both prime ideals of  $R \times S$ .

So suppose that  $P$  is a prime ideal in  $R \times S$ . Let  $e_1 = (1, 0)$  and  $e_2 = (0, 1)$ . Since  $P \neq R \times S$ , at least one of  $e_1$  or  $e_2$  is not in  $P$ . Without loss of generality assume that  $e_1 \notin P$ . But



$e_1 e_2 = 0 \in P$  and  $P$  being prime implies that  $e_2 \in P$ . Since  $e_2$  is the identity of  $\{0\} \times S \cong S$ , we conclude that  $\{0\} \times S \subseteq P$ . By the correspondence theorem, the projection map  $f_1 : R \times S \rightarrow R$  gives a bijection between prime ideals of  $R \times S$  that contain  $\{0\} \times S$  and prime ideals of  $R$ . So  $f_1(P)$  is a prime ideal of  $R$ . Thus  $P = f_1(P) \times S$  which is exactly what we wanted.

Now the bijection is clear.  $f_1^* \amalg f_2^*$  sends a prime ideal  $P$  of  $R$  to  $P \times S$  and it sends a prime ideal  $Q$  of  $S$  to  $R \times Q$ . This map is surjective by the above argument. It is injective by inspection.  $\square$

### Theorem 1.4.5

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Denote  $\varphi$  to be the inclusion preserving one-to-one bijection

$$\{\text{Ideals of } R \text{ containing } I\} \xleftrightarrow{1:1} \{\text{Ideals of } R/I\}$$

from the correspondence theorem for rings. In other words,  $\varphi(A) = A/I$ . Let  $J \subseteq R$  be an ideal containing  $I$ . Then the following are true.

- $J$  is a radical ideal if and only if  $\varphi(J) = J/I$  is a radical ideal.
- $J$  is a prime ideal if and only if  $\varphi(J) = J/I$  is a prime ideal.
- $J$  is a maximal ideal if and only if  $\varphi(J) = J/I$  is a maximal ideal.

*Proof.*

- Let  $J$  be a radical ideal. Suppose that  $r + I \in \sqrt{J/I}$ . This means that  $(r + I)^n = r^n + I \in J/I$  for some  $n \in \mathbb{N}$ . But this means that  $r^n \in J$ . This implies that  $r \in \sqrt{J} = J$ . Thus  $r + I \in J/I$  and we conclude that  $\sqrt{J/I} \subseteq J/I$ . Since we also have  $J/I \subseteq \sqrt{J/I}$ , we conclude.

Now suppose that  $J/I$  is a radical ideal. Let  $r \in \sqrt{J}$ . This means that  $r^n \in J$  for some  $n \in \mathbb{N}$ . Now  $r^n + I = (r + I)^n \in J/I$  implies that  $r + I \in \sqrt{J/I} = J/I$ . Hence  $r \in J$  and so  $\sqrt{J} \subseteq J$ . Since we also have that  $J \subseteq \sqrt{J}$ , we conclude.

- Let  $J$  be a prime ideal. Then  $R/J$  is an integral domain. By the second isomorphism theorem, we have that  $R/J \cong (R/I)/(J/I)$  and hence  $(R/I)/(J/I)$  is also an integral domain. Hence  $J/I$  is a prime ideal. The converse is also true.
- Let  $J$  be a maximal ideal. Then  $R/J$  is a field. By the second isomorphism theorem, we have that  $R/J \cong (R/I)/(J/I)$  and hence  $(R/I)/(J/I)$  is also a field. Hence  $J/I$  is a maximal ideal. The converse is also true.  $\square$

Another way to write the bijections is via spectra:

$$\text{Spec}(R/I) \xleftrightarrow{1:1} \{P \in \text{Spec}(R) \mid I \subseteq P\}$$

and

$$\text{maxSpec}(R/I) \xleftrightarrow{1:1} \{m \in \text{maxSpec}(R) \mid I \subseteq m\}$$

## 1.5 Extensions and Contractions of Ideals

### Definition 1.5.1: Extension of Ideals

Let  $R, S$  be commutative rings. Let  $f : R \rightarrow S$  be a ring homomorphism. Let  $I$  be an ideal of  $R$ . Define the extension  $I^e$  of  $I$  to  $S$  to be the ideal

$$I^e = \langle f(i) \mid i \in I \rangle$$

**Proposition 1.5.2**

Let  $R, S$  be commutative rings. Let  $f : R \rightarrow S$  be a ring homomorphism. Let  $I, I_1, I_2$  be an ideal of  $R$ . Then the following are true regarding the extension of ideals.

- Closed under sum:  $(I_1 + I_2)^e = I_1^e + I_2^e$
- $(I_1 \cap I_2)^e \subseteq I_1^e \cap I_2^e$
- Closed under products:  $(I_1 I_2)^e = I_1^e I_2^e$
- $(I_1/I_2)^e \subseteq I_1^e/I_2^e$
- $\text{rad}(I)^e \subseteq \text{rad}(I^e)$

**Definition 1.5.3: Contraction of Ideals**

Let  $R, S$  be commutative rings. Let  $f : R \rightarrow S$  be a ring homomorphism. Let  $J$  be an ideal of  $S$ . Define the contraction  $J^c$  of  $J$  to  $R$  to be the ideal

$$J^c = f^{-1}(J)$$

**Proposition 1.5.4**

Let  $R, S$  be commutative rings. Let  $f : R \rightarrow S$  be a ring homomorphism. Let  $J, J_1, J_2$  be an ideal of  $S$ . Then the following are true regarding the extension of ideals.

- $(J_1 + J_2)^e \supseteq J_1^e + J_2^e$
- Closed under intersections:  $(J_1 \cap J_2)^e = J_1^e \cap J_2^e$
- $(J_1 J_2)^e \supseteq J_1^e J_2^e$
- $(J_1/J_2)^e \subseteq J_1^e/J_2^e$
- Closed under taking radicals:  $\text{rad}(J)^e = \text{rad}(J^e)$

**Proposition 1.5.5**

Let  $R, S$  be commutative rings. Let  $f : R \rightarrow S$  be a ring homomorphism. Let  $I$  be an ideal of  $R$  and let  $J$  be an ideal of  $S$ . Then the following are true.

- $I \subseteq I^{ec}$
- $J^{ce} \subseteq J$
- $I^e = I^{ece}$
- $J^c = J^{cec}$

**1.6 Revisiting the Polynomial Ring**

**Proposition 1.6.1**

Let  $R$  be a commutative ring. Then we have

$$N(R[x]) = N(R)[x]$$

*Proof.* Let  $f = \sum_{k=0}^n a_k x^k \in N(R)[x]$ . Then each  $a_k$  is nilpotent in  $R$ , and there exists  $n_k \in \mathbb{N}$  such that  $a_k^{n_k} = 0$ . This also proves that  $a_k x^k$  is nilpotent. Since the sum of nilpotents is a nilpotent, we conclude that  $f$  is nilpotent.

Now suppose that  $f \in N(R[x])$ . We induct on the degree of  $f$ . Let  $\deg(f) = 0$ . Then  $f$  is nilpotent and  $f$  lies in  $R$ . Thus  $f \in N(R)[x]$ . Now suppose that the claim is true for  $\deg(f) \leq n-1$ . Let  $\deg(g) = n$  with leading coefficient  $b_n$ . Since  $g$  is nilpotent in  $R[x]$ , there exists  $m \in \mathbb{N}$  such that  $g^m = 0$ . Then in particular,  $b_n^m = 0$  so that  $b_n$  is nilpotent. Then  $b_n x^n$  is also nilpotent. Now since  $N(R[x])$  is an ideal of  $R[x]$ , we have that  $g - b_n x^n \in N(R[x])$ . By inductive hypothesis,  $g - b_n x^n \in N(R)[x]$ . Since  $N(R)$  is an ideal of  $R$ , we have that  $N(R)[x]$  is an ideal of  $R[x]$ . So  $g = (g - b_n x^n) + b_n x^n \in N(R)[x]$ . Thus we are done.  $\square$

Some more important results from Groups and Rings and Rings and Modules include:

- If  $R$  is an integral domain, then  $R[x]$  is an integral domain.
- $R$  is a UFD if and only if  $R[x]$  is a UFD
- If  $F$  is a field, then  $F[x]$  is an Euclidean domain, a PID and a UFD
- If  $F$  is a field, then the ideal generated by  $p$  is maximal if and only if  $p$  is irreducible.

Regarding ideals of the polynomial ring, the following maybe useful:

- $I[x]$  is an ideal of  $R$
- There is an isomorphism  $\frac{R[x]}{I[x]} \cong \frac{R}{I}[x]$  given by the map

$$\left( f = \sum_{k=0}^n a_k x^k + I[x] \right) \mapsto \left( \sum_{k=0}^n (a_k + I) x^k \right)$$

- If  $I$  is a prime ideal of  $R$ , then  $I[x]$  is a prime ideal of  $R[x]$ .

## 2 Basic Notions of Commutative Rings

### 2.1 Local Rings

#### Definition 2.1.1: Local Rings

Let  $R$  be a commutative ring. We say that  $R$  is a local ring if it has a unique maximal ideal  $m$ . In this case, we say that  $R/m$  is the residue field of  $R$ .

#### Example 2.1.2

Consider the following commutative rings.

- $\mathbb{Z}/6\mathbb{Z}$  is not a local ring.
- $\mathbb{Z}/8\mathbb{Z}$  is a local ring.
- $\mathbb{Z}/24\mathbb{Z}$  is not a local ring.
- $\mathbb{R}[x]$  is not a local ring.

*Proof.*

- The only ideals of  $\mathbb{Z}/6\mathbb{Z}$  are  $(2 + 6\mathbb{Z})$  and  $(3 + 6\mathbb{Z})$ . They do not contain each other and so they are both maximal.
- The only ideals of  $\mathbb{Z}/8\mathbb{Z}$  are  $(2 + 8\mathbb{Z})$  and  $(4 + 8\mathbb{Z})$ . But  $(2 + 8\mathbb{Z}) \supseteq (4 + 8\mathbb{Z})$ . Hence  $\mathbb{Z}/8\mathbb{Z}$  has a unique maximal ideal.
- A similar proof as above ensues.
- Any irreducible polynomial  $f \in \mathbb{R}[x]$  is such that  $(f)$  is a maximal ideal. Indeed the evaluation homomorphism gives an isomorphism  $\frac{\mathbb{R}[x]}{(f)} \cong \mathbb{R}$ .

□

#### Proposition 2.1.3

Let  $R$  be a ring and  $I$  an ideal of  $R$ . Then  $I$  is the unique maximal ideal of  $R$  if and only if  $I$  is the set containing all non-units of  $R$ .

*Proof.* Let  $I$  be the unique maximal ideal of  $R$ . Clearly  $I$  does not contain any unit else  $I = R$ . Now suppose that  $r$  is a non-unit. Suppose that  $r \notin I$ . Define  $J = \{sr | s \in R\}$ . Clearly  $J$  is an ideal. It must be contained in some maximal ideal. Since  $I$  is the unique maximal ideal,  $J \subseteq I$ . But this means that  $r \in I$ , a contradiction. Thus every non-unit is in  $I$ .

Suppose that  $I$  contains all non-units of  $R$ . Let  $r \notin I$ . Then there exists  $s \notin I$  such that  $rs = 1$ . Then  $(r + I)(s + I) = 1 + I$  in  $R/I$ . This means that every element of  $R/I$  has a multiplicative inverse which means that  $R/I$  is a field and thus  $I$  is a maximal ideal. Now let  $J \neq I$  be another maximal ideal. Then  $J$  contains some unit  $r$ . This implies that  $J = R$  and thus  $I$  is the unique maximal ideal.

□

#### Example 2.1.4

Let  $k$  be a field. Then the ring of power series  $k[[x]]$  is a local ring.

*Proof.* Let  $M$  be the set of all non-units of  $k[[x]]$ . I first show that  $f \in M$  if and only if the constant term of  $f$  is non-zero. Let  $g$  be a power series. Then the  $n$ th coefficient of  $f \cdot g$  is given by

$$c_n = \sum_{k=0}^n a_k b_{n-k}$$

If the constant term of  $f$  is 0, then  $c_0 = 0$  and so  $f \cdot g \neq 1$ . Now if the constant term of  $f$  is

$a_0 \neq 0$ , then set  $b_0 = \frac{1}{a_0}$ . Now we can use the formula  $0 = c_n$  to deduce

$$b_n = -\frac{\sum_{k=1}^n a_k b_{n-k}}{a_0}$$

This is such that  $a_n \cdot b_n = 0$ . Define  $g = \sum_{k=0}^{\infty} b_k x^k$ . Then  $f \cdot g = 1$ . Thus  $f$  is a unit.

By the above proposition, we conclude that  $M$  is the unique maximal ideal of  $k[[x]]$ .  $\square$

We will discuss more of local rings in the topic of localizations.

## 2.2 Noetherian Commutative Rings

We recall some facts about Noetherian rings. In the following, let  $R$  be a commutative ring, although they are also true if  $R$  is non-commutative if we take all modules defined below to be left (right)  $R$ -modules.

- If we have a short exact sequence of  $R$ -modules:

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

Then  $M_2$  is Noetherian if and only if  $M_1$  and  $M_3$  are Noetherian.

