Advanced Modern Algebra

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Contents

1 Things Past

1.1 Some Number Theory

Least Integer Axiom (**Well-ordering Principle**). There is a smallest integer in every nonempty subset C of $\mathbb{N}$

1.2 Roots of Unity

Proposition 1.1 (Polar Decomposition). *Every complex number z has a factorization*

$$z = r(\cos\theta + i\sin\theta)$$

where $r = |z| \geq 0$ *and* $0 \leq \theta \leq 2\pi$

Proposition 1.2 (Addition Theorem). *If* $z = \cos\theta + i\sin\theta$ *and* $w = \cos\psi + i\sin\psi$*, then*

$$zw = \cos(\theta + \psi) + i\sin(\theta + \psi)$$

Theorem 1.3 (De Moivre). $\forall x \in \mathbb{R}, n \in \mathbb{N}$

$$\cos(nx) + i\sin(nx) = (\cos x + i\sin x)^n$$

Theorem 1.4 (Euler). $e^{ix} = \cos x + i\sin x$

Definition 1.5. If $n \in \mathbb{N} \geq 1$, an **nth root of unity** is a complex number ξ with $\xi^n = 1$

Corollary 1.6. *Every nth root of unity is equal to*

$$e^{2\pi ik/n} = \cos(\frac{2\pi k}{n}) + i\sin(\frac{2\pi k}{n})$$

for $k = 0, 1, \ldots, n-1$

$$x^n - 1 = \prod_{\xi^n=1}(x - \xi)$$

If ξ is an nth root of unity and if n is the smallest, then ξ is a **primitive nth root of unity**

Definition 1.7. If $d \in \mathbb{N}^+$, then the \$d\$th **cyclotomic polynomial** is

$$\Phi_d(x) = \prod(x - \xi)$$

where ξ ranges over all the *primitive dth* roots of unity

Proposition 1.8. *For every integer $n \geq 1$*

$$x^n - 1 = \prod_{d|n} \Phi_d(x)$$

Definition 1.9. Define **Euler ϕ-function** as the degree of the nth cyclotomic polynomial

$$\phi(n) = \deg(\Phi_n(x))$$

Proposition 1.10. *If $n \geq 1$ is an integer, then $\phi(n)$ is the number of integers k with $1 \leq k \leq n$ and $(k, n) = 1$*

Proof. Suffice to prove $e^{2\pi ik/n}$ is a primitive nth root of unity if and only if k and n are relatively prime □

Corollary 1.11. *For every integer $n \geq 1$, we have*

$$n = \sum_{d|n} \phi(d)$$

1.3 Some Set Theory

Proposition 1.12.
1. *If $f : X \to Y$ and $g : Y \to X$ are functions s.t. $g \circ f = 1_X$, then f is injective and g is surjective*
2. *A function $f : X \to Y$ has an inverse $g : Y \to X$ if and only if f is a bijection*

2 Group I

2.1 Permutations

Definition 2.1. A **permutation** of a set X is a bijection from X to itself.

Definition 2.2. The family of all the permutations of a set X, denoted by S_X is called the **symmetric group** on X. When $X = \{1, 2, \ldots, n\}$, S_X is usually denoted by X_n and is called the **symmetric group on n letters**

Definition 2.3. Let $i_1, i_2, \ldots, i_r$ be distinct integers in $\{1, 2, \ldots, n\}$. If $\alpha \in S_n$ fixes the other integers and if

$$\alpha(i_1) = i_2, \alpha(i_2) = i_3, \ldots, \alpha(i_{r-1}) = i_r, \alpha(i_r) = i_1$$

then α is called an textbf{r-cycle}. α is a cycle of **length** r and denoted by

$$\alpha = (i_1 \ i_2 \ \ldots \ i_r)$$

2-cycles are also called the **transpositions**.

Definition 2.4. Two permutations $\alpha, \beta \in S_n$ are **disjoint** if every i moved by one is fixed by the other.

