Ring Theory

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7261 1. Rings Fall 2017

A **Ring** (with 1) is a set R with two binary operations $+$ and $\times$ such that

R1. $(R,+)$ is an Abelian group under $+$.

R2. $(R,\times)$ is a Monoid under $\times$, (so $\times$ is associative and has an identity 1).

R3. The distributive laws hold: $a(b+c)=ab+ac$, $(b+c)a=ba+ca$.

Many of the standard facts from algebra follow from these axioms. In particular,
$0a=a0=0,\quad a(-b)=(-a)b=-(ab),\quad -a=(-1)a,\quad (\sum_i a_i)(\sum_j b_j)=\sum_{i,j}a_ib_j.$

The ring R is **commutative** if $\times$ is commutative.
An element of R is a **unit** if it has a (2-sided) multiplicative inverse.
The set of units $R^\times$ (or $U(R)$) is a group under $\times$.
The **trivial ring** is the ring $\{0\}$ with $0+0=0.0=0$, and is the only ring in which $1=0$.
A **division ring** or **skew field** is a non-trivial ring in which every non-zero element is a unit.
A **field** is a commutative division ring.
An **Integral Domain** (ID) is a non-trivial commutative ring in which $ab=0$ implies $a=0$ or $b=0$. Note that any field is an ID.

Examples

1. $\mathbb{Z}$, $\mathbb{Q}$, $\mathbb{R}$, $\mathbb{C}$ are all rings under the usual $+$ and $\times$. $\mathbb{Q}$, $\mathbb{R}$, $\mathbb{C}$ are fields. $\mathbb{Z}$ is an ID.
2. $\mathbb{Z}/n\mathbb{Z}$ is a ring under $+$ and $\times$ mod n. This ring is an ID iff n is prime. In fact, if n is prime then $\mathbb{Z}/n\mathbb{Z}$ is a field.
3. If R is a ring then the set $M_n(R)$ of $n\times n$ matrices with entries in R is a ring under matrix addition and multiplication. $M_n(R)$ is non-commutative in general.
4. Let $(A,+)$ be an abelian group and let $\mathrm{End}(A)$ be the set of group homomorphisms $A\to A$. Define addition pointwise, $(f+g)(a)=f(a)+g(a)$, and multiplication by composition, $fg(a)=f(g(a))$. Then $\mathrm{End}(A)$ is a (usually non-commutative) ring.
5. If $A=\prod_{i\in\mathbb{N}}\mathbb{Z}=\{(a_0,a_1,\dots):a_i\in\mathbb{Z}\}$ then the maps $R((a_0,\dots))=(0,a_0,a_1,\dots)$ and $L((a_0,a_1,\dots))=(a_1,a_2,\dots)$ lie in $\mathrm{End}(A)$ and $LR=1\neq RL$. Hence R has a left, but not a right inverse. [Recall that left and right inverses must be equal if they both exist.]
6. Let $C[0,1]$ be the set of continuous functions from $[0,1]$ to $\mathbb{R}$ with addition and multiplication defined pointwise. Then $C[0,1]$ is a ring. It is not an ID (why?).

A subset S of R is a **subring** iff $(S,+)$ is a subgroup of $(R,+)$ and $(S,\times)$ is a submonoid of $(R,\times)$. Equivalently, $1_R\in S$ and $a,b\in S$ implies $a-b,ab\in S$.

A subset I of R is a **left ideal** iff $(I,+)$ is a subgroup of $(I,+)$ such that for all $r\in R$, $a\in I$, we have $ra\in I$. A subset I of R is a **right ideal** iff $(I,+)$ is a subgroup of $(I,+)$

such that for all $r \in R$, $a \in I$, we have $ar \in I$. An **ideal** is a subset that is both a left ideal and a right ideal. Equivalently, $I \neq \emptyset$ and $a, b \in I$, $r \in R$, implies $a - b, ra, ar \in I$. The sets $\{0\}$ and R are ideals of R. An ideal I is **proper** if $I \neq R$, and **non-trivial** if $I \neq \{0\}$.

Examples

1. $n\mathbb{Z}$ is an ideal of $\mathbb{Z}$ but not a subring (unless $n = \pm 1$).
2. $\mathbb{Z}$ is a subring of $\mathbb{R}$ but not an ideal.
3. The set of the matrices $I = \left\{ \begin{pmatrix} 0 & b \\ 0 & d \end{pmatrix} : b, d \in \mathbb{R} \right\}$ is a left ideal, but not a right ideal of $M_2(\mathbb{R})$. But I is a 2-sided ideal of the subring $T = \left\{ \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} : a, b, d \in \mathbb{R} \right\}$ of $M_2(\mathbb{R})$.
4. The **quaternions** $\mathbb{H} = \left\{ \begin{pmatrix} \alpha & \beta \\ -\bar{\beta} & \bar{\alpha} \end{pmatrix} : \alpha, \beta \in \mathbb{C} \right\}$ form a subring of $M_2(\mathbb{C})$. Any $x \in \mathbb{H}$ can be written uniquely as $x = a + bi + cj + dk$ where $i = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$, $j = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$, $k = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$. Then $i^2 = j^2 = k^2 = -1$, $ij = k$, $ji = -k$, and $(a + bi + cj + dk)^{-1} = (a/r) - (b/r)i - (c/r)j - (d/r)k$ where $r = a^2 + b^2 + c^2 + d^2$. Thus $\mathbb{H}$ is a non-commutative division ring.

Lemma 1.1 *If S_α, $\alpha \in A$, are subrings of R then $\bigcap_{\alpha \in A} S_\alpha$ is a subring of R. If I_α are ideals of R then $\bigcap_{\alpha \in A} I_\alpha$ is an ideal of R.*

The ideal (S) generated by a subset $S \subseteq R$ is the smallest ideal of R containing S. It can be defined as the intersection $\bigcap_{J \supseteq S} J$ of all ideals containing S.

An ideal I is **principal** if it is generated by a single element, $I = (a)$ for some $a \in R$. An ideal is **finitely generated** if it is generated by a finite set, $I = (S)$, $|S| < \infty$.

We can also define the subring generated by a subset. More generally, if R is a subring of R' and $S \subseteq R'$, then $R[S]$ is the smallest subring of R' containing R and S (= the intersection of all subrings of R' containing R and S).

Exercises

1. Show that an ideal is proper iff it does not contain a unit.
2. Show that $(S) = \{\sum_{i=1}^{n} r_i s_i r'_i : r_i, r'_i \in R,\ s_i \in S,\ n \in \mathbb{N}\}$.
3. Show that if R is commutative then the principal ideal (a) is $\{ra : r \in R\}$.
4. Show that $R[\alpha]$ is the set of all polynomial expressions $\sum_{i=0}^{n} a_i \alpha^i$ with coefficients $a_i \in R$.
5. Deduce that $\mathbb{Z}[i] = \{a + bi : a, b \in \mathbb{Z}\}$ as a subring of $\mathbb{C}$ and $\mathbb{Q}[\sqrt[3]{2}] = \{a + b\sqrt[3]{2} + c\sqrt[3]{4} : a, b, c \in \mathbb{Q}\}$ as a subring of $\mathbb{R}$.
6. Describe $\mathbb{Z}[1/2]$ as a subring of $\mathbb{Q}$.
7. Let I be the set of continuous functions $f \in C[0, 1]$ such that $f(0.5) = 0$. Show that I is an ideal of $C[0, 1]$ that is not principal (or even finitely generated).

7261 2. Ring homomorphisms Fall 2017

A (ring) **homomorphism** from the ring R to the ring S is a function $f\colon R \to S$ that is a group homomorphism $(R,+) \to (S,+)$ and a monoid homomorphism $(R,\times) \to (S,\times)$. Equivalently $f(a+b) = f(a)+f(b)$, $f(ab) = f(a)f(b)$, $f(1_R) = 1_S$.

Examples

1. The map $f\colon T \to \mathbb{R}$ given by $f(\begin{pmatrix} a & b \\ 0 & d \end{pmatrix}) = a$ where $T = \left\{ \begin{pmatrix} a & b \\ 0 & d \end{pmatrix} : a,b,d \in \mathbb{R} \right\}$.
2. If S is a subring of R then the inclusion map $i\colon S \to R$, $i(r) = r$, is a homomorphism.

A (ring) **isomorphism** is a homomorphism $R \to S$ that has a 2-sided inverse map $g\colon S \to R$ which is also a homomorphism. It is sufficient for f to be a bijective homomorphism.

If I is an ideal of R then the **quotient ring** R/I is the quotient group $(R/I,+)$ with multiplication defined by $(a+I)(b+I) = ab+I$.

Lemma 2.1 *The quotient ring R/I is indeed a ring and the projection map $\pi\colon R \to R/I$ given by $\pi(a) = a+I$ is a surjective ring homomorphism.*

Example $R = \mathbb{Z}$, $I = (n)$, then $R/I = \mathbb{Z}/n\mathbb{Z}$ is the integers mod n with addition and multiplication mod n.