- If  $M$  and  $N$  are  $R$ -modules, then  $M \oplus N$  is Noetherian if and only if  $M$  and  $N$  are Noetherian.
- If  $M$  is an  $R$ -module and  $N$  is an  $R$ -submodule of  $M$ , then  $M$  is Noetherian if and only if  $N$  and  $M/N$  are Noetherian.
- If  $R$  is Noetherian and  $I$  is an ideal of  $R$ , then  $R/I$  is Noetherian.
- Later when once has seen localization, we can also prove that: If  $R$  is Noetherian then  $S^{-1}R$  is Noetherian for any multiplicative subset  $S$  of  $R$ .

### Theorem 2.2.1: Hilbert's Basis Theorem

Let  $R$  be a commutative ring. If  $R$  is Noetherian, then

$$R[x_1, \dots, x_n]$$

is a Noetherian ring.

### Proposition 2.2.2

Let  $R = \bigoplus_{i=0}^n R_i$  be a graded ring. Then  $R$  is Noetherian if and only if  $R_0$  is Noetherian and  $R$  is finitely generated as an  $R_0$ -module.

## 2.3 Artinian Commutative Rings

We recall some facts about Artinian modules.

- If we have a short exact sequence of  $R$ -modules:

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

Then  $M_2$  is Artinian if and only if  $M_1$  and  $M_3$  are Artinian.

- If  $M$  and  $N$  are  $R$ -modules, then  $M \oplus N$  is Artinian if and only if  $M$  and  $N$  are Artinian.
- If  $M$  is an  $R$ -module and  $N$  is an  $R$ -submodule of  $M$ , then  $M$  is Artinian if and only if  $N$  and  $M/N$  are Artinian.

Let  $R$  be a (not necessarily commutative ring). If  $R$  is left Artinian, then the following are true.

- If  $I$  is an ideal of  $R$ , then  $R/I$  is Artinian.
- Every prime ideal of  $R$  is maximal.
- $R$  only has finitely many maximal ideals.
- $J(R)$  is a nilpotent ideal.
- $R$  is Noetherian.

There are also properties of Artinian rings that only commutative rings can realize.

### Proposition 2.3.1

Let  $R$  be an integral domain. Then  $R$  is Artinian if and only if  $R$  is a field.

*Proof.* It is clear that every field is Artinian. Conversely, let  $R$  be Artinian. Consider the following descending chain of ideals in  $R$ :

$$R \supseteq (x) \supseteq (x^2) \supseteq$$

for any  $0 \neq x \in R$ . Since  $R$  is Artinian, the chain terminates and  $(x^n) = (x^{n+1})$  for some  $n \in \mathbb{N}$ . Then there exists  $y \in R$  such that  $x^n = yx^{n+1}$ . This means that  $x^n(1 - yx) = 0$ . Since  $R$  is an integral domain,  $R$  has no nilpotents. Hence  $x^n$  is non-zero and  $1 = xy$ . Thus  $x$  has an inverse so that  $R$  is a field.  $\square$

### Proposition 2.3.2

Let  $R$  be a commutative ring. Let  $R$  be Artinian. Then every prime ideal in  $R$  is maximal.

*Proof.* Let  $P$  be a prime ideal. Since quotients of Artinian rings are Artinian,  $R/P$  is Artinian. Since  $R/P$  is also an integral domain, we conclude by the above that  $R/P$  is a field. Hence  $P$  is maximal.  $\square$

Recall some properties of the Jacobson radical from Rings and Modules. For a (not necessarily commutative ring  $R$ ),

- $J(R/J(R)) = 0$
- $J(R) = \bigcap_{m \in \max \text{Spec}(R)} m$

### Proposition 2.3.3

Let  $R$  be a commutative ring. If  $R$  is Artinian, then

$$N(R) = J(R)$$

*Proof.* Since every prime ideal in  $R$  is maximal, we have that

$$N(R) = \bigcap_{P \text{ a prime ideal}} P = \bigcap_{P \text{ a maximal ideal}} P = J(R)$$

and so we conclude.  $\square$

**Proposition 2.3.4**

Let  $R$  be a commutative ring. If  $R$  is Artinian, then  $R$  has finitely many maximal ideals.

*Proof.* Consider the collection

$$\{m_1 \cap \cdots \cap m_k \mid m_1, \dots, m_k \text{ are maximal ideals of } R\}$$

of  $R$ -submodules of  $R$ . Since  $R$  is Artinian, every collection of  $R$ -submodules of  $R$  has a minimal element. Hence this collection also has a minimal element, say  $m_1 \cap \cdots \cap m_k$ . Let  $m$  be another maximal ideal of  $R$ . Then

$$m \cap m_1 \cap \cdots \cap m_k \subseteq m_1 \cap \cdots \cap m_k$$

Since  $m_1 \cap \cdots \cap m_k$  is minimal, they are equal. By prp1.1.1, we conclude that  $m \supseteq m_i$  for some  $i$ . Since they are maximal, we have  $m = m_i$ . Hence  $m_1, \dots, m_k$  gives the full list of distinct maximal ideals of  $R$ .  $\square$

### 3 Modules over a Commutative Ring

Recall from Rings and Modules that a module consists of an abelian group  $M$  and a ring  $R$  such that there is a binary operation  $\cdot : R \times M \rightarrow M$  that mimic the notion of a group action:

- For  $r, s \in R$ ,  $s \cdot (r \cdot m) = (sr) \cdot m$  for all  $m \in M$ .
- For  $1_R \in R$  the multiplicative identity,  $1_R \cdot m = m$  for all  $m \in M$ .

When  $R$  is a commutative ring, the first axiom is relaxed so that the resulting element of  $M$  makes no difference whether you apply  $r$  first or  $s$  first. This makes module act even more similarly than fields (although one still need the notion of a basis, which appears in free modules). Therefore the first section concerns transferring techniques in linear algebra such as the Cayley Hamilton theorem to module over a ring that mimic the notion of vector spaces.

#### 3.1 Cayley-Hamilton Theorem

##### Definition 3.1.1: Characteristic Polynomial

Let  $R$  be a commutative ring. Let  $A \in M_{n \times n}(R)$  be a matrix. Define the characteristic polynomial of  $A$  to be the polynomial

$$c_A(x) = \det(A - xI)$$

##### Theorem 3.1.2: Cayley-Hamilton Theorem

Let  $R$  be a commutative ring. Let  $A \in M_{n \times n}(R)$  be a matrix. Then  $c_A(A) = 0$ .

##### Corollary 3.1.3

Let  $R$  be a commutative ring. Let  $M$  be a finitely generated  $R$ -module. Let  $I$  be an ideal of  $R$ . Let  $\varphi \in \text{End}_R(M)$ . If  $\varphi(M) \subseteq IM$ , then there exists  $a_1, \dots, a_n \in I$  such that

$$\varphi^n + a_1\varphi^{n-1} + \dots + a_{n-1}\varphi + \text{id}_M = 0 : M \rightarrow M$$

*Proof.* Suppose that  $M$  is generated by  $x_1, \dots, x_n$ . There exists a surjective map  $\rho : R^n \rightarrow M$  given by  $(r_1, \dots, r_n) \mapsto \sum_{k=1}^n r_k x_k$ . Since  $\varphi(M) \subseteq IM$ , we have that

$$\varphi(x_k) = \sum_{i=1}^n r_{ki} x_i$$

for some  $r_{ki} \in I$ . Write  $A$  to be the matrix  $A = (a_{ki})$ . We now have a commutative diagram:

In other words, we have the diagram:

$$\begin{array}{ccc} R^n & \xrightarrow{\rho} & M \\ A \downarrow & & \downarrow \varphi \\ R^n & \xrightarrow{\rho} & M \end{array}$$

By Cayley-Hamilton theorem, we have that  $c_A(A) = 0$  is the zero function. For all  $x \in R^n$ , we have that

$$\begin{aligned} c_A(A)(x) &= 0 \\ c_A(Ax) &= 0 \\ \rho(c_A(Ax)) &= \rho(0) \\ c_A(\rho(Ax)) &= 0 && (\rho \text{ is } R\text{-linear}) \\ c_A(\varphi(\rho(x))) &= 0 && (\text{Diagram is commutative}) \end{aligned}$$



Since  $\rho$  is surjective, we conclude that for any  $m \in M$ , the above calculation gives  $c_A(\varphi(m)) = 0$  so that  $c_A(\varphi)$  is the zero map.  $\square$

### 3.2 Nakayama's Lemma

#### Lemma 3.2.1: Nakayama's Lemma I

Let  $R$  be a commutative ring. Let  $M$  be a finitely generated  $R$ -module. Let  $I$  be an ideal of  $R$ . If  $IM = M$ , then there exists  $r \in R$  such that  $rM = 0$  and  $r - 1 \in I$ .

*Proof.* Choose  $\varphi = \text{id}_M$ . Then  $\varphi$  is surjective so that  $M = \varphi(M) \subseteq IM$ . By cor 4.1.3, there exists  $r_1, \dots, r_n \in I$  such that  $(1 + r_1 + \dots + r_n)M = 0$ . By choosing  $r = 1 + r_1 + \dots + r_n$ , we see that  $rM = 0$  and  $r - 1 \in I$  so that we conclude.  $\square$

#### Lemma 3.2.2: Nakayama's Lemma II

Let  $R$  be a commutative ring. Let  $M$  be a finitely generated  $R$ -module. Let  $I$  be an ideal of  $R$  such that  $I \subseteq J(R)$  and  $IM = M$ . Then  $M = 0$ .

*Proof.* By Nakayama's lemma I, there exists  $r \in R$  such that  $rM = 0$  and  $r - 1 \in I \subseteq J(R)$ . By 2.3.8, we have that  $1 - (r - 1)(-1) = r \in R^\times$ . This means that  $r$  is invertible. Hence  $rM = 0$  implies  $M = r^{-1}rM = 0$ .  $\square$

#### Corollary 3.2.3

Let  $R$  be a commutative ring. Let  $M$  be a finitely generated  $R$ -module. Let  $I$  be an ideal of  $R$  such that  $I \subseteq J(R)$ . Let  $N$  be an  $R$ -submodule of  $M$ . If

$$M = IM + N$$

then  $M = N$ .

*Proof.* Since quotients of finitely generated modules are finitely generated, we know that  $M/N$  is finitely generated. Define the map

$$\phi : IM + N \rightarrow I \frac{M}{N}$$

by  $\phi(im + n) = i(m + N)$ . This map is clearly surjective. Now I claim that  $\ker(\phi) = N$ . For any  $im + n \in \ker(\phi)$ , we see that  $i(m + N) = N$  means that  $im \in N$ . Hence  $im + n \in N$ . On the other hand, if  $im + n \in N$  then  $im \in N$ . But this means that  $im + N = N$ . Hence  $im + n \in \ker(\phi)$ . By the first isomorphism theorem for modules, we conclude that

$$\frac{M}{N} = \frac{IM + N}{N} \cong I \frac{M}{N}$$

We can now apply Nakayama's lemma II to conclude that  $M/N = 0$  so that  $M = N$ .  $\square$

#### Corollary 3.2.4

Let  $(R, m)$  be a local ring. Let  $M$  be a finitely generated  $R$ -module. Then the following are true.

- $M/mM$  is a finite dimensional vector space over  $R/m$ .
- $a_1, \dots, a_n \in M$  generates  $M$  as an  $R$ -module if and only if  $a_1 + mM, \dots, a_n + mM$

generates  $M/mM$  as a  $R/m$  vector space.

*Proof.* For the first part, we already know that  $M/mM$  is an  $R$ -module. We notice that for any  $k \in m$  and  $t + mM \in M/mM$  we have that  $k(t + mM) = kt + kmM$ . But  $kt \in m$  means that  $kt + kmM = mM$ . Hence  $M/mM$  is well defined as an  $R/m$ -module. Now suppose that  $M$  is finitely generated by the elements  $a_1, \dots, a_n$ . Let  $x + mM \in M/mM$ . Then there exists  $r_k \in R$  such that  $x = r_1 a_1 + \dots + r_n a_n$ . But this means that

$$x + mM = r_1(a_1 + mM) + \dots + r_n(a_n + mM)$$

This means that  $M/mM$  is generated by  $a_1 + mM, \dots, a_n + mM$ . We conclude that  $M/mM$  is finite dimensional.

Suppose that  $a_1, \dots, a_n \in M$  generates  $M$  as an  $R$ -module. By the same argument as above, we can see that  $a_1 + mM, \dots, a_n + mM$  is a set of generators for  $M/mM$ . For the other direction, suppose that  $a_1 + mM, \dots, a_n + mM$  generates  $M/mM$  as an  $R/m$ -vector space. Define  $N = Ra_1 + \dots + Ra_n \leq M$ . Set  $I = J(R) = m$ . We want to show that  $M = IM + N$ . It is clear that  $IM + N \leq M$ . If  $x \in M$ , then there exists  $r_k \in R$  such that  $x + mM = r_1(a_1 + mM) + \dots + r_n(a_n + mM)$ . In particular, this means that

$$x - \sum_{k=1}^n r_k a_k \in mM$$

Hence  $x \in IM + N$ . We can now apply the above corollary to deduce that  $M = N = Ra_1 + \dots + Ra_n$  so that  $M$  is generated by  $a_1, \dots, a_n$ . And so we are done.  $\square$

### 3.3 Change of Rings

#### Definition 3.3.1: Extension of Scalars

Let  $R, S$  be commutative rings. Let  $\varphi : R \rightarrow S$  be a ring homomorphism. Let  $M$  be an  $R$ -module. Define the extension of  $M$  to the ring  $S$  to be the  $S$ -module

$$S \otimes_R M$$

#### Definition 3.3.2: Restriction of Scalars

Let  $R, S$  be commutative rings. Let  $\varphi : R \rightarrow S$  be a ring homomorphism. Let  $M$  be an  $S$ -module. Define the restriction of  $M$  to the ring  $R$  to be the  $R$ -module  $M$  equipped with the action

$$r \cdot_R m = \varphi(r) \cdot_S m$$

for all  $r \in R$ .