Lemma 2.5. *Disjoint permutations $\alpha, \beta \in S_n$ commute*

Proposition 2.6. *Every permutation $\alpha \in S_n$ is either a cycle or a product of disjoint cycles.*

Proof. Induction on the number k of points moved by α $\square$

Definition 2.7. A **complete factorization** of a permutation α is a factorization of α into disjoint cycles that contains exactly one 1-cycle (i) for every i fixed by α

Theorem 2.8. *Let $\alpha \in S_n$ and let $\alpha = \beta_1 \ldots \beta_t$ be a complete factorization into disjoint cycles. This factorization is unique except for the order in which the cycles occur*

Proof. for all i, if $\beta_t(i) \neq i$, then $\beta_t^k(i) \neq \beta_t^{k-1}(i)$ for any $k \geq 1$ $\square$

Lemma 2.9. *If $\gamma, \alpha \in S_n$, then $\alpha\gamma\alpha^{-1}$ has the same cycle structure as γ. In more detail, if the complete factorization of γ is*

$$\gamma = \beta_1\beta_2 \ldots (i_1 \ i_2 \ \ldots) \ldots \beta_t$$

then $\alpha\gamma\alpha^{-1}$ is permutation that is obtained from γ by applying α to the symbols in the cycles of γ

Example 2.1. Suppose

$$\beta = (1\ 2\ 3)(4)(5)$$
$$\gamma = (5\ 2\ 4)(1)(3)$$

then we can easily find the α

$$\alpha = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 5 & 2 & 4 & 1 & 3 \end{pmatrix}$$

and so $\alpha = (1\ 5\ 3\ 4)$. Now $\alpha \in S_5$ and $\gamma = (\alpha 1\ \alpha 2\ \alpha 3)$

Theorem 2.10. *Permutations γ and σ in S_n has the same cycle structure if and only if there exists $\alpha \in S_n$ with $\sigma = \alpha\gamma\alpha^{-1}$*

Proposition 2.11. *If $n \geq 2$ then every $\alpha \in S_n$ is a product of tranpositions*

Proof. $(1\ 2\ \ldots\ r) = (1\ r)(1\ r-1)\ldots(1\ 2)$ $\square$

Example 2.2. The **15-puzzle** has a **starting position** that is a 4×4 array of the numbers between 1 and 15 and a symbol #, which we interpret as "blank". For example, consider the following starting position

3	15	4	8
10	11	1	9
2	5	13	12
6	7	14	#

A **simple move** interchanges the blank with a symbol adjacent to it. We win the game if after a sequence of simple moves, the starting position is transformed into the standard array $1, 2, \ldots, 15, \#$.

To analyze this game, note that the given array is really a permutation $\alpha \in S_{16}$. For example, the given starting position is

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 \\ 3 & 15 & 4 & 8 & 10 & 11 & 1 & 9 & 2 & 5 & 13 & 12 & 6 & 7 & 14 & 16 \end{pmatrix}$$

To win the game, we need special transpositions $\tau_1, \ldots, \tau_m$ sot that

$$\tau_m \ldots \tau_1 \alpha = (1)$$

Definition 2.12. A permutation $\alpha \in S_n$ is **even** if it can be factored into a product of an even number of transpositions. Otherwise **odd**

Definition 2.13. If $\alpha \in S_n$ and $\alpha = \beta_1 \ldots \beta_t$ is a complete factorization, then **signum** α is defined by

$$\operatorname{sgn}(\alpha) = (-1)^{n-t}$$

Theorem 2.14. *For all $\alpha, \beta \in S_n$*

$$\operatorname{sgn}(\alpha\beta) = \operatorname{sgn}(\alpha)\operatorname{sgn}(\beta)$$

Theorem 2.15.

1. *Let $\alpha \in S_n$; if $\operatorname{sgn}(\alpha) = 1$ then α is even. otherwise odd*
2. *A permutation α is odd if and only if it's a product of an odd number of transpositions*

Corollary 2.16. *Let $\alpha, \beta \in S_n$. If α and β have the same parity, then $\alpha\beta$ is even while if α and β have distinct parity, $\alpha\beta$ is odd*

Example 2.3. An analysis of the 15-puzzle shows that if $\alpha \in S_{16}$ is the starting position, then the game can be won if and only if α is an even permutation that fixes 16.