Theorem (1st Isomorphism Theorem) *If $f\colon R \to S$ then $\operatorname{Ker} f = \{r : f(r) = 0\}$ is an ideal of R, $\operatorname{Im} f = \{f(r) : r \in R\}$ is a subring of S and $f = i \circ \tilde{f} \circ \pi$ where*

- *$\pi\colon R \to R/\operatorname{Ker} f$ is the (surjective) projection homomorphism.*
- *$\tilde{f}\colon R/I \to \operatorname{Im} f$ is a (bijective) ring isomorphism.*
- *$i\colon \operatorname{Im} f \to S$ is the (injective) inclusion homomorphism.*

$$\begin{array}{ccc} R & \xrightarrow{f} & S \\ \pi\downarrow & & \uparrow i \\ R/\operatorname{Ker} f & \xrightarrow{\tilde{f}} & \operatorname{Im} f \end{array}$$

Theorem (2nd Isomorphism Theorem) *If I is an ideal of R then there is a bijection*

$$\{\textit{subgroups } H \textit{ of } (R,+) \textit{ with } I \le H \le R\} \leftrightarrow \{\textit{subgroups of } (R/I,+)\},$$

where H corresponds to H/I. In this correspondence subrings correspond to subrings and ideals correspond to ideals. Moreover, if J is an ideal with $I \le J \le R$ then there is an isomorphism $R/J \cong (R/I)/(J/I)$.

Theorem (3rd Isomorphism Theorem) *If I is an ideal of R and S is a subring of R then $S+I$ is a subring of R, $S \cap I$ is an ideal of S, and $(S+I)/I \cong S/(S\cap I)$.*

Example For any ring R define $f\colon \mathbb{Z} \to R$ by $f(n) = n.1_R$ ($n.1_R = 1_R + \cdots + 1_R$ defined as for additive groups). Then f is a ring homomorphism. The kernel is a subgroup of $(\mathbb{Z},+)$ so is $n\mathbb{Z}$ for some $n \ge 0$. The image $S = \{n.1_R : n \in \mathbb{Z}\}$ is called the **prime subring** of R and is isomorphic to $\mathbb{Z}/n\mathbb{Z}$. The **characteristic** of R, $\operatorname{char}(R)$, is the integer n. E.g., $\operatorname{char}(\mathbb{R}) = 0$, $\operatorname{char}(\mathbb{Z}/n\mathbb{Z}) = n$, $\operatorname{char}(\{0\}) = 1$.

A **maximal ideal** is a proper ideal M of R such that for any ideal I, $M \subseteq I \subseteq R$ implies $I = M$ or $I = R$.

Example The ideal (n) is a maximal ideal of $\mathbb{Z}$ iff n is prime.

A non-trivial ring is **simple** if the only ideals of R are (0) and R. Equivalently, (0) is maximal.

Lemma 2.2 *Let R be a commutative ring. Then R is simple iff R is a field.*

Proof. If R is a field and $I \neq (0)$ is an ideal then $u \in I$ for some $u \neq 0$. But u is a unit so $(ru^{-1})u = r \in I$ for all $r \in R$. Thus $I = R$. Conversely, if $a \neq 0$ and a is not a unit then $(a) = \{ra : r \in R\}$ is a non-trivial proper ideal of R. □

Note that if R is a division ring then R is simple. However the converse fails:

Lemma 2.3 *Let D be a division ring. Then $M_n(D)$ is a simple ring for any $n \geq 1$.*

Proof. Let I be a non-zero ideal of $M_n(D)$ and let $A = (a_{ij}) \in I$, $A \neq 0$. In particular $a_{kl} \neq 0$ for some k, l. Let E_{ij} be the matrix with 1 in entry (i,j) and zeros elsewhere. Then $E_{ik}AE_{lj} = a_{kl}E_{ij} \in I$. Since $a_{kl} \in D$ and D is a division ring, $a_{kl}^{-1} \in D$, so $a_{kl}^{-1}I \in M_n(D)$. Now $(a_{kl}^{-1}I)(a_{kl}E_{ij}) = E_{ij} \in I$. But any matrix $B = (b_{ij})$ is a linear combination $\sum(b_{ij}I)E_{ij}$, so $B \in I$ and $I = M_n(D)$. □

So by the 2nd Isomorphism Theorem, for commutative R, M is maximal iff R/M is a field, but for non-commutative R, M may be maximal without R/M being a division ring.

Exercises

1. Show that any finite ID is a field.
2. An element a of a ring is **nilpotent** if $a^n = 0$ for some $n \in \mathbb{N}$. Show that if a is nilpotent then $1 + a$ is a unit.
3. Show that if R is commutative then the set of nilpotent elements forms an ideal of R. [Hint: make sure you check that a, b nilpotent implies $a - b$ is nilpotent.]
4. Show that if $r \in R$ lies in the intersection of all maximal ideals of R then $1 + r$ is a unit.
5. Show that any homomorphism $f\colon F \to R$ from a field F to a non-trivial ring R is injective, so in particular R contains a subring isomorphic to F.

7261 3. Zorn's Lemma Fall 2017

A **partial ordering** on a set $\mathcal{X}$ is a relation $\leq$ satisfying the properties:

O1. $\forall x\colon x \leq x$,

O2. $\forall x, y\colon$ if $x \leq y$ and $y \leq x$ then $x = y$,

O3. $\forall x, y, z\colon$ if $x \leq y$ and $y \leq z$ then $x \leq z$.

A **total ordering** is a partial ordering which also satisfies:

O4. $\forall x, y\colon$ either $x \leq y$ or $y \leq x$.

Example Any collection of sets with $\subseteq$ as the ordering forms a partially ordered set that is not in general totally ordered.

If $(\mathcal{X}, \leq)$ is a partially ordered set, a **chain** in $\mathcal{X}$ is a non-empty subset $\mathcal{C} \subseteq \mathcal{X}$ that is totally ordered by $\leq$.

If $\mathcal{S} \subseteq \mathcal{X}$, and $x \in \mathcal{X}$, we say x is an **upper bound** for $\mathcal{S}$ if $y \leq x$ for all $y \in \mathcal{S}$. [Note that we do not require x to be an element of $\mathcal{S}$.]

A **maximal element** of $\mathcal{X}$ is an element x such that for any $y \in \mathcal{X}$, $x \leq y$ implies $x = y$. [Note: This does not imply that $y \leq x$ for all y since $\leq$ is only a partial order. In particular there may be many maximal elements.]

Theorem (Zorn's Lemma) *If $(\mathcal{X}, \leq)$ is a non-empty partially ordered set for which every chain has an upper bound then $\mathcal{X}$ has a maximal element.*

This result follows from (and is equivalent to) the Axiom of choice, which states that if X_i are non-empty sets then $\prod_{i\in I} X_i$ is non-empty. [I will not give the proof here as it is rather long.]

Note: If we had defined things so that $\emptyset$ were a chain, we would not need the condition that $\mathcal{X} \neq \emptyset$ in Zorn's Lemma since the existence of an upper bound for $\emptyset$ is just the condition that an element of $\mathcal{X}$ exists. However, in practice it is easier to check $\mathcal{X} \neq \emptyset$ and then check separately that each *non-empty* totally ordered subset has an upper bound.

Theorem 3.1 *If I is a proper ideal of a ring R (with 1) then there exists a maximal ideal M such that $I \subseteq M$.*

Proof. If an ideal J contains 1 then $J = R$, so an ideal is proper iff it does not contain 1. Let $\mathcal{X}$ be the set of proper ideals J of R with $I \subseteq J$. The partial order on $\mathcal{X}$ will be $\subseteq$. Since $I \in \mathcal{X}$, $\mathcal{X} \neq \emptyset$. Now let $\mathcal{C}$ be a chain in $\mathcal{X}$, i.e., a set of ideals $\{J_\alpha\}$ such that for every $J_\alpha, J_\beta \in \mathcal{C}$ either $J_\alpha \subseteq J_\beta$ or $J_\beta \subseteq J_\alpha$. Let $K = \bigcup_{J_\alpha\in\mathcal{C}} J_\alpha$. We shall show that K is an upper bound for $\mathcal{C}$.

Firstly $\mathcal{C} \neq \emptyset$, so some ideal J_α lies in $\mathcal{C}$ and $I \subseteq J_\alpha \subseteq K$. In particular $K \neq \emptyset$. If $x, y \in K$ then $x \in J_\alpha$, $y \in J_\beta$, say. Since $\mathcal{C}$ is totally ordered, we can assume without loss of generality that $J_\alpha \subseteq J_\beta$. Thus $x, y \in J_\beta$, and $x - y \in J_\beta \subseteq K$. If $x \in K$, $r \in R$, then $x \in J_\alpha$, say, so $xr, rx \in J_\alpha \subseteq K$. Hence K is an ideal with $I \subseteq K$. However $1 \notin J_\alpha$ for each $J_\alpha \in \mathcal{C}$, so $1 \notin K$. Hence K is proper. Therefore $K \in \mathcal{X}$ and is clearly an upper bound for $\mathcal{C}$.

The conditions of Zorn's Lemma apply, so $\mathcal{X}$ has a maximal element M, say. Now M is a proper ideal containing I and is maximal, since if $M \subset J \subset R$ then $J \in \mathcal{X}$ and M would not be maximal in $\mathcal{X}$. $\square$

We now give an example from linear algebra. Let V be a vector space (possibly infinite dimensional).

A set $S \subseteq V$ is called **linearly independent** if there are no non-trivial *finite* linear combinations that give 0. In other words if $\sum_{i=1}^{n} \lambda_i s_i = 0$ and the s_i are distinct elements of S then $\lambda_i = 0$ for each i.

A set $S \subseteq V$ is called **spanning** if every element $v \in V$ can be written as a *finite* linear combinations of elements of S, $v = \sum_{i=1}^{n} \lambda_i s_i$.

