Algebra II: Rings and Fields

MATH 340

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1 Beginning

Definition 1.1. A **group** is a pairing of a set and a binary operation such that the operation is associative, and each element of the set has both an inverse and an identity.

Remark 1.1.1. Considering an identity element is defined both as a left and a right identity, it can be proven that it is unique for the group.

Remark 1.1.2. Considering the binary operation is well defined, it can be proven that the inverse is distinct for every element of the set.

Definition 1.1.1. A **commutative group** is a group where the binary operation is commutative.

Definition 1.2. A **ring** is a commutative group with another operation defined such that the two operations are similar to "addition" and "multiplication" of the integers. The multiplication operation must be associative and distributive.

Definition 1.2.1. A **commutative ring** is a ring where multiplication is commutative.

Definition 1.2.2. We say that a ring has **unity** if there is a multiplicative identity.

Remark 1.2.1. For any ring R with additive identity 0, it can be proven that $0a = 0$ for all $a \in R$.

Remark 1.2.2. Using Remark 1.2.1, it can be proven that $-ab = (-a)b = a(-b)$ for all $a, b \in R$.

Definition 1.2.3. For some non-zero $a, b \in R$, we say a and b are **zero divisors** if $ab = 0$.

Remark 1.2.3. For some non-zero $a \in R$, it can be proven that a is a left zero divisor if and only if there exists non-zero $b, c \in R$ such that $b \neq c$ and $ab = ac$.

Remark 1.2.4. It follows from Remark 1.2.3, that if a ring R does *not* have any zero divisors, then $ab = ac \implies b = c$ for all $a, b, c \in R$ and $a \neq 0$.

Definition 1.2.4. A **unit** in a ring with unity is an element which has a multiplicative inverse.

Remark 1.2.5. A unit cannot be a zero-divisor.

Definition 1.3. An **integral domain** is a commutative ring with unity and no zero divisors.

Definition 1.4. A **field** is a commutative ring where every non-zero element is a unit, and the additive and multiplicative identities are not equal.

2 Developing

Definition 2.1. The **characteristic** of a ring is the lowest integer c such that $\underbrace{1 + 1 + \cdots + 1}_{c \text{ times}} = 0$.

Theorem 2.1.1. *If the characteristic of a ring is composite, it must have zero divisors.*

Proof. Let c be the characteristic of some ring where there exists positive integers m, n such that $c = mn$ and $m, n < c$. Consider, using the distributivity of multiplication, that $(\underbrace{1+1+\cdots+1}_{m \text{ times}})(\underbrace{1+1+\cdots+1}_{n \text{ times}}) = 0$. □

Theorem 2.1.2 (Euler's Theorem). *Let R^* be the finite set of the units in a ring. For all $a \in R^*$, $a^{|R^*|} = 1$.*

Proof. We have $R^* = \{r_1, \ldots, r_n\} = \{ar_1, \ldots, ar_n\}$ since multiplication is one-to-one. Then, $r_1 \cdots r_n = (ar_1) \cdots (ar_n) = a^n(r_1 \cdots r_n) \implies a^n = 1$. □

Theorem 2.1.3. *For a finite ring with unity, any element is either 0, a zero divisor, or a unit.*

Proof. For an element r that is not zero or a zero divisor, we have the following set of non-zero elements $\{r, r^2, \ldots\}$. Since the ring is finite, we have $r^{e_1} = r^{e_2}$ for some $e_1 < e_2$. Then, $r^{e_1} = r^{e_2} = r^{e_1} r^{e_2 - e_1} \implies r^{e_2-e_1} = 1$. Therefore, $r \cdot r^{e_2 - e_1 - 1} = 1$. □

Remark 2.1.1. Theorem 2.1.3 shows every finite integral domain is a field.

Definition 2.2. A **quadratic ring** extension $R[\gamma]$ of some ring R is created by adding an element γ to R such that $\gamma^2 = c$ for some $c \in R$ and $\gamma \notin R$.