#### Theorem 3.3.3

Let  $R, S$  be commutative rings. Let  $\varphi : R \rightarrow S$  be a ring homomorphism. Then there is an isomorphism

$$\text{Hom}_S(S \otimes_R M, N) \cong \text{Hom}_R(M, N)$$

for any  $R$ -module  $M$  and  $S$ -module  $N$  given as follows.

- For  $f \in \text{Hom}_S(S \otimes_R M, N)$ , define the map  $f^+ \in \text{Hom}_R(M, N)$  by

$$f^+(m) = f(1 \otimes m)$$

- For  $g \in \text{Hom}_R(M, N)$ , define the map  $g^- \in \text{Hom}_S(S \otimes_R M, N)$  by

$$g^-(s \otimes m) = s \cdot g(m)$$

### 3.4 Properties of the Hom Set

Let  $R$  be a ring. Let  $M, N$  be  $R$ -modules. Recall that in Rings and Modules that  $\text{Hom}_R(M, N)$  is a  $Z(R)$ -modules. When  $R$  is commutative,  $Z(R) = R$  so that the Hom set becomes an  $R$ -module.

#### Proposition 3.4.1

Let  $R$  be a commutative ring. Let  $M, N$  be  $R$ -modules. Then

$$\text{Hom}_R(M, N)$$

is an  $R$ -module with the following binary operations.

- For  $\phi, \varphi : M \rightarrow N$  two  $R$ -module homomorphisms, define  $\phi + \varphi : M \rightarrow N$  by  $(\phi + \varphi)(m) = \phi(m) + \varphi(m)$  for all  $m \in M$
- For  $\phi : M \rightarrow N$  an  $R$ -module homomorphism and  $r \in R$ , define  $r\phi : M \rightarrow N$  by  $(r\phi)(m) = r \cdot \phi(m)$  for all  $m \in M$ .

In particular, it is an abelian group.

*Proof.* We first show that the addition operation gives the structure of a group.

- Since  $M$  is associative as an additive group, associativity follows
- Clearly the zero map  $0 \in \text{Hom}_R(M, N)$  acts as the additive inverse since for any  $\phi \in \text{Hom}_R(M, N)$ , we have that  $\phi(m) + 0 = 0 + \phi(m) = \phi(m)$  since  $0$  is the additive identity for  $M$
- For every  $\phi \in \text{Hom}_R(M, N)$ , the map taking  $m$  to  $-\phi(m)$  also lies in  $\text{Hom}_R(M, N)$ . Since  $-\phi(m)$  is the inverse of  $\phi(m)$  in  $M$  for each  $m \in M$ , we have that  $-\phi$  is the inverse of  $\phi$

We now show that

- Let  $r, s \in R$ , we have that  $((sr)\phi)(m) = (sr) \cdot \phi(m) = s \cdot (r \cdot \phi(m)) = s(r(\phi))(m)$  and hence we showed associativity.
- It is clear that  $1_R \in R$  acts as the identity of the operation.

Thus we are done.  $\square$

#### Proposition 3.4.2

Let  $R$  be a ring. Let  $I$  be an indexing set. Let  $M_i, N$  be  $R$ -modules for  $i \in I$ . Then the following are true.

- There is an isomorphism

$$\text{Hom} \left( \bigoplus_{i \in I} M_i, N \right) \cong \bigoplus_{i \in I} \text{Hom}(M_i, N)$$

- There is an isomorphism

$$\text{Hom} \left( \prod_{i \in I} M_i, N \right) \cong \prod_{i \in I} \text{Hom}(M_i, N)$$

#### Definition 3.4.3: Induced Map of Hom

Let  $R$  be a commutative ring. Let  $M_1, M_2, N$  be  $R$ -modules. Let  $f : M_1 \rightarrow M_2$  be an  $R$ -module homomorphism. Define the induced map

$$f^* : \text{Hom}_R(M_2, N) \rightarrow \text{Hom}_R(M_1, N)$$

by the formula  $\varphi \mapsto \varphi \circ f$

**Lemma 3.4.4**

Let  $R$  be a commutative ring. Let  $M_1, M_2, N$  be  $R$ -modules. Let  $f : M_1 \rightarrow M_2$  be an  $R$ -module homomorphism. Then the induced map

$$f^* : \text{Hom}(M_2, N) \rightarrow \text{Hom}(M_1, N)$$

is an  $R$ -module homomorphism.

**3.5 Failure of Exactness of Hom and Tensoring****Proposition 3.5.1**

Let  $R$  be a commutative ring. Let the following be an exact sequence of  $R$ -modules.

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

Let  $N$  be an  $R$ -module. Then the following two sequences

$$0 \longrightarrow \text{Hom}_R(M_3, N) \longrightarrow \text{Hom}_R(M_2, N) \longrightarrow \text{Hom}_R(M_1, N)$$

$$\text{Hom}_R(N, M_1) \longrightarrow \text{Hom}_R(N, M_2) \longrightarrow \text{Hom}_R(N, M_3) \longrightarrow 0$$

are exact.

*Proof.*

- We first show that  $g^*$  is injective. Let  $\phi, \rho \in \text{Hom}(C, G)$  such that  $g^*(\phi) = g^*(\rho)$ . This means that  $\phi \circ g = \rho \circ g$ . Let  $c \in C$ . Since  $g$  is surjective, there exists  $b \in B$  such that  $g(b) = c$ . Then

$$\phi(c) = \phi(g(b)) = \rho(g(b)) = \rho(c)$$

Hence  $\phi = \rho$ .

Now we show that  $\text{im}(g^*) \subseteq \ker(f^*)$ . Let  $g^*(\phi) \in \text{Hom}(B, G)$  for  $\phi \in \text{Hom}(C, G)$ . We want to show that  $f^*(g^*(\phi)) = 0$ . But we have that

$$(\phi \circ g \circ f)(a) = \phi(g(f(a))) = \phi(0) = 0$$

since  $\text{im}(f) = \ker(g)$ . Thus we conclude.

Finally we show that  $\ker(f^*) \subseteq \text{im}(g^*)$ . Let  $f^*(\phi) = 0$  for  $\phi \in \text{Hom}(B, G)$ . This means that  $\phi \circ f = 0$  or in other words,  $\text{im}(f) \subseteq \ker(\phi)$ . Since  $\phi(k) = 0$  for all  $k \in \text{im}(f)$ ,  $\phi$  descends to a map  $\bar{\phi} : \frac{B}{\text{im}(f)} \rightarrow G$ . But  $\text{im}(f) = \ker(g)$  hence this is equivalent to a map  $\bar{\phi} : \frac{B}{\ker(g)} \rightarrow G$ . But by the first isomorphism theorem and the fact that  $g$  is surjective, we conclude that  $\bar{g} : \frac{B}{\ker(g)} \xrightarrow{g} C$ , where  $b + \ker(g) \mapsto g(b)$ . Thus we have constructed a map  $\bar{\phi} \circ \bar{g}^{-1} : C \rightarrow G$  given by  $g(b) \mapsto b + \ker(g) \mapsto \phi(b)$ . But now  $g^*(\bar{\phi} \circ \bar{g}^{-1})$  is the map defined by

$$b \mapsto g(b) \mapsto b + \ker(g) \mapsto \phi(b)$$

and so this map is exactly  $\phi$ . Thus  $\phi \in \text{im}(g^*)$ . □

**Proposition 3.5.2**

Let  $R$  be a commutative ring. Let the following be an exact sequence of  $R$ -modules.

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

Let  $N$  be an  $R$ -module. Then the following sequence

$$M_1 \otimes N \xrightarrow{f \otimes \text{id}_N} M_2 \otimes N \xrightarrow{g \otimes \text{id}_N} M_3 \otimes N \longrightarrow 0$$

is exact.

However, one can observe that we did not imply that  $M_1 \otimes N \rightarrow M_2 \otimes N$  is injective. Indeed, this is because tensoring does not preserve injections.

## 4 Algebra Over a Commutative Ring

### 4.1 Commutative Algebras

#### Definition 4.1.1: Commutative Algebras

Let  $R$  be a commutative ring. A commutative  $R$ -algebra is an  $R$ -algebra  $A$  that is commutative.

#### Proposition 4.1.2

Let  $R$  be a commutative ring. Then the following are equivalent characterizations of a commutative  $R$ -algebra.

- $A$  is a commutative  $R$ -algebra
- $A$  is a commutative ring together with a ring homomorphism  $f : R \rightarrow A$

*Proof.* Suppose that  $A$  is an  $R$ -algebra. Then define a map  $f : R \rightarrow A$  by  $f(r) = r \cdot 1$  where  $r \cdot 1$  is the module operation on  $A$ . Then clearly this is a ring homomorphism.

Suppose that  $A$  is a commutative ring together with a ring homomorphism  $f : R \rightarrow A$ . Define an action  $\cdot : R \times A \rightarrow A$  by  $r \cdot a = f(r)a$ . Then this action clearly allows  $A$  to be an  $R$ -module.  $\square$

Under the correspondence of associative algebra, the above proposition gives a another correspondence between the first one.

$$\left\{ (A, R) \mid \begin{array}{l} A \text{ is a commutative} \\ R\text{-algebra} \end{array} \right\} \xleftrightarrow{1:1} \left\{ \phi : R \rightarrow A \mid \begin{array}{l} \phi \text{ is a ring homomorphism} \\ \text{such that } f(R) \subseteq Z(A) = A \end{array} \right\}$$

In particular, the construction above are inverses of each other so that it gives the one-to-one correspondence.

### 4.2 Finitely Generated Algebra

#### Definition 4.2.1: Finitely Generated Algebras

Let  $R$  be a commutative ring. Let  $A$  be an  $R$ -algebra. We say that  $A$  is finitely generated if there exists  $a_1, \dots, a_n \in A$  such that every element  $a \in A$  can be written as a polynomial in  $a_1, \dots, a_n$ . This means that

$$a = \sum_{i_1, \dots, i_n} r_{i_1, \dots, i_n} a_1^{i_1} \cdots a_n^{i_n}$$

Finitely generated algebras are also called algebra of finite type.

#### Theorem 4.2.2

Let  $A$  be a commutative algebra over a ring  $R$ . Then the following are equivalent.

- $A$  is a finitely generated algebra over  $R$
- There exists elements  $a_1, \dots, a_n \in A$  such that the evaluation homomorphism

$$\phi : R[x_1, \dots, x_n] \rightarrow A$$

given by  $\phi(f) = f(a_1, \dots, a_n)$  is a surjection

- There is an isomorphism

$$A \cong \frac{R[x_1, \dots, x_n]}{I}$$

for some ideal  $I$

**Definition 4.2.3: Finitely Presented Algebra**

Let  $R$  be a ring. Let  $A = R[x_1, \dots, x_n]/I$  be a finitely generated algebra over  $R$  for some ideal  $I$ . We say that  $A$  is finitely presented if  $I$  is finitely generated.

**Lemma 4.2.4**

Let  $R$  be a ring, considered as an algebra over  $\mathbb{Z}$ . If  $R$  is finitely generated over  $\mathbb{Z}$ , then  $R$  is finitely presented.

*Proof.* Trivial since  $\mathbb{Z}$  is a principal ideal domain. □

**4.3 Finite Algebras****Definition 4.3.1: Finite Algebras**

Let  $R$  be a commutative ring. Let  $A$  be an  $R$ -algebra. We say that  $A$  is finite if  $A$  is finitely generated as an  $R$ -module.

**Example 4.3.2**

Let  $R$  be a commutative ring. Then  $R[x]$  is a finitely generated algebra over  $R$  but is not a finite  $R$ -algebra.

**4.4 Zariski's Lemma****Lemma 4.4.1**

Let  $F$  be a field. Let  $f \in F[x]$ . Then the localization  $F[x]_f$  is not a field.

**Theorem 4.4.2: Zariski's Lemma**

Let  $F$  be a field. Let  $K$  be a field that is also a finitely generated algebra over  $F$ . Then  $K$  is a finite algebra. In particular,  $K$  is a finite dimensional vector space over  $F$ .

**Corollary 4.4.3**

Let  $F$  be an algebraically closed field. Let  $K$  be a field that is also a finitely generated algebra over  $F$ . Then the inclusion homomorphism  $F \hookrightarrow K$  is an  $F$ -algebra isomorphism.

**Corollary 4.4.4**

Let  $F$  be an algebraically closed field. Then every maximal ideal of  $F[x_1, \dots, x_n]$  is of the form  $(x_1 - a_1, \dots, x_n - a_n)$  for some  $a_1, \dots, a_n \in F$ .