A set $S \subseteq V$ is called a **basis** if it is a linearly independent spanning set. Note that every element $v \in V$ can be written as a linear combination of elements of a basis in a unique way. [Spanning implies existence, linear independence implies uniqueness.]

Theorem 3.2 *Every vector space has a basis.*

Proof. Let $\mathcal{X}$ be the set of all linearly independent sets in V partially ordered by $\subseteq$. Since $\emptyset$ is linearly independent, $\mathcal{X} \neq \emptyset$. Let $\mathcal{C}$ be a chain in $\mathcal{X}$ and let $S = \bigcup_{S_\alpha \in \mathcal{C}} S_\alpha$. We shall show that S is linearly independent.

Suppose $\sum_{i=1}^{n} \lambda_i s_i = 0$ and $s_i \in S_{\alpha_i} \in \mathcal{C}$ (the s_i are distinct but the α_i need not be). Then by total ordering of the S_{α_i}, there must be one S_{α_j} that contains all the others (use induction on n). But then $\sum_{i=1}^{n} \lambda_i s_i = 0$ is a linear relation in S_{α_j} which is linearly independent. Thus $\lambda_i = 0$ for all i. Hence S is linearly independent, so $S \in \mathcal{X}$ and is an upper bound for $\mathcal{C}$.

Now apply Zorn's Lemma to give a maximal linearly independent set M. We shall show that M spans V and so is a basis. Clearly any element of M is a linear combination of elements of M, so pick any $v \notin M$ and consider $M \cup \{v\}$. By maximality of M this cannot be linearly independent. Hence there is a linear combination $\lambda v + \sum_{i=1}^{n} \lambda_i s_i = 0$, $s_i \in M$, with not all the λ's zero. If $\lambda = 0$ this gives a linear relation in M, contradicting linear independence of M. Hence $\lambda \neq 0$ and $v = \sum_{i=1}^{n}(-\lambda_i/\lambda)s_i$ is a linear combination of elements of M. $\square$

Anti-isomorphisms

An **anti-homomorphism** is a map $f\colon R \to S$ such that $f(a+b) = f(a) + f(b)$, $f(1) = 1$, and $f(ab) = f(b)f(a)$. An **anti-isomorphism** is an invertible anti-homomorphism.

Examples The transpose map ${}^T\colon M_n(\mathbb{R}) \to M_n(\mathbb{R})$.
The map $\mathbb{H} \to \mathbb{H}$ given by $f(a + bi + cj + dk) = a - bi - cj - dk$.

The **opposite ring** R^o of R is the ring R with multiplication defined by $a \times_{R^o} b = b \times_R a$. Note that $R^{oo} = R$.

Lemma 4.1 *A map $f\colon R \to S$ is an anti-homomorphism iff it is a homomorphism viewed as a map $R \to S^o$ (or $R^o \to S$).*

Example $M_n(\mathbb{R})^o$ is isomorphic to $M_n(\mathbb{R})$, one isomorphism being the transpose map ^{T}.

Rngs (Rings without 1s)

A **Rng** (or "ring which does not necessarily have a 1") is a set R with $+$ and $\times$ defined so that $(R, +)$ is an abelian group, $(R, \times)$ is a semigroup ($\times$ is associative), and the distributive laws hold. However, R need not contain a multiplicative identity.

Subrngs, rng-homomorphisms etc., can be defined without the conditions involving 1. The definition of an ideal is the same, and an ideal is a special case of a subrng. The theory of rngs is similar to that of rings, although they are more awkward to deal with later on. The following lemma shows that we can regard a rng as an ideal of a bigger ring.

Lemma 4.2 *Let R be a rng and define $R_1 = \mathbb{Z} \times R$ with addition $(n, r) + (m, s) = (n+m, r+s)$ and multiplication $(n, r)(m, s) = (nm, n.s+m.r+rs)$, where $n.s = s+\cdots+s$ etc.. Then R_1 is a ring containing an ideal $\{0\} \times R$ isomorphic to R.*

Direct sums and the Chinese Remainder Theorem

If R_1 and R_2 are rings, define the ring $R_1 \oplus R_2$ as the set $R_1 \times R_2$ with addition $(a_1, a_2) + (b_1, b_2) = (a_1 + b_1, a_2 + b_2)$ and multiplication $(a_1, a_2)(b_1, b_2) = (a_1 b_1, a_2 b_2)$. The identity is $(1, 1)$. The direct sum $R_1 \oplus \cdots \oplus R_n$ is defined similarly. Note that even if R_1 and R_2 are IDs, $R_1 \oplus R_2$ will not be since $(1, 0)(0, 1) = (0, 0)$.

If R is a ring and I and J are ideals of R, we can define the following ideals.

- $I + J = \{a + b : a \in I,\ b \in J\}$
- $I \cap J = \{c : c \in I,\ c \in J\}$
- $IJ = \{\sum_{i=1}^{n} a_i b_i : a_i \in I,\ b_i \in J,\ n \in \mathbb{N}\}$

It is easily checked that each of these is indeed an ideal. Note that in general $IJ \neq \{ab : a \in I,\ b \in J\}$, but IJ is the ideal generated by all the products ab, $a \in I$, $b \in J$.

Example For $R = \mathbb{Z}$, $I = (x) = \{ax : a \in \mathbb{Z}\}$, $J = (y) = \{by : b \in \mathbb{Z}\}$

1. $I + J = (\gcd(x, y))$.
   Note $\gcd(x, y) = ax + by$ for some $a, b \in \mathbb{Z}$, so $\gcd(x, y) \in I + J$. Conversely $I + J = \{ax + by : a, b \in \mathbb{Z}\}$ and $ax + by$ is always a multiple of $\gcd(x, y)$.
2. $I \cap J = (\operatorname{lcm}(x, y))$.
   $m \in I \iff x \mid m$ and $m \in J \iff y \mid m$. Hence if $m \in I \cap J$ then m must be a common multiple of x and y. Thus $m \in (\operatorname{lcm}(x, y))$ Conversely $\operatorname{lcm}(x, y)$ is a common multiple of x and y so lies in $I \cap J$. Hence $I \cap J = (\operatorname{lcm}(x, y))$.
3. $IJ = (xy)$.
   $IJ = \{\sum a_i x b_i y : a_i, b_i \in \mathbb{Z}\} \subseteq (xy)$. Conversely $xy \in IJ$, so $(xy) \subseteq IJ$.

Ideals I and J are **relatively prime** if $I + J = R$. Equivalently $\exists a \in I, b \in J \colon a + b = 1$ (recall that an ideal equals R iff it contains 1).

Lemma 4.3 *$IJ \subseteq I \cap J$. Moreover, if R is commutative and $I + J = R$ then $IJ = I \cap J$.*

Proof. If $a_i \in I$ then $\sum a_i b_i \in I$. If $b_i \in J$ then $\sum a_i b_i \in J$. Hence $IJ \subseteq I \cap J$.
Now let $I + J = R$ so that $a + b = 1$ for some $a \in I$, $b \in J$. Then if $c \in I \cap J$, $ac + cb \in IJ$. But $ac + cb = c(a + b) = c$, so $c \in IJ$. Thus $I \cap J \subseteq IJ$ and so $IJ = I \cap J$. □

Theorem (Chinese Remainder Theorem) *If I and J are ideals of a commutative ring R and $I + J = R$ then $R/IJ \cong R/I \oplus R/J$.*

Proof. Let $f \colon R \to R/I \oplus R/J$ be defined by $f(r) = (r + I, r + J)$. Then $f(r + s) = (r+s+I, r+s+J) = (r+I, r+J) + (s+I, s+J) = f(r) + f(s)$, $f(rs) = (rs+I, rs+J) = (r+I, r+J)(s+I, s+J) = f(r)f(s)$, and $f(1) = (1+I, 1+J)$ is the identity in $R/I \oplus R/J$. Now $\operatorname{Ker} f = \{r : r+I = I,\ r+J = J\} = I \cap J$ so $\operatorname{Ker} f = IJ$ by Lemma 4.3. For the image of f, write $1 = a+b$ with $a \in I$, $b \in J$. Then $f(sa+rb) = (sa+r(1-a)+I, s(1-b)+rb+J) = (r + I, s + J)$. Thus f is surjective. Hence $R/IJ \cong R/I \oplus R/J$. □

Example If $\gcd(n, m) = 1$ then $\mathbb{Z}/nm\mathbb{Z} \cong \mathbb{Z}/n\mathbb{Z} \oplus \mathbb{Z}/m\mathbb{Z}$.

Exercises

1. Show that composing two anti-homomorphisms gives a homomorphism and composing an anti-homomorphism with a homomorphism gives an anti-homomorphism.
2. Define $\phi(n) = |(\mathbb{Z}/n\mathbb{Z})^{\times}|$. Show that if $\gcd(n, m) = 1$ then $\phi(nm) = \phi(n)\phi(m)$. If $n = p_1^{a_1} \dots p_r^{a_r}$ is the prime factorization of n, deduce that $\phi(n) = \prod_i p_i^{a_i - 1}(p_i - 1)$.
3. Generalize the CRT: if $I_1, \dots, I_n$ are ideals of a commutative ring R and for each i and j, $I_i + I_j = R$, show that $R/I_1 I_2 \dots I_n \cong I_1 \oplus I_2 \oplus \cdots \oplus I_n$.

Throughout this section we shall assume R is a commutative ring.

Recall: An **Integral Domain** (ID) is a non-trivial ring in which $ab = 0$ implies either $a = 0$ or $b = 0$.