The blank 16 starts in position 16. Each simple move takes 16 up, down, left or right. Thus the total number m of moves is $u + d + l + r$. If 16 is to return home, each one of these must be undone. Thus the total number of moves is even: $m = 2u + 2r$. Hence $\alpha = \tau_1 \ldots \tau_m$ and so α is an even permutation. In example

$$\alpha = (1\ 3\ 4\ 8\ 9\ 2\ 15\ 14\ 7)(5\ 10)(6\ 11\ 13)(12)(16)$$

Now $\operatorname{sgn}(\alpha) = (-1)^{16-5} = -1$.

2.2 Groups

Definition 2.17. A **binary operation** on a set G is a function

$$* : G \times G \to G$$

Definition 2.18. A **group** is a set G equipped with a binary operation * s.t.

1. the **associative law** holds
2. **identity**
3. every $x \in G$ has an **inverse**, there is a $x' \in G$ with $x * x' = e = x' * x$

Definition 2.19. A group G is called **abelian** if it satisfies the **commutative law**

Lemma 2.20. *Let G be a group*

1. *The **cancellation laws** holds: if either $x * a = x * b$ or $a * x = b * x$, then $a = b$*
2. *e is unique*
3. *Each $x \in G$ has a unique inverse*
4. *$(x^{-1})^{-1} = x$*

Definition 2.21. An expression $a_1 a_2 \ldots a_n$ **needs no parentheses** if all the ultimate products it yields are equal

Theorem 2.22 (Generalized Associativity)**.** *If G is a group and $a_1, a_2, \ldots, a_n \in G$ then the expression $a_1 a_2 \ldots a_n$ needs no parentheses*

Definition 2.23. Let G be a group and let $a \in G$. If $a^k = 1$ for some $k > 1$ then the smallest such exponent $k \geq 1$ is called the **order** or a; if no such power exists, then one says that a has **infinite order**

Proposition 2.24. *If G is a finite group, then every $x \in G$ has finite order*

Definition 2.25. A **motion** is a distance preserving bijection $\varphi : \mathbb{R}^2 \to \mathbb{R}^2$. If π is a polygon in the plane, then its **symmetry group** $\Sigma(\pi)$ consists of all the motions φ for which $\varphi(\pi) = \pi$. The elements of $\Sigma(\pi)$ are called the **symmetries** of π

Let π_4 be a square. Then the group $\Sigma(\pi_4)$ is called the **dihedral group** with 8 elements, denoted by D_8

Definition 2.26. If π_n is a regular polygon with n vertices $v_1, \ldots, v_n$ and center O, then the symmetry group $\Sigma(\pi_n)$ is called the {dihedral group} with $2n$ elements, and it's denoted by D_{2n}

Exercise 2.2.1. If G is a group in which $x^2 = 1$ for every $x \in G$, prove that G must be abelian

Exercise 2.2.2. If G is a group with an even number of elements, prove that the number of elements in G of order 2 is odd. In particular, G must contain an element of order 2.

Proof. 1 is an element of order 1. □

2.3 Lagrange's Theorem

Theorem 2.27.

Definition 2.28. A subset H of a group G is a **subgroup** if
1. $1 \in H$
2. if $x, y \in H$, then $xy \in H$
3. if $x \in H$, then $x^{-1} \in H$

If H is a subgroup of G, we write $H \leq G$. If H is a proper subgroup, then we write $H < G$

The four permutations

$$\mathbf{V} = \{(1), (12)(34), (13)(24), (14)(23)\}$$

form a group because $\mathbf{V} \leq S_4$

Proposition 2.29. *A subset H of a group G is a subgroup if and only if H is nonempty and whenever $x, y \in H$, $xy^{-1} \in H$*

Proposition 2.30. *A nonempty subset H of a finite group G is a subgroup if and only if H is closed; that is, if $a, b \in H$, then $ab \in H$*