## 5 Localization

### 5.1 Localization of a Ring

#### Definition 5.1.1: Multiplicative Set

Let  $R$  be a commutative ring.  $S \subseteq R$  is a multiplicative set if  $1 \in S$  and  $S$  is closed under multiplication:  $x, y \in S$  implies  $xy \in S$

#### Definition 5.1.2: Localization of a Ring

Let  $R$  be a commutative ring and  $S \subseteq R$  be a multiplicative set. Define the ring of fractions of  $R$  with respect to  $S$  by

$$S^{-1}R = \left\{ \frac{r}{s} \mid r \in R, s \in S \right\} / \sim$$

where we say that  $r/s \sim r'/s'$  if there exists  $t \in S$  such that  $t(rs' - r's) = 0$ .

#### Lemma 5.1.3

Let  $R$  be a commutative ring. Let  $f \in R$  be non-zero. Then the set  $\{f^n \mid n \in \mathbb{N}\}$  is a multiplicative set.

#### Definition 5.1.4: Localization at an Element

Let  $R$  be a commutative ring. Let  $f \in R$  be non-zero. Define the localization of  $R$  at  $f$  to be the ring

$$R_f = \{f^n \mid n \in \mathbb{N}\}^{-1}R$$

It is also denoted as  $R[1/f]$ .

#### Proposition 5.1.5

Let  $S^{-1}R$  be a ring of fractions.

- $\sim$  as defined in the ring of fractions is an equivalence relation
- $(S^{-1}R, +, \times)$  is a ring
- The map  $k : R \rightarrow S^{-1}R$  defined by  $r \mapsto r/1$  is a ring homomorphism, called the localization map.

*Proof.*

- Trivial
- Define addition by  $\frac{r}{s} + \frac{r'}{s'} = \frac{rs' + r's}{ss'}$  and multiplication by  $\frac{r}{s} \cdot \frac{r'}{s'} = \frac{rr'}{ss'}$ . Clearly addition is abelian, and has identity  $\frac{0}{1}$  and inverse  $\frac{-r}{s}$  for any  $\frac{r}{s} \in S^{-1}R$ . Multiplication also has identity  $\frac{1}{1}$ .

□

#### Proposition 5.1.6: Universal Property

Let  $R$  be a commutative ring. Let  $S$  be a multiplicative set. Then  $S^{-1}R$  and the localization map  $k : R \rightarrow S^{-1}R$  satisfies the following universal property.

For any commutative ring  $B$  and ring homomorphism  $\phi : R \rightarrow B$  such that  $\phi(s) \in B^\times$  for all  $s \in S$ , there exists a unique ring homomorphism  $\phi : S^{-1}R \rightarrow B$  such that the following diagram commutes:



$$\begin{array}{ccc}
 R & \xrightarrow{k} & S^{-1}R \\
 & \searrow \phi & \downarrow \exists! \psi \\
 & & B
 \end{array}$$

Moreover,  $S^{-1}R$  is the unique commutative ring (up to unique isomorphism) that has such a property.

#### Lemma 5.1.7

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset of  $R$ . If  $R$  is Noetherian, then  $S^{-1}R$  is Noetherian.

#### Lemma 5.1.8

Let  $R$  be a ring and  $P$  a prime ideal of  $R$ . Then  $R \setminus P$  is a multiplicative set.

*Proof.* By definition,  $xy \in P$  implies  $x \in P$  or  $y \in P$ , since  $R \setminus P$  removes all these elements, we have that  $x \notin P$  and  $y \notin P$  implies that  $xy \notin P$ .  $\square$

#### Definition 5.1.9: Localization at Prime Ideals

Let  $R$  be a commutative ring. Let  $P$  be a prime ideal. Denote

$$R_P = (R \setminus P)^{-1}R$$

the localization of  $R$  at  $P$ .

## 5.2 Localization of a Module

#### Definition 5.2.1: Localization of a Module

Let  $R$  be a commutative ring and  $S \subseteq R$  be a multiplicative set. Let  $M$  be a  $R$ -module. Define the ring of fractions of  $M$  with respect to  $S$  by

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

where  $\sim$  is defined by

$$\frac{m}{s} \sim \frac{m'}{s'} \text{ if and only if } \exists v \in S \text{ such that } v(mu' - m'u) = 0$$

If  $S = \{1, f, f^2, \dots\}$  then we write

$$S^{-1}M = M_f = M[1/f]$$

#### Lemma 5.2.2

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Let  $S \subseteq R$  be a multiplicative subset. Then  $S^{-1}M$  is an  $S^{-1}R$ -module with operation given by

$$\left( \frac{r}{s_1}, \frac{m}{s_2} \right) \mapsto \frac{r \cdot m}{s_1 s_2}$$

**Definition 5.2.3: Induced Map of Localization**

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset. Let  $M, N$  be  $R$ -modules. Let  $\phi : M \rightarrow N$  be an  $R$ -module homomorphism. Define the induced map

$$S^{-1}\phi : S^{-1}M \rightarrow S^{-1}N$$

by the formula  $\frac{m}{s} \mapsto \frac{\phi(m)}{s}$ .

**Lemma 5.2.4**

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset. Let  $M, N$  be  $R$ -modules. Let  $\phi : M \rightarrow N$  be an  $R$ -module homomorphism. Then the induced map

$$S^{-1}\phi : S^{-1}M \rightarrow S^{-1}N$$

is a well defined ring homomorphism.

**Proposition 5.2.5**

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset. Let the following be an exact sequence of  $R$ -modules.

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

Then the following is an exact sequence of  $S^{-1}R$ -modules.

$$0 \longrightarrow S^{-1}M_1 \xrightarrow{S^{-1}f} S^{-1}M_2 \xrightarrow{S^{-1}g} S^{-1}M_3 \longrightarrow 0$$

**Corollary 5.2.6**

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset. Let  $M$  be an  $R$ -module. Then the following are true.

- If  $N_1, N_2$  are  $R$ -submodules of  $M$ , then

$$S^{-1}(N_1 + N_2) = S^{-1}N_1 + S^{-1}N_2$$

as  $S^{-1}R$ -submodules of  $S^{-1}M$ .

- If  $N_1, N_2$  are  $R$ -submodules of  $M$ , then

$$S^{-1}(N_1 \cap N_2) = S^{-1}N_1 \cap S^{-1}N_2$$

as  $S^{-1}R$ -submodules of  $S^{-1}M$ .

- If  $N$  is an  $R$ -submodule of  $M$ , then

$$S^{-1}\frac{M}{N} \cong \frac{S^{-1}M}{S^{-1}N}$$

as  $S^{-1}R$ -modules.

- If  $N$  is an  $R$ -module, then

$$S^{-1}(M \oplus N) \cong S^{-1}M \oplus S^{-1}N$$

as  $S^{-1}R$ -modules.

**Proposition 5.2.7**

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Then there is an isomorphism

$$S^{-1}M \cong S^{-1}R \otimes_R M$$

of  $S^{-1}R$ -modules given by  $\frac{m}{s} \mapsto \frac{1}{s} \otimes m$ .

**Lemma 5.2.8**

Let  $R$  be a commutative ring. Let  $S \subseteq R$  be a multiplicative subset. Let  $M, N$  be  $R$ -modules. Let  $\phi : M \rightarrow N$  be an  $R$ -module homomorphism. Then the following are true.

- Localization commutes with kernels:

$$S^{-1}\ker(\phi) \cong \ker(S^{-1}\phi)$$

- Localization commutes with images:

$$S^{-1}(\operatorname{im} \phi) \cong \operatorname{im}(S^{-1}\phi)$$

- Localization commutes with cokernels:

$$S^{-1} \frac{N}{\operatorname{im}(\phi)} \cong \frac{S^{-1}N}{\operatorname{im}(S^{-1}\phi)}$$

**5.3 Localization of Integral Domains****Lemma 5.3.1**

Let  $R$  be a commutative ring. Let  $S$  be a multiplicative subset of  $R$ . If  $R$  is an integral domain, then the following are true.

- The localization map  $R \rightarrow S^{-1}R$  is injective.
- If  $0 \notin S$ , then  $S^{-1}R$  is an integral domain.

*Proof.* Suppose that  $0 = \frac{a}{s} \cdot \frac{b}{t}$ . By the equivalence relation this is the same as saying that  $uab = 0$  for some  $u \in S$ . Since  $R$  is an integral domain and  $0 \neq S$ , we conclude that  $u \notin S$  so that  $ab = 0$ . Again since  $R$  is an integral domain this implies that  $a = 0$  or  $b = 0$ . Hence either  $a/s = 0$  or  $b/t = 0$  in  $S^{-1}R$ . Hence  $S^{-1}R$  is an integral domain.  $\square$

**Proposition 5.3.2**

Let  $R$  be an integral domain. Then the following are true.

- $\operatorname{Frac}(R) = R_{(0)}$
- $R = \bigcap_{m \text{ a maximal ideal}} R_m$

**5.4 Ideals of a Localization****Definition 5.4.1: Ideals Closed Under Division**

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Let  $S \subseteq R$  be a multiplicative subset. We say that  $I$  is closed under division by  $s$  if for all  $s \in S$  and  $a \in R$  such that  $sa \in I$ , we have  $a \in I$ .

**Lemma 5.4.2**

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Let  $S \subseteq R$  be a multiplicative subset. Then we have

$$I^e = S^{-1}I$$

**Proposition 5.4.3**

Let  $R$  be a commutative ring. Let  $S$  be a multiplicative subset of  $R$ . Let  $P$  be a prime ideal of  $R$ . Then the following are true.

- $S^{-1}P$  is a prime ideal of  $S^{-1}R$  if and only if  $S \cap P = \emptyset$ .
- $S^{-1}P = S^{-1}R$  if and only if  $S \cap P \neq \emptyset$ .

*Proof.* Recall that  $R/P$  is an integral domain if  $P$  is prime. Since  $S^{-1}$  commutes with quotients, we have that

$$\frac{S^{-1}R}{S^{-1}P} \cong S^{-1} \frac{R}{P}$$

If  $S \cap P = \emptyset$ , then  $0 \in P$  implies that  $0 \notin S$ . This means that  $0 \notin \phi(S)$ . By 5.3.1 we conclude that  $S^{-1}(R/P)$  is an integral domain. Hence  $S^{-1}P$  is a prime ideal. If  $S \cap P \neq \emptyset$ , suppose that  $x \in S \cap P$ . Then ????? □

**Theorem 5.4.4**

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Let  $S \subseteq R$  be a multiplicative subset. Let  $\phi : R \rightarrow S^{-1}R$  denote the localization map. Then there is a one-to-one bijection

$$\{J \mid J \text{ is an ideal of } S^{-1}R\} \xleftrightarrow{1:1} \{I \mid I \text{ is an ideal of } R \text{ and closed under division by } S\}$$

whose map is given by  $J \mapsto J^c = \phi^{-1}(J)$  and inverse is given by  $I \mapsto I^e = S^{-1}I$ .

*Proof.* We first show that our map of sets are well defined. Let  $J$  be an ideal of  $S^{-1}R$ . We first show that  $\phi^{-1}(J)$  is closed under division by  $S$ . Suppose that  $s \in S$  and  $r \in R$  such that  $sr \in \phi^{-1}(J)$ . Then  $sr/1 \in J$ . Now since  $J$  is an ideal of  $S^{-1}R$ , we know that  $1/s \cdot sr/1 \in J$ . But  $1/s \cdot sr/1 = r/1 = \phi(r)$ . This means that  $\phi(r) \in J$  and hence  $r \in \phi^{-1}(J)$ . Thus  $\phi^{-1}(J)$  is an ideal closed under division by  $S$ .

Now let  $I$  be an ideal of  $R$  closed under division. I claim that  $S^{-1}I$  is an ideal of  $S^{-1}R$ . Let  $a/s, b/t \in S^{-1}I$ . Then  $a/s + b/t = (at + bs)/st$ . Since  $I$  is an ideal, we know that  $at + bs \in I$ . Also since  $S$  is a multiplicative subset,  $st \in S$ . Hence  $(at + bs)/st \in S^{-1}I$ . Now let  $a/s \in S^{-1}I$  and  $r/t \in S^{-1}R$ . Then  $(a/s) \cdot (r/t) = ar/st$ . Since  $I$  is an ideal,  $ar \in I$ . Thus  $ar/st \in S^{-1}I$  so that  $I$  is an ideal.

It remains to show that the two maps are inverses of each other. Let  $J$  be an ideal of  $S^{-1}R$ . We want to show that  $J = S^{-1}(\phi^{-1}(J))$ . Let  $a/s \in J$ . Since  $J$  is an ideal, we have  $\phi(a) = a/1 = 1/s \cdot a/s \in J$ . Hence  $a \in \phi^{-1}J$  so that  $a/s \in S^{-1}\phi^{-1}(J)$ . Thus  $J \subseteq S^{-1}(\phi^{-1}(J))$ . Now by 1.5.5 the extension of the contraction of  $J$  is a subset of  $J$ . Hence we conclude.