A **prime** ideal of a commutative ring R is a proper ideal such that $ab \in P$ implies either $a \in P$ or $b \in P$.

Lemma 5.1 *An ideal P is prime iff R/P is an ID.*

Proof. Assume P is prime. Then R/P is non-trivial since P is proper. If $(a+P)(b+P) = 0+P$ then $ab+P = P$ and so $ab \in P$. Thus either $a \in P$ or $b \in P$, so either $a + P = P$ or $b + P = P$. Thus R/P is an ID. Conversely, if R/P is an ID then P is proper since R/P is non-trivial. If $a, b \notin P$, then $a + P, b + P \neq 0 + P$, so $(a + P)(b + P) = ab + P \neq 0 + P$, so $ab \notin P$. Thus P is a prime ideal. □

Corollary 5.2 *Any maximal ideal of a commutative ring is also a prime ideal.*

Proof. M maximal $\Rightarrow R/M$ is a field $\Rightarrow R/M$ is an ID $\Rightarrow M$ is prime. □

The converse does not hold: (0) is prime but not maximal in $\mathbb{Z}$.
Examples of prime ideals: (p) in $\mathbb{Z}$, (0) in any ID. The ideal (X) in the ring $\mathbb{Z}[X]$ of polynomials in X with coefficients in $\mathbb{Z}$. This last example is also not maximal.

Every field is an ID. Furthermore, every subring of a field is an ID (e.g., $\mathbb{Z} \subseteq \mathbb{Q}$). We shall show that conversely, every ID can be embedded as a subring of a field.

Assume R is a commutative ring and $S \subseteq R$ is a submonoid of $(R, \times)$. In other words, $1 \in S$ and $a, b \in S$ implies $ab \in S$. For example, set $S = R \setminus P$ for any prime P. One particularly important case is when R is an ID and $S = R \setminus \{0\}$.

Define $S^{-1}R$ as $(R \times S)/\!\sim$, where $(r, s) \sim (r', s')$ iff $\exists u \in S$: $urs' = ur's$. We write r/s for the equivalence class $\overline{(r, s)} \in S^{-1}R$.

Note: if S contains no zero-divisors then $(r, s) \sim (r', s')$ iff $rs' = r's$.

Lemma 5.3 *The relation $\sim$ defined above is an equivalence relation and $S^{-1}R$ can be made into a ring so that the map $i\colon R \to S^{-1}R$, $i(r) = r/1$ is a homomorphism. Also $i(S) \subseteq (S^{-1}R)^\times$ and the map i is injective iff S contains no zero-divisors.*

Proof. Reflexivity and symmetry of $\sim$ are immediate. For transitivity, if $(r, s) \sim (r', s') \sim (r'', s'')$ then $\exists u, u' : urs' = ur's,\ u'r's'' = u'r''s'$. Hence $(uu's')(rs'') = u's''us'r = u's''usr' = usu'r's'' = usu'r''s' = (uu's')(r''s)$. But $uu's' \in S$, so $(r, s) \sim (r'', s'')$.
Define addition by $r_1/s_1 + r_2/s_2 = (r_1s_2 + r_2s_1)/(s_1s_2)$ and multiplication by $(r_1/s_1)(r_2/s_2) = (r_1r_2)/(s_1s_2)$. A long and rather tedious check shows that under these operations $S^{-1}R$ becomes a commutative ring with identity $1/1$.

The map $i(r) = r/1$ is a ring homomorphism since $i(r) + i(r') = r/1 + r'/1 = (r + r')/1 = i(r + r')$, $i(r)i(r') = (r/1)(r'/1) = (rr')/1 = i(rr')$, and $i(1) = 1/1$.
The element $1/s \in S^{-1}R$ is the inverse of $i(s) = s/1$, so $i(S) \subseteq (S^{-1}R)^{\times}$.
The kernel of i is $\{r \in R : r/1 = 0/1\} = \{r \in R : \exists u \in S : ur = 0\}$. Thus $\operatorname{Ker} i = \{0\}$ iff S contains no zero-divisors. □

Lemma 5.4 *$S^{-1}R$ satisfies the following universal property: If $f \colon R \to R'$ is a homomorphism with $f(S) \subseteq (R')^{\times}$ then f factors uniquely as $f = h \circ i$ where $h \colon S^{-1}R \to R'$ is a homomorphism.*

$$\begin{tikzcd} R \arrow[r, "f"] \arrow[d, "i"'] & R' \\ S^{-1}R \arrow[ur, "h"'] & \end{tikzcd}$$

Proof. Any such $\tilde{f}$ must satisfy $\tilde{f}(r/s)\tilde{f}(s/1) = \tilde{f}(r/1)$ and $\tilde{f}(t/1) = f(t)$. Hence $\tilde{f}(r/s)f(s) = f(r)$ and $\tilde{f}(r/s) = f(r)f(s)^{-1}$. Conversely, defining $\tilde{f}(r/s) = f(r)f(s)^{-1}$ gives a homomorphism $S^{-1}R \to R'$ (check this!). □

Notation: If $S = R \setminus P$ for some prime ideal P, we also write $S^{-1}R$ as R_P and call it the **localization of R at P**.

Lemma 5.5 *If R is an ID then $(R \setminus \{0\})^{-1}R = R_{(0)}$ is a field containing a subring isomorphic to R.*

Proof. Let $S = R \setminus \{0\}$. If $r/s \neq 0/1$ then $r \neq 0$, so $s/r \in S^{-1}R$ and $(s/r)(r/s) = 1/1$. Hence any non-zero element of $S^{-1}R$ is invertible. The map i is injective, so $\operatorname{Im} i$ is a subring of $S^{-1}R$ isomorphic to R. □

In this case we call $R_{(0)} = S^{-1}R$ the **field of fractions** of R, or $\operatorname{Frac} R$. For example $\operatorname{Frac}(\mathbb{Z}) = \mathbb{Q}$.

Exercises

1. Show that the units of R_P consists of the elements r/s where $r \notin P$ and there is a unique maximal ideal of R_P consisting of all the non-unit elements. [Rings that have a unique maximal ideal are called **local rings**.]

2. Show that if R is an ID, then for any prime ideal P, R_P is isomorphic to a subring of $\operatorname{Frac} R$.

3. Describe $\mathbb{Z}_{(2)}$ explicitly as a subring of $\mathbb{Q}$.

4. What is the field of fractions of a field?

5. What is the field of fractions of the ring of entire functions (holomorphic functions $f \colon \mathbb{C} \to \mathbb{C}$)?

6. What is the field of fraction of the ring of polynomial functions $\mathbb{C}[X] = \{\sum_{i=0}^{n} a_i X^i : a_i \in \mathbb{C},\ n \in \mathbb{N}\}$?

7261 6. Polynomial rings Fall 2017

Assume that R is a commutative ring. We wish to construct the ring $R[X]$ of polynomials in X with coefficients in R.

Define $R[X]$ as the set of sequences $(a_0, a_1, \dots)$ with the property that all but finitely many of the a_is are zero. Define $(a_0, \dots) + (b_0, \dots) = (a_0 + b_0, a_1 + b_1, \dots)$ (so $R[X] = \bigoplus_{i\in\mathbb{N}} R$ as group under $+$) and define $(a_0, \dots)(b_0, \dots) = (c_0, c_1, \dots)$ where $c_i = \sum_{0\le j\le i} a_j b_{i-j}$. We call $R[X]$ the ring of polynomials in X over R. Let $i\colon R \to R[X]$ be defined by $i(a) = (a, 0, 0, \dots)$ and let $X \in R[X]$ be the element $X = (0, 1, 0, 0, \dots)$. Note that $X(a_0, a_1, \dots) = (0, a_0, a_1, \dots)$ and $i(a)(a_0, a_1, \dots) = (aa_0, aa_1, \dots)$.

Lemma 6.1 *$R[X]$ is a ring, $i\colon R \to R[X]$ is an injective ring homomorphism, and if $a_i = 0$ for all $i > n$ then $(a_0, a_1, \dots) = \sum_{i=0}^n i(a_i)X^i$*

We shall normally identify $i(a)$ with a and write polynomials $f(X) \in R[X]$ in the form $\sum_{i=0}^n a_i X^i$. The **degree** $\deg f(X)$ of a polynomial is the largest n such that $a_n \neq 0$, (or $-\infty$ if $f = 0$). The **leading coefficient** of $f(X)$ is a_n where $n = \deg f$, (or 0 if $f = 0$). A polynomial is **monic** if the leading coefficient is 1.

Lemma 6.2 *If $f, g \in R[X]$ then*

1. $\deg(f + g) \le \max\{\deg f, \deg g\}$,
2. $\deg(fg) \le \deg f + \deg g$, *with equality holding if R is an ID.*

Lemma 6.3 *If R is an ID then $R[X]$ is an ID and $(R[X])^\times = R^\times$.*

Proof. If $f, g \in R[X]$ and $f, g \neq 0$ then $\deg(fg) = \deg f + \deg g \ge 0$, so $fg \neq 0$. If $fg = 1$ then $0 = \deg(fg) = \deg f + \deg g$ so $\deg f = \deg g = 0$ and $f, g \in R$. Hence $f \in (R[X])^\times$ implies $f \in R^\times$. Conversely $f \in R^\times$ clearly implies $f \in (R[X])^\times$. □

Theorem (Universal property of polynomial rings) *If $\phi\colon R \to R'$ is a ring homomorphism and $\alpha \in R'$ then there exists a unique homomorphism $\mathrm{ev}_{\phi,\alpha}\colon R[X] \to R'$ such that $\mathrm{ev}_{\phi,\alpha}(a)$ $[= \mathrm{ev}_{\phi,\alpha}(i(a))] = \phi(a)$ for all $a \in R$ and $\mathrm{ev}_{\phi,\alpha}(X) = \alpha$.*

If R is a subring of R' and ϕ is the inclusion map we write $f(\alpha)$ for $\mathrm{ev}_{\phi,\alpha}(f)$. More generally, if just R is a subring of R' we write $\phi(f)(\alpha)$ for $\mathrm{ev}_{\phi,\alpha}(f)$.