Remark 2.2.1. Elements in $R[\gamma]$ are denoted $a + \gamma b$ for $a, b \in R$. This means elements in $R[\gamma]$ can be seen as elements in $R \times R$.

Theorem 2.2.1. *The norm map[1] $N : R[\gamma] \to R$ is defined as $N(a + \gamma b) = a^2 - cb^2$ and has the property that $N(a + \gamma b)$ is a unit in R if and only if $a + \gamma b$ is a unit in $R[\gamma]$.*

[1] We have not yet formally defined a *norm map*.

Proof. We see that $N(a+\gamma b)^{-1}$ exists if and only if $N(a+\gamma b)$ is a unit. Then, $(a+\gamma b)(a-\gamma b) = N(a+\gamma b)$ so $(a+\gamma b)\left[(a-\gamma b)N(a+\gamma b)^{-1}\right] = 1$. □

Remark 2.2.2. Theorem 2.2.1 shows the quadratic ring extension of any field or integral domain maintains that status.

Definition 2.3. An element in an integral domain is called **irreducible** if it cannot be written as a product of two non-units.

Definition 2.4. Elements a, b in an integral domain R are called **associates** if there exists a unit $u \in R$ such that $a = ub$.

Definition 2.5. An integral domain has **unique factorization** if every element can be written as a product of irreducibles which are unique up to order and associates.

Theorem 2.5.1. *A ring R has unique factorization if all irreducible elements are prime.*

Proof. Let $x = a_1 \cdots a_n = b_1 \cdots b_m$. Since a_1 is prime, we know that it divides one of b_i. Without loss of generality, let $b_1 = ca_1$. However, since b_1 is irreducible and $a_1 \neq 1$, we have $c = 1$. Then, we can repeat this process on $a_2 \cdots a_n = b_2 \cdots b_m$. □

Definition 2.6. A **polynomial ring** $R[x]$ of some ring R is created by using polynomials of the variable x using coefficients from R.

Remark 2.6.1. For some field F, Euclidean division works on $F[x]$ because all non-zero coefficients are units. It then follows that irreducible elements are prime, so unique factorization exists in $F[x]$.

Theorem 2.6.1 (Fundamental Theorem of Algebra)**.** *The only irreducible polynomials in $\mathbb{C}[x]$ are linear.*

Remark 2.6.2. It follows from Theorem 2.6.1 that the only irreducible polynomials in $\mathbb{R}[x]$ are linear or quadratic. This can be proven using $\mathbb{R}[x] \subset \mathbb{C}[x]$ and that multiplying some linear $f(x) \in \mathbb{C}[x]$ with its conjugate results in some $F(x) \in \mathbb{R}[x]$ with $\deg(F(x)) = 2$.

Definition 2.7. A subset I of ring R is called an **ideal** if for all $a, b \in I$ and $r \in R$, $a + b, -a, ra, ar \in I$.

Definition 2.8. For a commutative ring R and $a \in R$, a **principal ideal** generated by a is defined as $aR = \{ar : r \in R\}$. For some $a, b \in R$, we can also generate $(a, b)R = \{xa + yb : x, y \in R\}$.

Remark 2.8.1. For $a \in R$ with integral domain R, $aR = 1R = R$ if and only if a is a unit.

Remark 2.8.2. For $a, b \in R$, $b \mid a \implies bR \subseteq aR$. Furthermore, $aR = bR$ if and only if a and b are associates.

Remark 2.8.3. For $a, b \in R$, if a is irreducible and $b \mid a$, then $aR \subseteq bR \subseteq R$ so either $aR = bR$ or $bR = R$. Therefore, aR is not properly contained in any other principal ideal. Also, if a is not irreducible, then $aR \subset bR \subset R$.