On the other hand, we also want to show that  $I = \phi^{-1}(S^{-1}I)$ . Again by 1.5.5 we know that  $I \subseteq \phi^{-1}(S^{-1}I)$ . Conversely, let  $x \in \phi^{-1}(S^{-1}I)$ . Then  $\phi(x) = x/1 \in S^{-1}I$ . This means that  $x/1 = b/t$  for some  $b \in I$  and  $t \in S$ . Then there exists  $u \in S$  such that  $uxt = ub$ . Since  $b \in I$ ,  $ub \in I$  hence  $uxt \in I$ . Since  $ut \in S$  and  $I$  is closed under division, we have  $x \in I$ .

This shows that  $S^{-1}(-)$  and  $\phi^{-1}(-)$  are mutual inverses of each others. Thus we conclude. □

Using the theorem we conclude that every ideal of  $S^{-1}R$  is of the form  $S^{-1}I$  for some ideal  $I$  of  $R$  such that  $I$  is closed under division by  $S$ .

#### Proposition 5.4.5

Let  $R$  be a commutative ring. Let  $I$  be an ideal of  $R$ . Let  $S \subseteq R$  be a multiplicative subset. Then the above bijection restricts to the following bijection

$$\{J \mid J \text{ is a prime ideal of } S^{-1}R\} \xleftrightarrow{1:1} \left\{ I \mid \begin{array}{l} I \text{ is a prime ideal of } R \\ \text{and } I \cap S = \emptyset \end{array} \right\}$$

*Proof.* Let  $\phi : R \rightarrow S^{-1}R$  be the localization map. From the above we know that  $Q = S^{-1}\phi^{-1}(Q)$  for any prime ideal  $Q$  of  $S^{-1}R$ . This implies that  $S^{-1}\phi^{-1}(Q)$  is prime. By 5.4.3 this implies that  $\phi^{-1}(Q) \cap S = \emptyset$ . Thus the map  $J \mapsto \phi^{-1}(J)$  induces a well defined map on our given sets of prime ideals.

Conversely, by 5.4.3 we know that if  $P$  is a prime ideal of  $R$  such that  $S \cap P = \emptyset$ , then  $S^{-1}P$  is a prime ideal of  $S^{-1}R$ . Hence the inverse map is also well defined on our domain and codomain. By the above theorem it is already a bijection, hence we are done.  $\square$

#### Proposition 5.4.6

Let  $R$  be a commutative ring. Let  $P$  be a prime ideal of  $R$ . Then the above bijection gives

$$\{J \mid J \text{ is a prime ideal of } R_P\} \xleftrightarrow{1:1} \left\{ I \mid \begin{array}{l} I \text{ is a prime ideal of } R \\ \text{and } I \subseteq P \end{array} \right\}$$

*Proof.* Notice that the condition that  $I \cap S = \emptyset$  in the above proposition translates to  $I \cap (R \setminus P) = \emptyset$ , which is the same as saying  $I \subseteq P$ .  $\square$

#### Proposition 5.4.7

Let  $R$  be a commutative ring and let  $P$  be a prime ideal of  $R$ . Then  $R_P$  is a local ring with unique maximal ideal given by

$$PR_P = \left\{ \frac{r}{s} \mid r \in P, s \notin P \right\}$$

*Proof.* We show that  $PR_P$  is the only unique maximal ideal. Suppose that  $I$  is an ideal in  $R_P$  such that  $I$  is not a subset of  $PR_P$ . Then there exists  $a/s \in I$  such that  $a \notin P$  and  $s \notin P$ . It is clear that  $s/a$  is then an element of  $R_P$ . So  $a/s$  is invertible. Hence  $I = R_P$ .  $\square$

Be wary that in general localizations does not result in a local ring. This happens only when we are localizing with respect to a prime ideal. The importance of prime ideals is not explicit in the above because only using prime ideals  $P$  can  $R \setminus P$  be a multiplicative set which ultimately allows localization to make sense.

## 5.5 Local Properties

### Definition 5.5.1: Local Properties of Modules

Let  $R$  be a commutative ring. A property of  $R$ -modules is local if for any  $R$ -modules  $M$ , the following are equivalent.

- $M$  has the property
- $M_P$  has the property for all prime ideals  $P$
- $M_m$  has the property for all maximal ideals  $m$

### Proposition 5.5.2: Injectivity and Surjectivity are Local Properties

Let  $R$  be a commutative ring. Let  $M, N$  be  $R$ -modules. Let  $\phi : M \rightarrow N$  be an  $R$ -module homomorphism. Let  $S$  be a multiplicative subset of  $R$ . Then the following are equivalent.

- $\phi$  is injective (surjective)
- For each prime ideal  $P$  of  $R$ , the induced map  $\phi_P : S^{-1}M \rightarrow S^{-1}N$  is injective (surjective)
- For each maximal ideal  $m$  of  $R$ , the induced map  $\phi_m : S^{-1}M \rightarrow S^{-1}N$  is injective (surjective)

More local properties: zero, nilpotent

Non-local properties: freeness, domain

### Proposition 5.5.3: Exactness is Local

Let  $R$  be a commutative ring. Let  $M_1, M_2, M_3$  be  $R$ -modules. Let  $f : M_1 \rightarrow M_2$  and  $g : M_2 \rightarrow M_3$  be  $R$ -module homomorphisms. Then the following conditions are equivalent.

- The following sequence is exact:

$$0 \longrightarrow M_1 \xrightarrow{f} M_2 \xrightarrow{g} M_3 \longrightarrow 0$$

- The following sequence is exact:

$$0 \longrightarrow (M_1)_P \xrightarrow{f_P} (M_2)_P \xrightarrow{g_P} (M_3)_P \longrightarrow 0$$

for all prime ideals  $P$  of  $R$ .

- The following sequence is exact:

$$0 \longrightarrow (M_1)_m \xrightarrow{f_m} (M_2)_m \xrightarrow{g_m} (M_3)_m \longrightarrow 0$$

for all maximal ideals  $m$  of  $R$ .

### Definition 5.5.4: Local Properties of Elements

A property of an element of  $M$  is local if the following is true.  $m \in M$  has the property if and only if  $m \in M_P$  has the property.

## 6 Primary Decomposition

### 6.1 Support of a Module

#### Definition 6.1.1: Support of a Module

Let  $A$  be a commutative ring. Let  $M$  be an  $A$ -module. The support of  $M$  is the subset

$$\text{Supp}(M) = \{P \text{ a prime ideal of } A \mid M_P \neq 0\}$$

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Recall that the annihilator of an element  $m \in M$  is the ideal

$$\text{Ann}_R(m) = \{r \in R \mid r \cdot m = 0\}$$

Moreover, we define

$$\text{Ann}_R(M) = \{r \in R \mid r \cdot m = 0 \text{ for all } m \in M\} = \bigcap_{m \in M} \text{Ann}_R(m)$$

#### Proposition 6.1.2

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Let  $P$  be a prime ideal of  $R$ . Then  $P \in \text{Supp}(M)$  if and only if  $\text{Ann}_R(M) \subseteq P$ .

### 6.2 Associated Prime

#### Definition 6.2.1: Associated Prime

Let  $M$  be an  $A$ -module. An associated prime of  $M$  is a prime ideal  $P$  of  $A$  such that

$$P = \text{Ann}_A(m)$$

for some  $m \in M$ . Also define

$$\text{Ass}(M) = \{P \text{ a prime ideal of } A \mid P \text{ is an associated prime of } M\}$$

#### Proposition 6.2.2

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Then

$$\text{Ass}(M) \subseteq \text{Supp}(M)$$

#### Proposition 6.2.3

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Then the following are true.

- $\text{Ass}(M)$  is a finite set.
- For  $P \in \text{Ass}(M)$ ,  $\text{Ann}_R(M) \subseteq P$ .
- We have

$$\text{Ass}(M) = \{P \in \text{Spec}(R) \mid \text{For any prime ideal } Q \subseteq P, Q \text{ does not contain } \text{Ann}_R(M)\}$$

*Proof.*

- 
- We have seen that every  $P \in \text{Supp}(M)$  is such that  $\text{Ann}_R(M) \subseteq P$ . Since  $\text{Ass}(M) \subseteq \text{Supp}(M)$ , we are done.

□

**Proposition 6.2.4**

Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Then

$$\bigcup_{P \in \text{Ass}(M)} P = \{m \in M \mid m \text{ is a zero divisor of } M\} \cup \{0\}$$

**Theorem 6.2.5: Disassembly of an  $R$ -Module**

Let  $R$  be a Noetherian commutative ring. Let  $M$  be a finitely generated  $R$ -module. Then there exists a chain of  $R$ -submodules

$$0 = M_0 \subset M_1 \subset \cdots \subset M_k = M$$

such that

$$\frac{M_{i+1}}{M_i} \cong \frac{R}{P_i}$$

for some prime ideal  $P_i$  of  $R$ .

**6.3 Primary Ideals****Definition 6.3.1: Primary Ideals**

Let  $R$  be a commutative ring. Let  $Q$  be a proper ideal of  $R$ . We say that  $Q$  is a primary ideal of  $R$  if  $fg \in Q$  implies  $f \in Q$  or  $g^m \in Q$  for some  $m > 0$ .

**Lemma 6.3.2**

Let  $A$  be a commutative ring. Let  $Q$  be a primary ideal of  $A$ . Then  $\sqrt{Q}$  is the smallest prime ideal containing  $Q$ .

**Lemma 6.3.3**

Let  $R$  be a Noetherian ring and  $I$  be a proper ideal that is not primary. Then

$$I = J_1 \cap J_2$$

for some ideals  $J_1, J_2 \neq I$ .

**Definition 6.3.4:  $P$ -Primary Ideals**

Let  $A$  be a commutative ring. Let  $P$  be a prime ideal. Let  $Q$  be an ideal. We say that  $Q$  is a  $P$ -primary ideal of  $A$  if

$$Q = \sqrt{P}$$

**Theorem 6.3.5**

Let  $A$  be a Noetherian ring and  $Q$  an ideal of  $A$ . Then  $Q$  is  $P$ -primary if and only if  $\text{Ann}(A/Q) = \{P\}$ .

**6.4 Primary Decomposition**

We want to express ideal  $I$  in  $R$  as  $I = P_1^{e_1} \cdots P_n^{e_n}$  similar to a factorization of natural numbers, for some prime ideals  $P_1, \dots, P_n$ . However this notion fails and thus we have the following new type of ideal.



**Definition 6.4.1: Primary Decompositions**

Let  $A$  be a commutative ring. Let  $I$  be an ideal of  $A$ . A primary decomposition  $I$  consists of primary ideals  $Q_1, \dots, Q_r$  of  $A$  such that

$$I = Q_1 \cap \dots \cap Q_r$$

**Definition 6.4.2: Minimal Primary Decompositions**

Let  $A$  be a commutative ring. Let  $I$  be an ideal of  $A$ . Let

$$I = Q_1 \cap \dots \cap Q_r$$

be a primary decomposition of  $I$ . We say that the decomposition is minimal if the following are true.

- Each  $\sqrt{Q_i}$  are distinct for  $1 \leq i \leq r$
- Removing a primary ideal changes the intersection. This means that for any  $i$ ,  
 $I \neq \bigcap_{j \neq i} Q_j$

**Theorem 6.4.3**

Every proper ideal in a Noetherian ring has a primary decomposition.

**Lemma 6.4.4**

Let  $\phi : R \rightarrow S$  be a ring homomorphism and  $Q$  be a primary ideal in  $S$ . Then  $\phi^{-1}(Q)$  is primary in  $R$ .

## 7 Integral Dependence

### 7.1 Integral Elements

#### Definition 7.1.1: Integral Elements

Let  $B$  be a commutative ring and let  $A \subseteq B$  be a subring. Let  $b \in B$ . We say that  $b$  is integral over  $A$  if there exists a monic polynomial  $p(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_0 \in A[x]$  such that  $p(b) = 0$ .

When  $A$  and  $B$  are field, this is a familiar notion in Field and Galois theory.

#### Lemma 7.1.2

Let  $K$  be a field. Let  $F \subseteq K$  be a subfield. Let  $k \in K$ . Then  $k$  is integral over  $F$  if and only if  $k$  is algebraic over  $F$ .

#### Proposition 7.1.3

Let  $B$  be a commutative ring and let  $A \subseteq B$ . Let  $b \in B$ . Then the following are equivalent.

- $b$  is integral over  $A$
- $A[b] \subseteq B$  is finitely generated  $A$ -submodule.
- There exists an  $A$  sub-algebra  $A' \subseteq B$  such that  $A[b] \subseteq A'$  and  $A'$  is finitely generated as an  $A$ -module.

#### Proposition 7.1.4

Let  $A \subseteq B$  be commutative rings. Then  $B$  is a finitely generated  $A$ -module if and only if  $B = A[x_1, \dots, x_n]$  for some  $x_1, \dots, x_n \in B$  that is integral over  $A$ .

#### Proposition 7.1.5

Let  $B$  be a commutative ring and let  $A \subseteq B$  be a subring. Let  $b_1, b_2 \in B$  be integral over  $A$ . Then  $b_1 + b_2$  and  $b_1 b_2$  are both integral over  $A$ .

### 7.2 Integral Closure

#### Definition 7.2.1: Integral Closure

Let  $B$  be a commutative ring. Let  $A \subseteq B$  be a subring. Define the subring

$$\overline{A} = \{b \in B \mid b \text{ is integral over } A\}$$

to be the integral closure of  $A$  in  $B$ .