Lemma 6.4 *If R is a subring of R' and $\alpha \in R'$ then $R[\alpha]$ is isomorphic to a quotient $R[X]/I$ where I is an ideal of $R[X]$ containing no non-zero constants: $I \cap R = \{0\}$.*

Proof. Apply 1st Isomorphism Theorem to $\mathrm{ev}_\alpha\colon R[X] \to R'$. □

We say $\alpha \in R'$ is **transcendental over** $R \subseteq R'$ if the map ev_α is injective. In other words, if $f(\alpha) = 0$ implies $f(X) = 0$. Otherwise we say that α is **algebraic over** R.

Examples The element $\pi \in \mathbb{R}$ is transcendental over $\mathbb{Z}$, so $\mathbb{Z}[\pi] \cong \mathbb{Z}[X]$. The elements $i, \sqrt{2}, \sqrt[4]{3} \in \mathbb{C}$ are all algebraic over $\mathbb{Z}$. However π is algebraic over $\mathbb{R}$ (since it is a root of $X - \pi \in \mathbb{R}[X]$).

Theorem (Division Algorithm) *If $f, g \in R[X]$ and the leading coefficient of g is a unit in R, then there exist unique $q, r \in R[X]$ such that $f = qg + r$ and $\deg r < \deg g$ (or $r = 0$).*

If $a, b \in R$, we say a **divides** b, $a \mid b$, if there exists $c \in R$ such that $b = ca$.

Examples In any ring, $u \mid 1$ iff $u \in R^\times$, $a \mid 0$ for all a. In $\mathbb{Z}$, $7 \mid 21$. In $\mathbb{Q}$, $21 \mid 7$.

Lemma 6.5 *If $\alpha \in R$ and $f \in R[X]$ then $f(X) = (X - \alpha)q(X) + f(\alpha)$ for some $q \in R[X]$. In particular, $X - \alpha \mid f$ iff $f(\alpha) = 0$.*

Lemma 6.6 *If R is an ID and $f \in R[X]$, $f \neq 0$, then $|\{\alpha \in R : f(\alpha) = 0\}| \leq \deg f$.*

Lemma 6.7 *If R is an ID and G is a finite subgroup of $R^\times$ then G is cyclic.*

Proof. G is a finite abelian group, so $G \cong C_{d_1} \times \cdots \times C_{d_r}$. But then $x^{d_1} = 1$ for all $x \in G$. Thus the polynomial $X^{d_1} - 1$ has $|G|$ zeros. Thus $|G| = d_1 d_2 \dots d_r \leq d_1$, so $d_2 = \cdots = d_r = 1$ and $G \cong C_{d_1}$ is cyclic. $\square$

We can generalize polynomial rings to polynomials in many variables. If $\{X_i\}_{i \in I}$ is a set (possibly infinite) of indeterminates, define a **term** t to be a function $I \to \mathbb{N}$ which is non-zero for only finitely many $i \in I$. We think of t as corresponding to a *finite* product $\prod_{i \in I} X_i^{t(i)}$. Let T be the set of terms. Now define the ring

$$R[\{X_i\}_{i \in I}] = \bigoplus_{t \in T} R = \{(a_t)_{t \in T} \mid a_t = 0 \text{ for all but finitely many } t\},$$

with addition of coefficients componentwise $(a_t) + (b_t) = (a_t + b_t)$ and multiplication defined by $(a_t)(b_t) = (c_t)$ where $c_t = \sum_{r+s=t} a_r b_s$ (note that this is a finite sum). As for $R[X]$ we can identify R as a subring of $R[\{X_i\}_{i \in I}]$ and define elements X_i so that $(a_t)_{t \in T}$ is equal to the (finite) sum $\sum_{t \in T} a_t \prod_{i \in I} X_i^{t(i)}$.

Theorem (Universal property of polynomial rings) *If $\phi \colon R \to R'$ is a ring homomorphism and $\alpha_i \in R'$ for all $i \in I$ then there exists a unique homomorphism $\mathrm{ev}_{\phi,(\alpha_i)} \colon R[\{X_i\}_{i \in I}] \to R'$ such that $\mathrm{ev}_{\phi,(\alpha_i)}(a) = \phi(a)$ for all $a \in R$ and $\mathrm{ev}_{\phi,(\alpha_i)}(X_i) = \alpha_i$ for all $i \in I$.*

If I is finite then we can also identify $R[X_1, \dots, X_n]$ with $R[X_1, \dots, X_{n-1}][X_n]$ (use universal properties to define the isomorphism).

7261 7. Euclidean Domains and PIDs Fall 2017

A **Euclidean Domain** is an ID for which there is a function $d\colon R\setminus\{0\}\to\mathbb{N}$ such that if $a,b\in R$, $b\neq 0$ then there exists $q,r\in R$ such that $a=qb+r$ with either $d(r)<d(b)$ or $r=0$.

Examples

1. $\mathbb{Z}$ with $d(a)=|a|$.
2. $F[X]$, where F is a field, $d(f)=\deg f$.
3. F, where F is a field, $d(a)=0$.
4. $\mathbb{Z}[i]$, with $d(a+ib)=|a+ib|^2=a^2+b^2$. [Write $a/b=x+iy$ and let $q=x'+iy'$ with $|x-x'|,|y-y'|\leq\frac{1}{2}$. Then $d(r)=|qb-a|^2=|q-a/b|^2|b|^2=((x-x')^2+(y-y')^2)d(b)\leq\frac{1}{2}d(b)$.]

A **Principal Ideal Domain** (PID) is an ID in which every ideal I is principal, i.e., $I=(a)$ for some $a\in R$.

Theorem 7.1 *Every Euclidean Domain is a PID.*

Proof. If R is Euclidean then R is an ID, so it is enough to show that any ideal I is principal. Let I be an ideal of R and assume $I\neq(0)$. Pick $b\in I\setminus\{0\}$ with minimal value of $d(b)$ (by well ordering of $\mathbb{N}$). If $a\in I$ then $a=qb+r$ with $d(r)<d(b)$ or $r=0$. But $r=a-qb\in I$, so by choice of b we must have $r=0$. Thus $a=qb\in(b)$. Thus $I\subseteq(b)$. But $b\in I$, so $(b)\subseteq I$. Thus $I=(b)$ is principal. □

Note: PID $\not\Rightarrow$ Euclidean.

If $I=(a)$ is a principal ideal then $b\in I$ implies there exists a $c\in R$ with $b=ca$. Thus $b\in I$ is equivalent to $a\mid b$. In particular $(b)\subseteq(a)\iff a\mid b$. If $(a)=(b)$ then $b=ua$ and $a=vb$. Thus either $a=b=0$ or $uv=1$ and $u,v\in R^\times$. Conversely, if $a=ub$ with $u\in R^\times$ then $(a)=(b)$.

The elements $a,b\in R$ are called **associates** if $b=ua$ for some $u\in R^\times$. Equivalently, $a\mid b$ and $b\mid a$ both hold, or $(a)=(b)$. Write $a\sim b$ if a and b are associates.

A **greatest common divisor** (gcd) of a set of elements $S\subseteq R$ is an element $d\in R$ such that

G1. $d\mid a$ for all $a\in S$, and

G2. if $c\mid a$ for all $a\in S$ then $c\mid d$.

Greatest common divisors are unique up to multiplication by units. To see this, let d,d' be two gcds. Then condition G2 with $c=d'$ and G1 with $d=d'$ imply $d'\mid d$. Similarly $d\mid d'$, so $d'=ud$ for some unit $u\in R^\times$.

Lemma 7.2 *If R is a PID then gcds of any $S \subseteq R$ exist. Indeed, if $(S) = (d)$ then d is a gcd of S and hence can be written in the form $d = \sum_{i=1}^{n} c_i a_i$, for some $a_i \in S$, $c_i \in R$.*

Proof. Since R is a PID, $(S) = (d)$ for some d. If $a \in S$ then $a \in (S) = (d)$, so $d \mid a$. If $c \mid a$ for all $a \in S$, then $a \in (c)$ for all $a \in S$, so $(S) = (d) \subseteq (c)$. Hence $c \mid d$. Thus d is a gcd of S. $\square$

Note: In an arbitrary ID, gcds may not exist, and even if they do, they may not be a linear combination of elements of S. For example the elements 2 and X in $\mathbb{Z}[X]$ have 1 as a gcd, but 1 is not of the form $2c_1 + Xc_2$, $c_1, c_2 \in \mathbb{Z}[X]$. For an example where the gcd does not exist, consider $R = \mathbb{Z}[\sqrt{-5}]$. If $a \in R$ then $|a|^2 \in \mathbb{Z}$. Hence if $a \mid b$ in R then $|a|^2 \mid |b|^2$ in $\mathbb{Z}$. Now let $x = -3(3 - \sqrt{-5}) = (1 + 2\sqrt{-5})(1 + \sqrt{-5})$ and $y = -7(1 + \sqrt{-5}) = (1 - 2\sqrt{-5})(3 - \sqrt{-5})$. Then $1 + \sqrt{-5}$ and $3 - \sqrt{-5}$ are two common factors of x and y. If d is a gcd of x and y, then $|d|^2$ must be a factor of $|x|^2 = 2.3^2.7$ and $|y|^2 = 2.3.7^2$. On the other hand, $|d|^2$ must be a multiple of $|1 + \sqrt{-5}|^2 = 2.3$ and $|3 - \sqrt{-5}|^2 = 2.7$. Thus $|d|^2 = 2.3.7 = 42$. However, if $d = \alpha + \beta\sqrt{-5}$ then $|d|^2 = \alpha^2 + 5\beta^2$, which is never equal to 42.