Example 2.4. The subset A_n of S_n, consisting of all the even permutations, is a subgroup called the **alternating group** on n letters

Definition 2.31. If G is a group and $a \in G$

$$\langle a \rangle = \{a^n : n \in \mathbb{Z}\} = \{\text{all powers of } a\}$$

$\langle a \rangle$ is called the **cyclic subgroup** of G **generated** by a. A group G is called **cyclic** if there exists $a \in G$ s.t. $G = \langle a \rangle$, in which case a is called the **generator**

Definition 2.32. The **integers mod** m, denoted by $\mathbb{I}_m$ is the family of all congruence classes mod m

Proposition 2.33. *Let $m \geq 2$ be a fixed integer*

1. *If $a \in \mathbb{Z}$, then $[a] = [r]$ for some r with $0 \leq r < m$*
2. *If $0 \leq r' < r < m$, then $[r'] \neq [r]$*
3. *$\mathbb{I}_m$ has exactly m elements*

Theorem 2.34.
1. *If $G = \langle a \rangle$ is a cyclic group of order n, then a^k is a generator of G if and only if $(k, n) = 1$*
2. *If G is a cyclic group of order n and $\operatorname{gen}(G) = \{$all generators of $G\}$, then*

$$\left|\operatorname{gen}(G)\right| = \phi(n)$$

where ϕ is the Euler ϕ-function

Proof.
1. there is $t \in \mathbb{N}$ s.t. $a^{kt} = a$ hence $a^{kt-1} = 1$ and $n \mid kt - 1$

□

Proposition 2.35. *Let G be a finite group and let $a \in G$. Then the order of a is $\left|\langle a \rangle\right|$.*

Definition 2.36. If G is a finite group, then the number of elements in G, denoted by $|G|$ is called the **order** of G

Proposition 2.37. *The intersection $\bigcap_{i \in I} H_i$ of any family of subgroups of a group G is again a subgroup of G*

Corollary 2.38. *If X is a subset of a group G, then there is a subgroup $\langle X \rangle$ of G containing X tHhat is **smallest** in the sense that $\langle X \rangle \leq H$ for every subgroup H of G that contains X*

Definition 2.39. If X is a subset of a group G, then $\langle X \rangle$ is called the **subgroup generated by** X

A **word** on X is an element $g \in G$ of the form $g = x_1^{e_1} \dots x_n^{e_n}$ where $x_i \in X$ and $e_i = \pm 1$ for all i

Proposition 2.40. *If X is a nonempty subset of a group G, then $\langle X \rangle$ is the set of all words on X*

Definition 2.41. If $H \leq G$ and $a \in G$, then the **coset** aH is the subset aH of G, where

$$aH = \{ah : h \in H\}$$

aH **left coset**, Ha **right coset**

Lemma 2.42. $H \leq G, a, b \in G$

1. $aH = bH$ *if and only if* $b^{-1}a \in H$
2. *if* $aH \cap bH \neq \emptyset$, *then* $aH = bH$
3. $|aH| = |H|$ *for all* $a \in G$

Proof. define a relation $a \equiv b$ if $b^{-1}a \in H$ □

Theorem 2.43 (Lagrange's Theorem)**.** *If H is a subgroup of a finite group G, then $|H|$ is a divisor of $|G|$*

Proof. Let $\{a_1H, a_2H, \dots, a_tH\}$ be the family of all the distinct cosets of H in G. Then

$$G = a_1H \cup a_2H \cup \cdots \cup a_tH$$

hence

$$|G| = |a_1H| + \cdots + |a_tH|$$

But $|a_iH| = |H|$ for all i. Hence $|G| = t|H|$ □

Definition 2.44. The **index** of a subgroup H in G denoted by $[G : H]$, is the number of left cosets of H in G

Note that $|G| = [G : H]|H|$

Corollary 2.45. *If G is a finite group and $a \in G$, then the order of a is a divisor of $|G|$*

Corollary 2.46. *If G is a finite group, then $a^{|G|} = 1$ for all $a \in G$*

Corollary 2.47. *If p is a prime, then every group G of order p is cyclic*

Proposition 2.48. *The set $U(\mathbb{I}_m)$, defined by*

$$U(\mathbb{I}_m) = \{[r] \in \mathbb{I}_m : (r, m) = 1\}$$

is a multiplicative group of order $\phi(m)$. If p is a prime, then $U(\mathbb{I}_p) = \mathbb{I}_p^\times$, the nonzero elements of $\mathbb{I}_p$.