Theorem 2.8.1. *If an element $a \in R$ cannot be written as a finite product of irreducibles, then R has an infinite ascending chain of principal ideals.*

Proof. Assume that a cannot be written as a finite product of irreducibles. Then, $a = r_1 a_1 = r_1 r_2 a_2 = \dots$ for non-units r_i, a_i and reducible a_i. This implies $aR \subset a_1 R \subset a_2 R \subset \cdots$. $\square$

Remark 2.8.4. This tells us that every element in $\mathbb{N}$ has a factorization into irreducibles since every proper divisor is "smaller" so there cannot be an infinite chain.

Definition 2.9. An integral domain R is a **principal ideal domain** if every ideal in R is a principal ideal.

Proposition 2.9.1. *The ring $\mathbb{Z}$ is a principal ideal domain.*

Proof. If $I = \{0\}$, then $I = 0\mathbb{Z}$. Therefore, we prove with $I \neq \{0\}$. Then, there exists a positive element in I. Let a be the the least positive element in I and we claim that $I = a\mathbb{Z}$.

Let $b \in I$ be some other element in I. Then we have $b = qa+r$ for $0 \leq r < a$. This also means $b - qa = r$ so $r \in I$. However, by the minimality of a, this implies $r = 0$ so b is a multiple of a and $b \in a\mathbb{Z}$. □

Corollary 2.9.1. *For field F, $F[x]$ is a principal ideal domain.*

Theorem 2.9.1. *For a principal ideal domain, every ascending chain of ideals stabilizes.*

Proof. Let $I_1 \subseteq I_2 \subseteq \cdots$ be an ascending chain of ideals in a principal ideal domain R. Then, $\bigcup_{i=1}^{\infty} I_i$ is a principal ideal aR. For some j, $a \in I_j$ so $aR = I_j = I_{j+1} = \cdots$. □

Definition 2.10. Let I, J be ideals of R. Then, $I + J$ is the smallest ideal which contains both I and J. Therefore, $I + J = \{a + b : a \in I \text{ and } b \in J\}$.

Remark 2.10.1. Since $\mathbb{Z}$ is a principal ideal domain, $a\mathbb{Z} + b\mathbb{Z} = d\mathbb{Z}$. Then, $d\mathbb{Z} = \{xa + yb : x, y \in \mathbb{Z}\}$. Therefore, $d = \gcd(a, b)$ since it is the least positive element (by proof of Theorem 2.9.1).

Definition 2.11. An ideal I of ring R is a **prime ideal** if $ab \in I$ implies $a \in I$ or $b \in I$ for all $a, b \in R$.

Remark 2.11.1. An element $p \in R$ is prime if and only if pR is prime.

Remark 2.11.2. Not all prime ideals are principal (eg. $(x, y) \subset \mathbb{Q}[x, y]$).

Definition 2.12. An ideal I in ring R is called **maximal** if for any ideal $J \subseteq R$ where $I \subseteq J \subseteq R$, it follows that $I = J$ or $J = R$.

Remark 2.12.1. In a principal ideal domain, the principal ideal generated by an irreducible element is maximal.

Theorem 2.12.1. *In an integral domain, maximal ideals are prime.*

Proof. Let I be a maximal ideal of ring R with $bc \in I$ and $b \notin I$. Then, we have $I \subsetneq I + bR \subseteq R$ so, by the maximality of I, $I + bR = R$. This also means that $1 \in I + bR$ so $1 = a + br$ for $a \in I$ and $r \in R$. Multiplying through by c, this gives us $c = ac + bcr \in I$ since $a, bc \in I$. $\square$

Remark 2.12.2. For a principal ideal domain R, this gives us that $a \in R$ is irreducible implies aR is maximal implies aR is prime implies a is prime. Therefore, by Theorem 2.5.1, every principal ideal domain has unique factorization.

Definition 2.13. A ring is a unique factorization domain if every non-zero non-unit can be written uniquely as a product of irreducible elements, up to order and associates. Duplicate of Definition 2.5; don't ask why.

Remark 2.13.1. Unique factorization domains exist which are not principal ideal domains. For example, $\mathbb{Z}[x]$ with $2\mathbb{Z}[x] + x\mathbb{Z}[x]$.