The Euclidean Algorithm

We can turn Lemma 1 into an algorithm in the case when R is Euclidean. Assume we need to find the gcd of $a_0 = a$ and $a_1 = b$. Inductively define a_{n+1} for $n \geq 1$ and $a_n \neq 0$ by

$$a_{n-1} = q_n a_n + a_{n+1}, \qquad d(a_{n+1}) < d(a_n) \text{ or } a_{n+1} = 0$$

Since the $d(a_n)$ are a sequence of decreasing non-negative integers, eventually $a_{n+1} = 0$. However $a_{i+1} \in (a_i, a_{i-1})$ and $a_{i-1} \in (a_i, a_{i+1})$ imply the two ideals (a_{i-1}, a_i) and (a_i, a_{i+1}) are equal. Hence $(a_0, a_1) = (a_n, a_{n+1}) = (a_n)$ and a_n is a gcd of a_0 and a_1.

This algorithm is called the **Euclidean Algorithm**. For more than two elements, one can calculate the gcd inductively by using $\gcd(c_1, c_2, \ldots, c_r) = \gcd(c_1, \gcd(c_2, \ldots, c_r))$.

Exercises

1. Prove that $\gcd(c_1, \ldots, c_r) = \gcd(c_1, \gcd(c_2, \ldots, c_r))$ provided the gcds on the RHS exist. What is $\gcd(\emptyset)$?

2. Let $R = \mathbb{Z}[\omega]$ where $\omega = \frac{1}{2}(1 + \sqrt{-3})$. Show that $R = \{a + b\omega : a, b \in \mathbb{Z}\}$ and that R is Euclidean.

3. Use the Euclidean algorithm to find the gcd of $7 - 3i$ and $5 + 3i$ in $\mathbb{Z}[i]$.

4. Determine $((\mathbb{Z}/n\mathbb{Z})[X])^\times$. [Hint: Consider the case $n = p^r$ first.]

5. Solve the congruences

$$x \equiv i \bmod 1 + i \qquad x \equiv 1 \bmod 2 - i$$

in $\mathbb{Z}[i]$ (use Chinese Remainder Theorem).

7261 8. Unique Factorization Fall 2017

An element $a \in R$ is **irreducible** if $a \neq 0$, $a \notin R^\times$, and $a = bc$ implies $b \in R^\times$ or $c \in R^\times$. An element $a \in R$ is a **prime** if $a \neq 0$, $a \notin R^\times$ and $a \mid bc$ implies $a \mid b$ or $a \mid c$.

Lemma 8.1 *Let R be an ID, and $a \in R$. Then*

1. *a is a prime element iff (a) is a non-zero prime ideal,*
2. *a is irreducible iff (a) is maximal among proper principal ideals (i.e., $(a) \subseteq (b)$ implies $(b) = (a)$ or $(b) = R$),*
3. *if a is prime then a is irreducible,*
4. *if a is irreducible and R is a PID then a is prime.*

Proof.
1. If a is prime and $bc \in (a)$ then $a \mid bc$. Hence $a \mid b$ or $a \mid c$, so either $b \in (a)$ or $c \in (a)$. Also, $a \neq 0$, $a \notin R^\times$ implies $(a) \neq (0), R$. Conversely, if (a) is a prime ideal and $a \mid bc$, then $bc \in (a)$, so either $b \in (a)$ or $c \in (a)$, so either $a \mid b$ or $a \mid c$ and $(a) \neq (0), R$ implies $a \neq 0$, $a \notin R^\times$.
2. If $a \in R$ be irreducible and $(a) \subseteq (b)$ then $a = bc$, so either $c \in R^\times$ and $(b) = (a)$ or $b \in R^\times$ and $(b) = R$. Conversely if (a) is maximal among all proper principal ideals and $a = bc$ then $(a) \subseteq (b)$, so either $(a) = (b)$ and c is a unit or $(b) = R$ and b is a unit.
3. If a is a prime and $a = bc$ then $a \mid bc$. Thus either $a \mid b$ and $c \in R^\times$, or $a \mid c$ and $b \in R^\times$.
4. By part 2, (a) is a maximal ideal. Hence (a) is prime and so a is prime. □

A ring R is a **Unique Factorization Domain** (UFD) if R is an ID such that

- U1. Every $a \in R \setminus \{0\}$ can be written in the form $a = up_1 \dots p_r$ where $u \in R^\times$ and the p_i are irreducible.
- U2. Any two such factorizations are unique in the sense that if $up_1 \dots p_r = vq_1 \dots q_s$ then $r = s$ and there is a permutation $\pi \in S_r$ such that $p_i \sim q_{\pi(i)}$ for all i.

Lemma 8.2 *R is a UFD iff R is an ID satisfying*

- A. *there is no infinite sequence $(a_i)_{i \in \mathbb{N}}$ with $a_{i+1} \mid a_i$ and $a_{i+1} \not\sim a_i$, and*
- B. *every irreducible is prime.*

Proof.
A $\Rightarrow$ U1. Suppose $a_1 \in R$ has no such factorization. Then a_1 is neither a unit nor irreducible, so $a_1 = bc, b, c \notin R^\times$, and either b or c also has no factorization into irreducibles. Assume b has no factorization into irreducibles and set $a_2 = b$. Repeating this process we get a sequence a_i with $a_{i+1} \mid a_i$ and $a_{i+1} \not\sim a_i$.
B $\Rightarrow$ U2. Since p_1 is prime and $p_1 \mid vq_1 \dots q_s$, we must have $p_1 \mid q_i$ for some i. But q_i is irreducible, so $p_1 \sim q_i$. Cancelling a factor of p_1 from both sides (R is an ID) and using induction on r gives the result.
U1 and U2 $\Rightarrow$ A and B is clear. □

A ring is **Noetherian** if every sequence of ideals I_i with $I_i \subseteq I_{i+1}$ is eventually constant, $I_n = I_{n+1} = \dots$, for some n.

Lemma 8.3 *R is Noetherian iff every ideal is finitely generated.*

Proof. $\Leftarrow$: Let $I = \cup I_n$. Then I is an ideal, so $I = (d_1, \dots, d_r)$ for some $d_i \in R$. But then there is an n_i with $d_i \in I_n$. Let $n = \max n_i$, so that $I = (d_1, \dots, d_r) \subseteq I_n \subseteq I_{n+1} \subseteq \dots \subseteq I$, and so $I_n = I_{n+1} = \dots$.
$\Rightarrow$: Assume I is not finitely generated. Then (using Axiom of choice), pick inductively $d_n \in I \setminus (d_1, \dots, d_{n-1})$. Then $I_n = (d_1, \dots d_n)$ is a strictly increasing sequence of ideals. □

Theorem *Every PID is a UFD.*

Proof. Every ideal in a PID is finitely generated (by one element), so PID $\Rightarrow$ Noetherian. By considering the ideals (a_i), Noetherian rings satisfy condition A of Lemma 8.2. Lemma 8.1 part 4 implies condition B of Lemma 8.2, so PID $\Rightarrow$ UFD. □

GCDs and factorizations

Lemma 8.4 *If R is a UFD and $S \subseteq R$ then a gcd of S exists.*

Proof. The relation $\sim$ is an equivalence relation on the set of irreducibles in R. So by choosing a representative irreducible from each equivalence class we can construct a set P of pairwise non-associate irreducible elements of R. We can write any element $a \in R$ as $u \prod_{p \in P} p^{n_p}$ and if $b = v \prod_{p \in S} p^{m_p}$ then U2 implies $a \mid b$ iff $n_p \leq m_p$ for all p. Write each $a_i \in S$ as $a_i = u_i \prod_{p \in P} p^{n_{i,p}}$. If we let $d = \prod_{p \in P} p^{m_p}$ with $m_p = \min_{a_i \in S} n_{i,p}$ then it is clear that d is a gcd for S. □

A partial converse to Lemma 8.4 is true.