#### Proposition 7.2.2

Let  $B$  be a commutative ring. Let  $A \subseteq B$  be a subring. Let  $S$  be a multiplicatively closed subset of  $A$ . Then

$$\overline{S^{-1}A} = S^{-1}\overline{A}$$

#### Definition 7.2.3: Integral Extensions

Let  $B$  be a commutative ring and let  $A \subseteq B$  be a subring. We say that  $B$  is integral over  $A$  if  $\overline{A} = B$ . We also say that  $B$  is the integral extension of  $A$ .

**Lemma 7.2.4**

Let  $A \subseteq B \subseteq C$  be commutative rings. Then  $C$  is integral over  $B$  and  $B$  is integral over  $A$  if and only if  $C$  is integral over  $A$ .

**Proposition 7.2.5**

Let  $A, B$  be commutative rings such that  $A \subset B$  is an integral extension. Let  $J$  be an ideal of  $B$ . Then  $\frac{B}{J}$  is integral over  $\frac{A}{J \cap A}$ .

**Proposition 7.2.6**

Let  $A, B$  be commutative rings such that  $A \subset B$  is an integral extension. Let  $S$  be a multiplicative subset of  $B$ . Then  $S^{-1}B$  is integral over  $S^{-1}A$ .

**Lemma 7.2.7**

Let  $A, B$  be integral domains such that  $A \subset B$  is an integral extension. Then  $A$  is a field if and only if  $B$  is a field.

**Definition 7.2.8: Integrally Closed**

Let  $B$  be a commutative ring. Let  $A \subseteq B$  be a subring. We say that  $A$  is integrally closed in  $B$  if  $\overline{A} = A$ .

**7.3 The Going-Up and Going-Down Theorems**

We want to compare prime ideals between integral extensions.

**Proposition 7.3.1**

Let  $A, B$  be rings such that  $A \subset B$  is an integral extension. Let  $Q$  be a prime ideal of  $B$ . Then  $Q \cap A$  is a maximal ideal of  $A$  if and only if  $Q$  is a maximal ideal of  $B$ .

**Proposition 7.3.2**

Let  $A, B$  be rings such that  $A \subset B$  is an integral extension. Let  $P$  be a prime ideal of  $A$ . Then the following are true.

- There exists a prime ideal  $Q$  of  $B$  such that  $P = Q \cap A$
- If  $Q_1, Q_2$  are prime ideals of  $B$  such that  $Q_1 \cap A = P = Q_2 \cap A$  and  $Q_1 \subseteq Q_2$ , then  $Q_1 = Q_2$ .

**Theorem 7.3.3: The Going-Up Theorem**

Let  $A, B$  be rings such that  $A \subset B$  is an integral extension. Let  $0 \leq m < n$ . Consider the following situation

$$\begin{array}{ccc} B & Q_1 \subseteq \cdots \subseteq Q_m & \text{(Prime ideals of } B) \\ \uparrow & & \\ A & P_1 \subseteq \cdots \subseteq P_m \subseteq P_{m+1} \subseteq \cdots \subseteq P_n & \text{(Prime ideals of } A) \end{array}$$

where  $Q_i \cap A = P_i$  for  $1 \leq i \leq m$ . Then there exists prime ideals  $Q_{m+1}, \dots, Q_n$  of  $B$  such that the following are true.

- $Q_{m+1} \subseteq \cdots \subseteq Q_n$
- $Q_i \cap A = P_i$  for  $m+1 \leq i \leq n$

## 7.4 Normal Domains

We now concern ourselves with integral domains. Let  $R$  be an integral domain. A special fact about  $R$  is that the canonical homomorphism  $R \rightarrow R_{(0)} = \text{Frac}(R)$  is an injection. This means that we can think of  $R$  as living inside of  $\text{Frac}(R)$  while preserving all the structure of  $R$ .

### Definition 7.4.1: Normal Domains

Let  $R$  be an integral domain. We say that  $R$  is normal if  $R$  is integrally closed in  $\text{Frac}(R)$ .

### Proposition 7.4.2

Let  $R$  be a normal domain. Let  $S$  be a multiplicative subset of  $R$ . Then  $S^{-1}R$  is a normal domain.

*Proof.* We want to show that  $S^{-1}R$  is integrally closed in  $\text{Frac}(R) = \text{Frac}(S^{-1}R)$ . This means that we want to show  $\overline{S^{-1}R} = S^{-1}R$ . It is clear that  $S^{-1}R \subseteq \overline{S^{-1}R}$ . So let  $g \in \overline{S^{-1}R}$ . Suppose that  $p(x) = x^n + \sum_{k=0}^{n-1} a_k x^k \in (S^{-1}R)[x]$  such that  $p(g) = 0$ . Choose  $s \in S$  such that  $sa_i \in R$  for  $0 \leq i \leq n-1$ . Then notice that  $sg \in S^{-1}R$  satisfies the monic polynomial

$$q(x) = x^n + \sum_{k=0}^{n-1} s^{n-k} a_k x^k$$

since  $q(sg) = s^n g^n + \sum_{k=0}^{n-1} s^n a_k x^k = s^n p(g) = 0$ . But  $q$  is a polynomial in  $R$  since  $s^{n-k} a_k \in R$ . Thus we have that  $sg \in \overline{R} = R$  since  $R$  is normal. This means that  $g \in S^{-1}R$  and hence we conclude.  $\square$

### Proposition 7.4.3

Let  $R$  be a commutative ring. If  $R$  is a UFD, then  $R$  is normal.

### Proposition 7.4.4: Normal is a Local Property

Let  $R$  be an integral domain. Then the following are equivalent.

- $R$  is normal
- $R_P$  is normal for all prime ideals  $P$
- $R_m$  is normal for all maximal ideals  $m$ .

*Proof.* Notice that an integral domain  $R$  is normal if and only if the canonical inclusion map  $R \hookrightarrow \overline{R}$  is surjective. Since surjectivity is a local property, this map is surjective if and only if for all prime ideals  $P$  of  $R$ ,  $R_P \hookrightarrow \overline{R}_P$  is surjective. But  $\overline{R}_P = \overline{R_P}$  by the above. Hence  $R \hookrightarrow \overline{R}$  is surjective if and only if  $R_P \rightarrow \overline{R_P}$  is surjective. Hence  $R$  is normal if and only if  $R_P$  is normal for all prime ideals  $P$  of  $R$ . The similar holds for all maximal ideals.  $\square$

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### Proposition 7.4.5

Let  $R$  be a normal domain. Then  $R[x]$  is a normal domain.

### Proposition 7.4.6

Let  $R$  be a normal domain. Let  $K/\text{Frac}(R)$  be an algebraic extension. Let  $f \in K$ . Then  $f$  is integral over  $R$  if and only if the minimal polynomial  $\min(K, f) \in R[x]$ .

## 8 Introduction to Dimension Theory for Rings

### 8.1 Krull Dimension

#### Definition 8.1.1: Krull Dimension

Let  $R$  be a commutative ring. Define the Krull dimension of  $R$  to be

$$\dim(R) = \max\{t \in \mathbb{N} \mid p_0 \subset \cdots \subset p_t \text{ for } p_0, \dots, p_t \text{ prime ideals}\}$$

In particular, notice that a commutative ring  $R$  has  $\dim(R) = 0$  if and only if every prime ideal is maximal.

#### Lemma 8.1.2

Let  $R, S$  be commutative rings such that  $R \subseteq S$  is an integral extension. Then  $\dim(R) = \dim(S)$ .

#### Proposition 8.1.3

Let  $F$  be a field. Let  $n \in \mathbb{N} \setminus \{0\}$ . Then the following are true.

- $\dim(F[x_1, \dots, x_n]) = n$ .
- Every maximal chain prime ideals in  $F[x_1, \dots, x_n]$  is of length  $n$ .

#### Lemma 8.1.4

Let  $R$  be a commutative ring. Then the following are true.

- If  $R$  is a field, then  $\dim(R) = 0$
- If  $R$  is Artinian, then  $\dim(R) = 0$

*Proof.* Let  $R$  be a field. Then the only proper prime ideal of  $R$  is  $(0)$ . In particular,  $(0)$  forms the only chain of prime ideals in  $R$ . Hence  $\dim(R) = 0$ .

Now let  $R$  be Artinian. Let  $P$  be a prime ideal of  $R$ . Then  $R/P$  is an integral domain. Moreover, every quotient of an Artinian ring is Artinian. Hence  $R/P$  is Artinian. By prp1.3.1, we conclude that  $R/P$  is a field. Hence  $P$  is a maximal ideal. Any chain of prime ideals of  $R$  must terminate at the first prime ideal since it is maximal. Hence  $\dim(R) = 0$ . □

### 8.2 Height of Prime Ideals

#### Definition 8.2.1: Height of a Prime Ideal

Let  $R$  be a commutative ring. Let  $p$  be a prime ideal of  $R$ . Define the height of  $p$  to be

$$\text{ht}(p) = \max\{t \in \mathbb{N} \mid p_0 \subset \cdots \subset p_t = p \text{ for } p_0, \dots, p_t \text{ prime ideals}\}$$

#### Lemma 8.2.2

Let  $R$  be a commutative ring. Then

$$\dim(R) = \max\{\text{ht}(P) \mid P \in \text{Spec}(R)\}$$

**Lemma 8.2.3**

Let  $R$  be a commutative ring. Let  $P$  be a prime ideal of  $R$ . Then

$$\text{ht}(P) = \dim(R_P)$$

*Proof.* Let  $\dim(R_P) = n$ . Then there exists a strict chain of prime ideals of  $R_P$  of length  $n$  (and no chain of prime ideals of length  $> n$ ). By prp5.4.6, prime ideals of  $R_P$  are in bijection with prime ideals of  $R$  that  $P$  contains. Hence the maximal chain of prime ideals of length  $n$  correspond to a chain of prime ideals in  $R$  that contain  $P$ , of length  $n$ . Hence  $\dim(R_P) = n \leq \text{ht}(P)$ . Conversely, let  $m = \text{ht}(P)$ . Then there exists a strict chain of prime ideals that are subsets of  $P$ , that are of length  $m$ . By the same correspondence, the chain of prime ideals correspond to a chain of prime ideals in  $R_P$  of length  $m$ . Hence  $\text{ht}(P) = m \leq \dim(R_P)$ .

The two inequalities combine to show that  $\dim(R_P) = \text{ht}(P)$ . □

**Lemma 8.2.4**

Let  $R$  be a commutative ring. Let  $P$  be a prime ideal of  $R$ . Then

$$\dim(R) \geq \dim(R/P) + \text{ht}_R(P)$$

**Proposition 8.2.5**

Let  $k$  be a field. Let  $A$  be an integral domain that is a finitely generated  $k$ -algebra. Then the following are true.

- $\dim(A) = \text{trdeg}_k(\text{Frac}(A))$
- For any prime ideal  $P$  of  $A$ , we have

$$\dim(A) = \dim(A/P) + \text{ht}_A(P)$$

**Proposition 8.2.6: Dimension is a Local Concept**

Let  $R$  be a commutative ring. Then the following numbers are equal.

- The Krull dimension  $\dim(R)$
- The supremum  $\sup\{\dim(R_m) \mid m \text{ is a maximal ideal of } R\}$
- The supremum  $\sup\{\text{ht}_R(m) \mid m \text{ is a maximal ideal of } R\}$

**Theorem 8.2.7: Krull's Principal Ideal Theorem**

Let  $R$  be a Noetherian ring. Let  $I$  be a proper and principal ideal of  $R$ . Let  $p$  be the smallest prime ideal containing  $I$ . Then

$$\text{ht}_R(p) \leq 1$$

**8.3 Length of a Module over Commutative Rings**

Let  $R$  be a ring. Recall that the length of an  $R$ -module  $M$  is defined to be the supremum

$$l_R(M) = \sup\{n \in \mathbb{N} \mid 0 = M_0 \subset M_1 \subset \cdots \subset M_n = M\}$$

**Lemma 8.3.1**

Let  $(A, m)$  be a local ring and let  $M$  be an  $A$ -module. If  $mM = 0$ , then

$$l_A(M) = \dim_{A/m}(M)$$

**Proposition 8.3.2**

Let  $R$  be a commutative ring and let  $M$  be an  $R$ -module. Then the following are equivalent.

- $M$  is simple
- $l_R(M) = 1$
- $M \cong R/m$  for some maximal ideal  $m$  of  $R$

**8.4 The Hilbert Polynomial****Definition 8.4.1: The Hilbert Polynomial**

Let  $R = \bigoplus_{k=0}^{\infty} R_k$  be a Noetherian graded ring. Let  $M = \bigoplus_{k=0}^{\infty} M_k$  be a graded  $R$ -module. Define the Hilbert function  $H_M : \mathbb{N} \rightarrow \mathbb{N}$  of  $R$  to be the function defined by

$$H_M(n) = l_{R_0}(M_n)$$

**Definition 8.4.2: The Hilbert Series**

Let  $R = \bigoplus_{k=0}^{\infty} R_k$  be a Noetherian graded ring. Let  $M = \bigoplus_{k=0}^{\infty} M_k$  be a graded  $R$ -module. Define the Hilbert series  $HS_M \in \mathbb{Z}[[t]]$  of  $M$  to be the formal series

$$HS_M(t) = \sum_{k=0}^{\infty} H_M(k)t^k = \sum_{k=0}^{\infty} l_{R_0}(M_k)t^k$$

**Proposition 8.4.3**

Let  $R = \bigoplus_{k=0}^{\infty} R_k$  be a Noetherian graded ring such that  $R_0$  is Artinian. Let  $M = \bigoplus_{k=0}^{\infty} M_k$  be a graded  $R$ -module. Let  $\lambda : \{M_i \mid i \in I\} \rightarrow \mathbb{Z}$  be an additive function. Then the function

$$g(t) = \sum_{k=0}^{\infty} \lambda(M_k)t^k$$

is a rational function and can be written in the form

$$g(t) = \frac{f(t)}{\prod_{i=1}^r (1 - t^{d_i})}$$

for some  $f(t) \in \mathbb{Z}[t]$  and  $d_i \in \mathbb{N}$ .