Lemma 8.5 *If R is an ID in which the gcd of any pair of elements exists then every irreducible is prime.*

Proof. First we prove that if gcds exist then $\gcd(ab, ac) \sim a \gcd(b, c)$. Let $e = \gcd(ab, ac)$ and $d = \gcd(b, c)$. Then $d \mid b, c$, so $ad \mid ab, ac$, so $ad \mid e$. Writing $e = adu$ then $e \mid ab, ac$, so $du \mid b, c$, so $du \mid d$. Thus $u \in R^\times$ and $e \sim ad$ (or $d = 0 = e$).
Now let p be an irreducible and assume $p \nmid a, b$. Then $\gcd(p, b) \sim 1$ since the gcd must be a factor or p and $p \nmid b$. Hence $\gcd(p, ab) \mid \gcd(ap, ab) \sim a$. But $\gcd(p, ab) \mid p$, so $\gcd(p, ab) \mid \gcd(a, p) \sim 1$. Hence $\gcd(p, ab) \sim 1$ and $p \nmid ab$. Hence p is prime. □

Lemma 8.6 *If R is an ID in which every set S has a gcd which can be written in the form $\sum r_i a_i$ for some $a_i \in S$, $r_i \in R$, then R is a PID.*

Proof. Let I be an ideal and write $I = (S)$ for some S (e.g., $S = I$). Let $d = \sum r_i a_i$ be a gcd of S. Then $d \mid a$ for all $a \in S$. Hence $a \in (d)$, so $S \subseteq (d)$. Thus $I \subseteq (d)$. However $d = \sum r_i a_i \in I$. Then $(d) \subseteq I$. Hence $I = (d)$ is principal. □

7261 9. Factorization of Polynomials Fall 2017

Assume throughout this section that R is a UFD.

Let $f(X) = \sum_{i=0}^{n} a_i X^i \in R[X]$. Define the **content** of $f(X)$ to be $c(f) = \gcd\{a_0, a_1, \dots, a_n\}$. Note that if $f \neq 0$ then $c(f) \neq 0$. We call f **primitive** iff $c(f) \sim 1$.

Note that monic polynomials are primitive, but not conversely, e.g. $2X + 3 \in \mathbb{Z}[X]$.

Lemma (Gauss) *If R is a UFD and $f, g \in R[X]$ are primitive, then so is fg.*

Proof. Assume otherwise and let p be a prime dividing $c(fg)$. Reducing the polynomials mod p we get $\bar{f}, \bar{g} \in (R/(p))[X]$ with $\bar{f}, \bar{g} \neq 0$, but $\bar{f}\bar{g} = \overline{fg} = 0$ (the map $f \mapsto \bar{f}$ $R[X] \to (R/(p))[X]$ is a special case of the evaluation homomorphism $\mathrm{ev}_{\pi,X}$ where X is sent to X and $\mathrm{ev}_{\pi,X}$ acts as the projection map $\pi\colon R \to R/(p)$ on constants). Now p is prime, so (p) is a prime ideal and $R/(p)$ is an ID. Hence $\bar{f}, \bar{g} \neq 0$ implies $\bar{f}\bar{g} \neq 0$, a contradiction. □

Corollary 9.1 *If R is a UFD then $c(fg) \sim c(f)c(g)$.*

Proof. The result clearly holds if f or g is zero, so assume $f, g \neq 0$ and hence $c(f) \neq 0$. Since $\gcd\{aa_i\} \sim a \gcd\{a_i\}$, $c(af) \sim ac(f)$ for all $a \in R$. But $f/c(f) \in R[X]$, so $c(f)c(f/c(f)) = c(f)$ and so $f/c(f)$ is primitive. Now $fg/(c(f)c(g)) = (f/c(f))(g/c(g))$ is primitive. Hence $c(fg) \sim c(f)c(g)c(fg/c(f)c(g)) \sim c(f)c(g)$. □

Lemma 9.2 *If $\deg f > 0$ and f is irreducible in $R[X]$ then f is irreducible in $F[X]$, where $F = \operatorname{Frac} R$ is the field of fractions of R.*

Proof. Suppose $f = gh$ in $F[X]$. By multiplying by denominators, there exist non-zero $a, b \in R$ with $ag, bh \in R[X]$. Thus $abf = (ag)(bh) \in R[X]$ and $c(abf) \sim c(ag)c(bh)$. But $f = c(f)(f/c(f))$ is a factorization of f in $R[X]$ and if $\deg f > 0$, $f/c(f) \notin (R[X])^\times = R^\times$. Thus $c(f) \in R^\times$ and so $c(abf) \sim ab$. Now $ab/c(ag)c(bh) = u \in R^\times$ and $f = (u^{-1}ag/c(ag))(bh/c(bh))$ is a factorization of f in $R[X]$. Hence either $\deg g = 0$ or $\deg f = 0$ and so g or h is a unit in $F[X]$. □

Lemma 9.3 *If R is a UFD then $f \in R[X]$ is irreducible iff either*
(a) $f \in R$ is an irreducible in R, or (b) f is primitive in $R[X]$ and irreducible in $F[X]$.

Proof. Assume first that $\deg f = 0$. If $f = ab$ in R, $f = ab$ in $R[X]$. Conversely, if $f = gh$ in $R[X]$ then $\deg g = \deg h = 0$, so $f = gh$ in R. Since $R^\times = (R[X])^\times$, irreducibility in $R[X]$ is equivalent to irreducibility in R. Assume now that $\deg f > 0$. If f is irreducible in $R[X]$ then by the previous lemma, f is irreducible in $F[X]$. Also, $f = c(f)(f/c(f))$, so $c(f) \in (R[X])^\times = R^\times$ and f is primitive. Conversely, if f is primitive and irreducible in $F[X]$ and $f = gh$ in $R[X]$, then $f = gh$ in $F[X]$, so wlog $g \in (F[X])^\times \cap R[X] = R$. But then $g \mid c(f)$ in R, so $g \in R^\times = (R[X])^\times$. Thus f is irreducible in $R[X]$. □

Theorem 9.4 *If R is a UFD then $R[X]$ is a UFD.*

Proof. Write $f = c(f)f'$ where f' is primitive. Now $c(f) = up_1 \dots p_r$ where $u \in R^\times = (R[X])^\times$ and p_i are irreducible in R. If $f' = gh$ with $g, h \notin (R[X])^\times = R^\times$ then $c(g)c(h) \sim 1$, so g, h are primitive and $\deg g, \deg h > 0$ (since otherwise either g or h would lie in $R^\times$). By induction on the degree, f' is the product of irreducible primitive polynomials $f' = \prod f_i$. Hence f has a factorization into irreducibles.
Now assume $f = up_1 \dots p_r f_1 \dots f_t = vq_1 \dots q_s g_1 \dots g_u$ where $u, v \in R^\times$, p_1, q_j are irreducible in R and f_i, g_j are primitive and irreducible in $F[X]$. The ring $F[X]$ is a PID, so is a UFD. The elements $up_1 \dots p_r$ and $vq_1 \dots q_s$ are units in $F[X]$, so $t = u$ and wlog $f_i = \gamma_i g_i$ for some $\gamma_i \in (F[X])^\times = F \setminus \{0\}$. Write $\gamma_i = a_i/b_i$ with $a_i, b_i \in R$. Now $b_i f_i = a_i g_i$, so $b_i \sim c(b_i f_i) = c(a_i g_i) \sim a_i$. Thus $\gamma_i \in R^\times$ and $f_i \sim g_i$ in $R[X]$. Now $c(f) \sim up_1 \dots p_r \sim vq_1 \dots q_s$, so by unique factorization in R, $r = s$ and wlog $p_i \sim q_i$ in R and hence in $R[X]$. Hence the factorization of f is unique in $R[X]$. □

Factorization methods

Evaluation method: If $g \mid f$ in $R[X]$ then $g(c) \mid f(c)$ in R for all $c \in R$.

Example: If $f = X^3 - 4X + 1 \in \mathbb{Z}[X]$, then $f(\pm 2) = 1$. If $f = gh$ then we can assume wlog that g is linear. But then $g(\pm 2) = \pm 1$. The only linear polynomials with this property are $\pm X/2$ which do not lie in $\mathbb{Z}[X]$. Hence f is irreducible in $\mathbb{Z}[X]$ (and hence also in $\mathbb{Q}[X]$).

Reduction mod p: If $f = gh$ in $R[X]$ and p is a prime then $\bar{f} = \bar{g}\bar{h}$ in $(R/(p))[X]$.

Example: If $f = X^4 - X^2 + 4X + 3 \in \mathbb{Z}[X]$, then if $p = 2$, $\bar{f} = X^4 + X^2 + 1 = (X^2+X+1)(X^2+X+1)$ in $(\mathbb{Z}/2\mathbb{Z})[X]$ and if $p = 3$ then $\bar{f} = X^4 - X^2 + X = X(X^3 - X + 1)$ in $(\mathbb{Z}/3\mathbb{Z})[X]$. In $\mathbb{Z}[X]$, f cannot factor as a product of two quadratics (since there is no quadratic factor mod 3), nor can it have a linear factor (no linear factor mod 2), hence f is irreducible in $\mathbb{Z}[X]$.

Lemma (Eisenstein's irreducibility criterion) *Assume R is a UFD, $f = \sum_{i=0}^n a_n X^n \in R[X]$, is primitive, and p is a prime such that $p \not| a_n$, $p \mid a_i$ for $i < n$ and $p^2 \not| a_0$. Then f is irreducible in $R[X]$.*

Proof. Suppose $f = gh$. Then $\bar{g}\bar{h} = a_n X^n$ in $(R/(p))[X]$. Thus $\bar{g} = aX^i$ and $\bar{h} = bX^j$ for some $a, b \in R/(p)$ and $i + j = n$. But $\deg g + \deg h = n$ and $i \le \deg g$, $j \le \deg h$. Hence $i = \deg g$ and $j = \deg h$. If g and h are not units in $R[X]$ and f is primitive then $\deg g, \deg h > 0$. Hence $\bar{g}(0) = \bar{h}(0) = 0$, so $p \mid g(0), h(0)$. Thus $p^2 \mid g(0)h(0) = f(0) = a_0$, a contradiction. Hence f is irreducible. □

Exercises

1. Show that for p a prime in $\mathbb{Z}$, $f(X) = 1 + X + \dots X^{p-1} = (X^p - 1)/(X - 1)$ is irreducible in $\mathbb{Q}[X]$ [Hint: consider $f(X + 1)$ and use Eisenstein's criterion].
2. Let $f = X^3 - X + 1$. Show that $(\mathbb{Z}/3\mathbb{Z})[X]/(f)$ is a field with 27 elements.