**Theorem 8.4.4: The Fundamental Theorem of Dimension Theory**

Let  $(R, m)$  be a local Noetherian ring. Let  $I$  be an  $m$ -primary ideal. Then the following numbers are equal.

- Let  $J = \bigoplus_{k=0}^{\infty} \frac{I^k}{I^{k+1}}$ . The order of the pole at 1 of the rational function  $HS_J$ .
- The minimum number of elements of  $R$  that can generate an  $m$ -primary ideal of  $R$
- The dimension  $\dim_{R/m}(R)$

The following is a generalization of Krull's principal ideal theorem. Both of the theorems can actually be deduced directly from the fundamental theorem.

**Theorem 8.4.5: Krull's Height Theorem**

Let  $R$  be a Noetherian ring. Let  $I$  be a proper ideal generated by  $n$  elements. Let  $p$  be the smallest prime ideal containing  $I$ . Then

$$\text{ht}_R(p) \leq n$$

**Proposition 8.4.6**

Let  $(R, m)$  be a Noetherian local ring and let  $k = R/m$  be the residue field. Then

$$\dim(R) \leq \dim_k(m/m^2)$$

**8.5 Structure Theorem for Artinian Rings**

Let  $R$  be a ring. Let  $M$  be an  $R$ -module. Recall that a composition series for  $M$  is a sequence of  $R$ -submodules

$$0 = M_0 \subset M_1 \subset \cdots \subset M_k = M$$

such that  $\frac{M_{i+1}}{M_i}$  is a simple  $R$ -module for  $1 \leq i < k$ .

**Proposition 8.5.1**

Let  $R \neq 0$  be a commutative ring. Then  $R$  is Artinian if and only if  $R$  is Noetherian and  $\dim(R) = 0$ .

*Proof.* Let  $R$  be Artinian. In Rings and Modules, the Akizuki-Hopkins-Levitzki theorem proves that  $R$  is Noetherian. Moreover, Imm8.1.4 shows that  $\dim(R) = 0$ .

Now let  $R$  be Noetherian and  $\dim(R) = 0$ . This means that every prime ideal of  $R$  is maximal. Let  $S$  be the set of all ideals of  $R$  that admit a composition series. I claim that  $S$  is non-empty. Let  $T = \{\text{Ann}(x) \mid 0 \neq x \in R\}$ . Clearly  $T$  is non-empty. Let  $Y_1 \subseteq Y_2 \subseteq \cdots$  be a chain in  $T$ . Since  $R$  is Noetherian, the chain terminates at finitely many sets with  $Y = \text{Ann}(x) \subseteq R$  for some  $x \in R$ . I claim that  $Y$  is a prime ideal. By definition  $R = \text{Ann}(0) \notin T$  hence  $R \notin T$ . This means that  $Y \neq R$ . Let  $ab \in Y = \text{Ann}(x)$ . Suppose that  $b \notin Y$ . We know that  $abx = 0$  so  $a \in \text{Ann}(bx)$ . Since  $bx \neq 0$ , we have  $\text{Ann}(bx) \in T$ . Since  $R$  is commutative, we also have that  $\text{Ann}(x) \subseteq \text{Ann}(bx)$ . Since  $\text{Ann}(x)$  is maximal, we have that  $\text{Ann}(x) = \text{Ann}(bx)$ . Hence  $a \in \text{Ann}(x)$ . Thus  $\text{Ann}(x)$  is prime. Since  $\dim(R) = 0$  we have  $\text{Ann}(x)$  is a maximal ideal.  $R/\text{Ann}(x)$  is a field (and hence a simple  $R$ -module). The multiplication map  $r \mapsto rx$  has kernel  $\text{Ann}(x)$ . Hence the induced map  $R/\text{Ann}(x) \rightarrow R$  is injective, and we can consider  $R/\text{Ann}(x)$  as a subring of  $R$ . Together with the fact that it is a simple  $R$ -module makes it an  $R$ -submodule with composition series length of 1. Hence  $S$  is non-empty.

Let  $N_1 \subseteq N_2 \subseteq \cdots$  be a chain in  $S$ . Since  $R$  is Noetherian, the chain terminates with some ideal  $I \in S$ . If  $I = R$ , then  $R$  has a composition series. If  $I \neq R$ , then  $R/I$  is non-zero. Choose a prime ideal  $P$  of  $R$  such that  $I \subseteq P \neq R$  (this always exists since we can choose maximal ideals). Then we have  $0 \neq R/P \subseteq R/I$ . Let  $p : R \rightarrow R/I$  be the projection map. Let  $T = p^{-1}(R/P)$ . Then we have that  $N \subset T \subseteq M$  and  $T/N \cong R/P$ . Since  $\dim(R) = 0$ ,  $P$  is maximal hence  $R/P$  is a field (and a simple  $R$ -module). This proves that  $T \in S$ . But this contradicts the maximality of  $N$ . Hence  $N = R \in T$ . Thus  $R$  has a composition series. From Rings and Modules we know that this implies  $R$  is Noetherian. Hence we conclude.  $\square$

Recall from Rings and Modules that we have seen that Artinian rings have finitely many maximal ideals.

**Theorem 8.5.2: Structure Theorem for Commutative Artinian Rings**

Let  $R$  be an Artinian commutative ring. Then  $R$  decomposes into a direct product of Artinian local rings

$$R \cong \bigoplus_{i=1}^k R_i$$

Moreover, the decomposition is unique up to reordering of the direct product.



*Proof.* Let  $m_1, \dots, m_k$  be the full list of distinct maximal ideals of  $R$ . Then

$$\prod_{i=1}^k m_i^n = 0$$

for some  $n \in \mathbb{N} \setminus \{0\}$ . The ideals  $m_i^n$  and  $m_j^n$  are pairwise coprime for  $i \neq j$ . Hence by the Chinese Remainder Theorem we obtain ring isomorphisms

$$\begin{aligned} R &\cong \frac{R}{0} \\ &\cong \frac{R}{\prod_{i=1}^k m_i^n} \\ &\cong \frac{R}{\bigcap_{i=1}^k m_i^n} && (m_i^n \text{ and } m_j^n \text{ pairwise coprime}) \\ &\cong \bigoplus_{i=1}^k \frac{R}{m_i^n} && (\text{CRT}) \end{aligned}$$

By the correspondence of maximal ideals,  $R/m_i^n$  has a unique maximal ideal  $m_i/m_i^n$ . Hence it is local. Also since  $R$  is Artinian,  $R/m_i^n$  is Artinian. Thus we are done.  $\square$

## 9 Valuation and Valuation Rings

### 9.1 Valuation Rings

#### Definition 9.1.1: Valuation Rings

Let  $R$  be an integral domain. We say that  $R$  is a valuation ring if for all  $x \in \text{Frac}(R)$  and  $x \neq 0$ , then either  $x$  or  $x^{-1}$  is in  $R$ .

#### Lemma 9.1.2

Let  $R$  be a valuation ring. Then the following are true.

- $R$  is a local ring.
- $R$  is normal.

*Proof.* Let  $R$  be a valuation ring. The set of units of  $R$  are precisely  $S = \{x \in \text{Frac}(R) \mid x \in R \text{ and } x^{-1} \in R\}$ . Let  $m = R \setminus S$ . Let  $x \in m$  and  $r \in R$ . Then  $rx$  is not a unit because if  $arx = 1$ , then  $ar \in R$  is an inverse of  $x$ , which is a contradiction since  $x \in S$ . Hence  $rx \in m$ .

Let  $x, y \in m$ . If one of them are zero then their sum lies in  $m$ . If both are not zero, then  $xy^{-1}$  is an element of  $\text{Frac}(R)$ . Since  $R$  is a valuation ring, either  $xy^{-1}$  or  $yx^{-1}$  is in  $R$ . In either case, we have

$$x + y = y(y^{-1}x + 1) = x(1 + x^{-1}y) \in m$$

(one factor is in  $m$  and the other in  $R$ ). Hence  $m$  is an ideal. By prp2.1.3 we conclude that  $R$  is a local ring with unique maximal ideal  $m$ .

Let  $x \in \text{Frac}(R)$  be integral over  $R$ . Then

$$x^n + r_{n-1}x^{n-1} + \cdots + r_1x + r_0 = 0$$

for some  $r_0, \dots, r_{n-1} \in R$ . If  $x \in R$  then we are done. If  $x \notin R$  then since  $R$  is a valuation ring,  $x^{-1} \in R$ . Then

$$x = -(r_1 + r_2x^{-1} + \cdots + r_nx^{1-n}) \in R$$

so that  $R$  is normal. □

### 9.2 Valuations on a Field

#### Definition 9.2.1: Totally Ordered Group

Let  $G$  be an abelian group. We say that  $G$  is a totally ordered group if there is a total order " $\leq$ " on  $G$  such that  $a \leq b$  implies  $ca \leq cb$  for all  $a, b, c \in G$ .

#### Definition 9.2.2: Valuation on a Field

Let  $K$  be a field. Let  $G$  be a totally ordered abelian group. A valuation on  $K$  with values in  $G$  is a group homomorphism  $v : K^\times \rightarrow G$  such that for all  $x, y \in K^*$ , we have

- $v(xy) = v(x) + v(y)$
- $v(x + y) \geq \min\{v(x), v(y)\}$

We use the convention that  $v(0) = \infty$ .

#### Definition 9.2.3: Associated Valuation Ring

Let  $K$  be a field and  $v : K \rightarrow \mathbb{Z}$  a discrete valuation. Define the associated valuation ring of

$K$  to be the subring

$$R_v = \{x \in K \mid v(x) \geq 0\}$$

#### Lemma 9.2.4

Let  $K$  be a field. Let  $v$  be a discrete valuation on  $K$ . Then  $R_v$  is a valuation ring.

### 9.3 Discrete Valuations and Normalizations

#### Definition 9.3.1: Discrete Valuations

Let  $K$  be a field. A discrete valuation on  $K$  is a valuation  $v : K^\times \rightarrow \mathbb{Z}$ .

#### Definition 9.3.2: Normalized Discrete Valuations

Let  $(K, v)$  be a discrete valuation ring. We say that it is normalized if  $v$  is surjective.

#### Lemma 9.3.3

Let  $K$  be a field with a discrete valuation  $v$ . Then  $v(K^\times) = n\mathbb{Z}$  for some  $n \in \mathbb{N}$ .

#### Lemma 9.3.4: Normalization of a Discrete Valuation

Let  $K$  be a field with a discrete valuation  $v$  such that  $v(K^\times) = n\mathbb{Z}$  for some  $n \in \mathbb{N}$ . Define the normalization of  $v$  to be the valuation  $v_N : K^\times \rightarrow \mathbb{Z}$  defined by

$$v_N(k) = \frac{1}{n}v(k)$$

for all  $k \in K^\times$ .

Therefore we always work on normalized discrete valuation rings.

### 9.4 Discrete Valuation Rings

#### Definition 9.4.1: Discrete Valuation Rings

Let  $R$  be a commutative ring. We say that  $R$  is a discrete valuation ring if there exists a field  $K$  and a discrete valuation  $v$  on  $K$  such that

$$R = R_v$$

is the associated valuation ring of  $K$ .

#### Proposition 9.4.2

Let  $R$  be a discrete valuation ring with valuation  $v$ . Let  $t \in R$  be such that  $v(t) = 1$ . Then the following are true.

- A nonzero element  $u \in R$  is a unit if and only if  $v(u) = 0$
- $\dim(R) = 1$

*Proof.*

- Let  $R$  be a discrete valuation ring. Suppose that  $x \in R$  is a unit. Then  $v(x^{-1}) = -v(x)$ . Then  $-v(x), v(x) \geq 0$  implies  $v(x) = 0$ . Now if  $v(y) > 0$ , suppose for contradiction that

$u \in R$  is an inverse of  $y$ , then

$$0 = v(1) = v(uy) = v(u) + v(y)$$

But  $v(y) > 0$  implies that  $v(u) < 0$  which implies that  $u \notin R$ , a contradiction.  $\square$

#### Definition 9.4.3: Uniformizing Parameter

Let  $R$  be a discrete valuation ring with valuation  $v$ . A uniformizing parameter for  $R$  is an element  $t \in R$  such that  $v(t) = 1$ .

#### Proposition 9.4.4

Let  $R$  be a discrete valuation ring with valuation  $v$ . Let  $t \in R$  be a uniformizing parameter of  $R$ . Then the following are true.

- Every non-zero ideal of  $R$  is a principal ideal of the form  $(t^n)$  for some  $n \geq 0$
- Every  $r \in R \setminus \{0\}$  can be written in the form  $r = ut^n$  for some unit  $u$  and  $n \geq 0$ .

*Proof.*

- Let  $t \in R$  such that  $v(t) = 1$ . Let  $x \in m$  where  $v(x) = n > 0$ . Then  $v(x) = nv(t) = v(t^n)$  means that every  $x \in m$  is of the form  $t^n$ . Thus  $m = (t)$ . Since every ideal  $I$  is a subset of this maximal ideal, any ideal is of the form  $I = (t^n)$  for some  $n > 0$ .
- Follows from the fact that  $(t^n)$  is the unique maximal ideal.  $\square$

The rest of the section devotes efforts to recognizing discrete valuation rings.

#### Proposition 9.4.5

Let  $R$  be a valuation ring. Then the following are equivalent.

- $R$  is a discrete valuation ring.
- $R$  is a principal ideal domain.
- $R$  is Noetherian.

#### Proposition 9.4.6: Equivalent Characterizations of DVRs I

Let  $R$  be an integral domain. Then the following are equivalent.

- $R$  is a discrete valuation ring
- $R$  is Noetherian, local,  $\dim(R) = 1$  and normal.
- $R$  is local, a PID and not a field.
- $R$  is a UFD with a unique irreducible element up to multiplication of a unit

*Proof.*

- (1)  $\implies$  (3): We have seen that the set of non-units is precisely the set  $m = \{x \in R \mid v(x) > 0\}$ . We show that this is an ideal. Clearly  $x, y \in m$  implies  $v(x+y) = \min\{v(x), v(y)\} > 0$ . Let  $u \in R$ . Then  $v(ux) = v(u) + v(x) > 0$  since  $v(x) > 0$  and  $v(u) \geq 0$ .

We have seen that every ideal is of the form  $(t^n)$  for some  $n > 0$ . Thus every ascending chains of ideal must be of the form

$$(t^{n_1}) \subset (t^{n_2}) \subset \dots$$

for  $n_1 > n_2 > \dots$ . Since  $n_1, n_2, \dots$  is strictly decreasing, the chain must eventually stabilize. This proves that  $R$  is Noetherian and has principal maximal ideal.

- (1)  $\implies$  (3):

□

#### Proposition 9.4.7: Equivalent Characterizations of DVRs II

Let  $R$  be an integral domain that is Noetherian and local with unique maximal ideal  $m$ . Then the following are equivalent.

- $R$  is a discrete valuation ring.
- $\dim(R) = 1$  and  $R$  is normal.
- $\dim(R) = 1$  and  $\dim_{R/m}(m/m^2) = 1$
- $R$  is not a field and  $m$  is principal.
- $I = m^k$  for all non-zero ideals  $I$  of  $R$
- There exists  $t \in R$  and  $k > 0$  such that  $I = (t^k)$  for all non-zero ideal  $I$  of  $R$

*Proof.*

□

#### Proposition 9.4.8

Let  $R$  be a Noetherian integral domain and  $\dim(R) = 1$ . Then  $R$  is normal if and only if  $R_m$  is a discrete valuation ring for all maximal ideals  $m$ .

In summary, if  $R$  is a discrete valuation ring, then  $R$  has the following properties.

- $R$  is integrally closed and in particular is normal.
- $R$  is a PID and in particular is a UFD and an integral domain.
- $R$  is Noetherian and local
- $R$  has Krull dimension 1.
- $\dim_{R/m}(m/m^2) = 1$  (these are called regular local rings as we will see in Commutative Algebra 2)
- Every ideal  $I$  of  $R$  is equal to the power  $m^k$  of the maximal ideal  $m$ . In particular if  $m$  is generated by the uniformizing parameter  $t$ , then  $I = (t^k)$  in this case.
- Such a  $t$  is an irreducible element (that is unique up to multiplication by a unit), and every element of  $R$  can be written as  $ut^n$  for  $u$  a unit and  $n \in \mathbb{N}$ .

There is a simple diagram of relationships between DVRs and some other standard types of commutative rings.

DVRs  $\subset$  PIDs  $\subset$  UFDs  $\subset$  Normal Domains  $\subset$  Integral Domains

## 10 Dedekind Domains

### 10.1 Fractional Ideals

#### Definition 10.1.1: Fractional Ideal

Let  $R$  be an integral domain. Let  $I$  be a  $R$ -submodule of  $\text{Frac}(R)$ . We say that  $I$  is a fractional ideal of  $R$  if there exists  $r \in R \setminus \{0\}$  such that  $rI \subseteq R$ .

While  $I$  is not exactly an ideal of  $R$ , we can think of it as if it were an ideal because it is isomorphic to an actual ideal of  $R$ .

#### Lemma 10.1.2

Let  $R$  be an integral domain. Let  $I$  be a fractional ideal of  $R$  where  $rI \subseteq R$  for some  $r \in R \setminus \{0\}$ . Then there is an  $R$ -module isomorphism

$$I \cong rI \subseteq R$$

given by  $i \mapsto ri$ .

*Proof.* I claim that there is an  $R$ -module isomorphism  $I \cong rI$  for  $rI \subseteq R$  given by  $i \mapsto ri$ . The kernel of this  $R$ -module homomorphism is given by  $\{i \in I \mid ri = 0\}$ . But  $ri = 0$  if and only if  $r = 0$  or  $i = 0$ . Since  $r \neq 0$  we must have  $i = 0$  so that the kernel is trivial. Moreover, this  $R$ -module homomorphism is surjective since for any  $k \in rI$  it can be written as  $k = ri$  for some  $i$ . Then  $i \in I$  maps to  $ri$  under the morphism. Hence  $I \cong rI$  as  $R$ -modules.  $\square$

#### Lemma 10.1.3

Let  $R$  be an integral domain. Let  $I$  be a fractional ideal of  $R$ . If  $R$  is Noetherian, then  $I$  is finitely generated.

*Proof.* Let  $R$  be Noetherian. Since  $I$  is isomorphic to  $rI$  for some non-zero  $r \in R$ , and  $rI$  is an ideal of  $R$ ,  $R$  being Noetherian implies that  $rI$  is finitely generated and hence  $I$  is finitely generated.  $\square$

### 10.2 Invertible Ideals

#### Definition 10.2.1: Invertible Ideals

Let  $R$  be an integral domain. Let  $I$  be an  $R$ -submodule of  $\text{Frac}(R)$ . We say that  $I$  is invertible if there exists an ideal  $J$  of  $R$  such that  $JI = R$ .

#### Lemma 10.2.2

Let  $R$  be an integral domain. Let  $I$  be an  $R$ -submodule of  $\text{Frac}(R)$ . Then  $I$  is invertible if and only if  $I^{-1}I = R$  where we define

$$I^{-1} = \{s \in \text{Frac}(R) \mid sI \subseteq R\}$$

#### Proposition 10.2.3

Let  $R$  be an integral domain. Let  $I$  be an  $R$ -submodule of  $\text{Frac}(R)$ . Then the following are true.

- If  $I$  is a non-zero principal ideal of  $R$ , then  $I$  is invertible.
- If  $I$  is invertible, then  $I$  is fractional.

**Proposition 10.2.4**

Let  $R$  be an integral domain. Let  $I$  be a fractional ideal. Then  $I$  is invertible if and only if  $I$  is finitely generated, and for any maximal ideal  $m$  of  $R$ ,  $IR_m$  is a principal ideal of  $R_m$ .

**Proposition 10.2.5**

Let  $R$  be an integral domain. Let  $P$  be a non-zero prime ideal of  $R$ . If  $R$  is Noetherian and  $P$  is invertible, then  $R_P$  is a discrete valuation ring.

*Proof.* Let  $R$  be a Noetherian integral domain and  $P$  a non-zero invertible prime ideal. We know that  $PR_P$  is the unique maximal ideal of the local ring  $R_P$ . By the above prp,  $PR_P$  is a principal ideal. Thus  $R_P$  is now a Noetherian local ring with principal maximal ideal. By prp10.4.6 in Commutative Algebra 1, we conclude that  $R_P$  is a discrete valuation ring.  $\square$

**10.3 Dedekind Domains****Definition 10.3.1: Dedekind Domains**

Let  $R$  be an integral domain. We say that  $R$  is a dedekind domain if every non-zero ideal can be expressed uniquely as a direct product of finitely many prime ideals of  $R$ .

Dedekind sought for an integral domain whose ideals can be factorized uniquely as a product of primes.

**Proposition 10.3.2**

Let  $R$  be an integral domain that is not a field. Then the following are equivalent.

- $R$  is a Dedekind domain.
- Every non-zero fractional ideal  $I$  of  $R$  is invertible ( $I^{-1}I = R$ ).
- $R$  is Noetherian,  $\dim(R) = 1$  and normal
- $R$  is Noetherian,  $\dim(R) = 1$  and for any non-zero maximal ideal  $m$  of  $R$ ,  $R_m$  is a discrete valuation ring.
- $R$  is Noetherian,  $\dim(R) = 1$  and every primary ideal in  $R$  is a prime power.

*Proof.*

- (2)  $\implies$  (3): Let  $I$  be an ideal of  $R$ . Since  $I$  is invertible, by 1.1.5 we conclude that  $I$  is finitely generated. Hence  $R$  is Noetherian. Let  $P$  be a prime ideal of  $R$ . By assumption,  $P$  is invertible. prp1.2.5 implies that  $R_P$  is a DVR. In particular, it is integrally closed and  $\dim(R_P) = 1$ . This means that  $\text{ht}_R(P) = 1$ . Thus  $R$  is either a field or  $\dim(R) = 1$ . By assumption  $R$  is not a field. Hence  $\dim(R) = 1$ . We know that  $R = \bigcap_{m \text{ a maximal ideal}} R_m$ . Since prime ideals are maximal ideals in one dimensional rings, we can rewrite the intersection as

$$R = \bigcap_{P \text{ a prime ideal}} R_P$$

But each  $R_P$  is a DVR. Hence  $R$  is a DVR and we conclude that  $R$  is normal.

- (3)  $\implies$  (2):  $m$  be a maximal ideal of  $R$ . We have seen from Commutative Algebra 1 that  $R_m$  is a Noetherian local ring. By 7.4.2 in Commutative Algebra 1 we also conclude that  $R_m$  is normal. By 9.3.2 of Commutative Algebra 1 we know that  $\dim(R_m) = \text{ht}_R(m) = 1$ . By 10.4.6 of Commutative Algebra 1,  $R_m$  is a DVR and in particular  $m$  is a principal ideal.

Let  $I$  be a fractional ideal of  $R$ . We know by 1.1.3 that  $I$  is finitely generated. Since  $R_m$  is a normal Noetherian local ring of dimension 1, the ideal  $I_m$  of  $R_m$  must be principal. By 1.1.5 we conclude that  $I$  is invertible.

- (3)  $\implies$  (4):
- (4)  $\implies$  (3): Let  $m$  be a maximal ideal of  $R$ . We know that  $R_m$  is a DVR. In particular, it is a normal domain.

□

By virtue of the fourth item, we can think of Dedekind domains as a patching up of local discrete valuation rings.

### Proposition 10.3.3

Let  $R$  be a Dedekind domain. Let  $I$  and  $J$  be ideals of  $R$  whose prime factorization is given by

$$I = P_1^{a_1} \times \cdots \times P_n^{a_n} \quad \text{and} \quad J = P_1^{b_1} \times \cdots \times P_n^{b_n}$$

for  $P_1, \dots, P_n$  distinct prime ideals of  $R$ . Then the following are true.

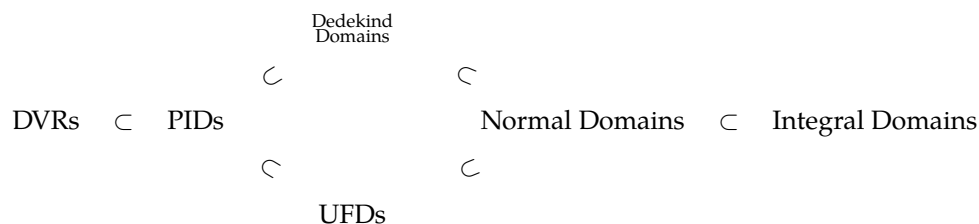
- $I + J = P_1^{\min\{a_1, b_1\}} \times \cdots \times P_n^{\min\{a_n, b_n\}}$
- $I \cap J = P_1^{\max\{a_1, b_1\}} \times \cdots \times P_n^{\max\{a_n, b_n\}}$
- $IJ = P_1^{a_1+b_1} \times \cdots \times P_n^{a_n+b_n}$

### Proposition 10.3.4

Let  $R$  be a Dedekind domain. Let  $I$  be an ideal of  $R$ . Then the following are true.

- For any  $a \in I$ , there exists  $b \in R$  such that  $I = (a, b)$ .
- $I$  is can be finitely generated by two elements.

We summarize the relation between Dedekind domains and other types of domains in the following diagram:



In particular, DVRs, PIDs and Dedekind domains are 1-dimensional. Moreover, notice that the only difference between DVRs and Dedekind domains is that DVRs are local rings. They both share the fact that they are Noetherian,  $\dim(R) = 1$  and normal.