7261 10. Symmetric Polynomials Fall 2017

A polynomial $f(X_1, \dots, X_n) \in R[X_1, \dots, X_n]$ is called **symmetric** if

$$f(X_1, \dots, X_n) = f(X_{\pi(1)}, \dots, X_{\pi(n)})$$

for any permutation $\pi \in S_n$.

Examples $X_1^2 + X_2^2 + X_3^2$ and $X_1X_2 + X_2X_3 + X_3X_1$ are symmetric polynomials in the ring $\mathbb{Z}[X_1, X_2, X_3]$, however $X_1^2X_2 + X_2^2X_3 + X_3^2X_1$ is not symmetric (consider the permutation $\pi = (12)$).

The **elementary symmetric polynomials** $\sigma_r \in R[X_1, \dots, X_n]$ are defined by $\sigma_r = \sum_{i_1 < i_2 < \cdots < i_r} X_{i_1} \dots X_{i_r} = \sum_{|S|=r} \prod_{i \in S} X_i$ where in the second expression the sum is over all subsets S of $\{1, \dots, n\}$ of size r.

Examples For $n = 3$, $\sigma_0 = 1$, $\sigma_1 = X_1 + X_2 + X_3$, $\sigma_2 = X_1X_2 + X_2X_3 + X_3X_1$, $\sigma_3 = X_1X_2X_3$.

Note: $(X + X_1)(X + X_2) \dots (X + X_n) = X^n + \sigma_1 X^{n-1} + \sigma_2 X^{n-2} + \cdots + \sigma_n$.

Define the **degree** of $cX_1^{a_1} \dots X_n^{a_n} \in R[X_1, \dots, X_n]$, $c \neq 0$, as the n-tuple $(a_1, \dots, a_n)$. More generally define the degree of $f = \sum_{a_1,\dots,a_n} c_{a_1,\dots,a_n} X_1^{a_1} \dots X_n^{a_n}$ as the maximum value of $(a_1, \dots, a_n)$ over all $c_{a_1,\dots,a_n} \neq 0$, where n-tuples are ordered lexicographically: $(a_1, \dots, a_n) < (b_1, \dots, b_n)$ iff there exists an i such that $a_i < b_i$ and $a_j = b_j$ for all $j < i$.

Example In $R[X_1, X_2, X_3]$, $\deg(X_1^2X_2^9 + X_1^7X_3) = (7, 0, 1)$.
In $R[X_1, \dots, X_n]$, $\deg \sigma_r = (1, \dots, 1, 0, \dots, 0)$, where there are r ones and $n - r$ zeros.

Lemma 10.1 *The lexicographic ordering on $\mathbb{N}^n$ is a well ordering: $\mathbb{N}^n$ is totally ordered and every non-empty $S \subseteq \mathbb{N}^n$ has a minimal element.*

Proof. To prove every $S \neq \emptyset$ has a minimal element, inductively construct sets S_i with $S_0 = S$ and S_i equal to the set of elements $(a_1, \dots, a_n)$ of S_{i-1} for which a_i is minimal. It is clear that $S_i \neq \emptyset$ and the (unique) element of S_n is the minimal element of S. □

Lemma 10.2 *If $f \in R[X_1, \dots, X_n]$ is symmetric and $\deg f = (a_1, \dots, a_n)$ then $a_1 \geq a_2 \geq \cdots \geq a_n$.*

Proof. Assume otherwise and let $a_i < a_j$ with $i > j$. Then if $\pi = (ij)$, $f(X_1, \dots, X_n) = f(X_{\pi(1)}, \dots, X_{\pi(n)})$ has a term with degree $(a_{\pi(1)}, \dots, a_{\pi(n)})$ which is larger than $(a_1, \dots, a_n)$, contradicting the definition of the degree. □

Lemma 10.3 *If $f, g \in R[X_1, \dots, X_n]$ and f, g are monic (the term with degree equal to $\deg f$ or $\deg g$ has coefficient 1) then $\deg fg = \deg f + \deg g$ where addition of degrees is performed componentwise: $(a_1, \dots, a_n) + (b_1, \dots, b_n) = (a_1 + b_1, \dots, a_n + b_n)$.*

Proof. Prove that in the lexicographical ordering, $\mathbf{a} < \mathbf{b}$ and $\mathbf{c} \leq \mathbf{d}$ imply $\mathbf{a}+\mathbf{c} < \mathbf{b}+\mathbf{d}$. The rest of the proof is the same as for the one variable case. $\square$

Theorem 10.1 *The polynomial $f \in R[X_1, \dots, X_n]$ is symmetric iff $f \in R[\sigma_1, \dots, \sigma_n]$.*

Clearly σ_i is symmetric, and the set of symmetric polynomials forms a subring of the ring $R[X_1, \dots, X_n]$. Hence every element of $R[\sigma_1, \dots, \sigma_n]$ is symmetric. We now need to show every symmetric polynomial can be written as a polynomial in $\sigma_1, \dots, \sigma_n$. We use induction on $\deg f$. Let f be a counterexample with minimal $\deg f$ (using Lemma 1). Let $\deg f = (a_1, \dots, a_n)$ and let the leading term have coefficient $c \in R$. Then $g = c\sigma_1^{a_1-a_2}\sigma_2^{a_2-a_3} \dots \sigma_n^{a_n}$ has $\deg g = (a_1, \dots, a_n) = \deg f$ (by Lemma 3) and the same leading coefficient c. Thus $\deg(f-g) < \deg f$. Now g is symmetric, so $f-g$ is symmetric. By induction on $\deg f$, $f - g \in R[\sigma_1, \dots, \sigma_n]$. But $g \in R[\sigma_1, \dots, \sigma_n]$. Hence $f \in R[\sigma_1, \dots, \sigma_n]$, contradicting the choice of f.

If $\alpha \in R'$ and R is a subring of R', we call α **algebraic** over R if the map $\mathrm{ev}_\alpha \colon R[X] \to R'$ is not injective, i.e., there exists a non-zero $f(X) \in R[X]$ with $f(\alpha) = 0$. More generally we say $\alpha_1, \dots, \alpha_n$ are **algebraically dependent** if $\mathrm{ev}_{\alpha_1,\dots,\alpha_n} \colon R[X_1, \dots, X_n] \to R'$ is not injective, or equivalently there exists a non-zero polynomial $f \in R[X_1, \dots, X_n]$ with $f(\alpha_1, \dots, \alpha_n) = 0$. We say $\alpha_1, \dots, \alpha_n$ are **algebraically independent** over R if they are not algebraically dependent.

Theorem 10.2 *The elements $\sigma_1, \dots, \sigma_n$ are algebraically independent over R. The elements X_i are algebraic over $R[\sigma_1, \dots, \sigma_n]$.*

Proof. Assume $\sum c_{a_1,\dots,a_n}\sigma_1^{a_1} \dots \sigma_n^{a_n} = 0$ in $R[X_1, \dots, X_n]$. Among the (finite set of) $(b_1, \dots, b_n)$ such that $c_{b_1,\dots,b_n} \neq 0$, pick one such that $(b_1 + \dots + b_n, b_2 + \dots + b_n, \dots, b_n)$ is maximal in the lexicographical ordering. The map sending $(a_1, \dots, a_n)$ to $(a_1 + \dots + a_n, a_2 + \dots + a_n, \dots, a_n)$ is an injection $\mathbb{N}^d$ to $\mathbb{N}^d$, so this $(b_1, \dots, b_n)$ is uniquely determined. Now $\deg \sum c_{a_1,\dots,a_n}\sigma_1^{a_1} \dots \sigma_n^{a_n} = (b_1 + \dots + b_n, b_2 + \dots + b_n, \dots, b_n)$ contradicting $\sum c_{a_1,\dots,a_n}\sigma_1^{a_1} \dots \sigma_n^{a_n} = 0$. Thus $\sigma_1, \dots, \sigma_n$ are algebraically independent. The elements X_i are algebraic over $R[\sigma_1, \dots, \sigma_n]$ since they are roots of $X_n - \sigma_1 X^{n-1} + \dots \pm \sigma_n = 0$. $\square$

As a consequence of Theorem 2, any symmetric polynomial $f \in R[X_1, \dots, X_n]$ can be written as $g(\sigma_1, \dots, \sigma_n)$ with g a *unique* element of $R[X_1, \dots, X_n]$. For example, $X_1^2 + X_2^2 + X_3^2 = \sigma_1^2 - 2\sigma_2$.

Exercises

1. Let $\delta = \prod_{i<j}(X_i - X_j) \in \mathbb{Z}[X_1, \dots, X_n]$. Show that δ^2 is symmetric and for $n = 3$ express δ^2 in terms of $\sigma_1, \sigma_2, \sigma_3$.

2. Let $f(X) = X^3 - 3X + 5$ have complex roots $\alpha_1, \alpha_2, \alpha_3$. Find a polynomial with complex roots $\alpha_1^2, \alpha_2^2, \alpha_3^2$.