Proof. $(r, m) = 1 = (r', m)$ implies $(rr', m) = 1$. Hence $U(\mathbb{I}_m)$ is closed under multiplication. If $(x, m) = 1$, then $rs + sm = 1$. There fore $(r, m) = 1$. Each of them have inverse. □

Corollary 2.49 (Fermat). *If p is a prime and $a \in \mathbb{Z}$, then*

$$a^p \equiv a \mod p$$

Proof. suffices to show $[a^p] = [a]$ in $\mathbb{I}_p$. If $[a] = [0]$, then $[a^p] = [a]^p = [0]$. Else, since $\left|\mathbb{I}_p^\times\right| = p - 1$, $[a]^{p-1} = [1]$ □

Theorem 2.50 (Euler). *If $(r, m) = 1$, then*

$$r^{\phi(m)} \equiv 1 \mod m$$

Proof. Since $\left|U(\mathbb{I}_m)\right| = \phi(m)$. Lagrange's theorem gives $[r]^{\phi(m)} = [1]$ for all $[r] \in U(\mathbb{I}_m)$.

In fact we construct a group to prove this. □

Theorem 2.51 (Wilson's Theorem). *An integer p is a prime if and only if*

$$(p - 1)! \equiv -1 \mod p$$

Proof. Assume that p is a prime. If $a_1, \dots, a_n$ is a list of all the elements of finite abelian group, then product $a_1 a_2 \dots a_n$ is the same as the product of all elements a with $a^2 = 1$. Since p is prime, $\mathbb{I}_p^\times$ has only one element of order 2, namely $[-1]$. It follows that the product of all the elements in $\mathbb{I}_p^\times$ namely $[(p - 1)!]$ is equal to $[-1]$.

Conversly assume that m is composite: there are integers a and b with $m = ab$ and $1 < a \le b < m$. If $a < b$ then $m = ab$ is a divisor of $(m - 1)!$. If $a = b$, then $m = a^2$. if $a = 2$, then $(a^2 - 1)! \equiv 2 \mod 4$. If $2 < a$, then $2a < a^2$ and so a and $2a$ are factors of $(a^2 - 1)!$ □

Exercise 2.3.1. Let G be a group of order 4. Prove that either G is cyclic or $x^2 = 1$ for every $x \in G$. Conclude, using Exercise 2.2.1 that G must be abelian.

Proof. □

2.4 Homomorphisms

Definition 2.52. If $(G, *)$ and $(H, \circ)$ are groups, then a function $f : G \to H$ is a **homomorphism** if

$$f(x * y) = f(x) \circ f(y)$$

for all $x, y \in G$. If f is also a bijection, then f is called an **isomorphism**. G and H are called **isomorphic**, denoted by $G \cong H$

Lemma 2.53. *Let $f : G \to H$ be a homomorphism*

1. $f(1) = 1$
2. $f(x^{-1}) = f(x)^{-1}$
3. $f(x^n) = f(x)^n$ *for all* $n \in \mathbb{Z}$

Definition 2.54. If $f : G \to H$ is a homomorphism, define

$$\ker f = \{x \in G : f(x) = 1$$

and

$$\operatorname{im} f = \{h \in H : h = f(x) \text{ for some } x \in G$$

Proposition 2.55. *Let $f : G \to H$ be a homomorphism*

1. $\ker f$ *is a subgroup of G and* $\operatorname{im} f$ *is a subgroup of H*
2. *if $x \in \ker f$ and if $a \in G$, then $axa^{-1} \in \ker f$*
3. *f is an injection if and only if* $\ker f = \{1\}$

Proof. 3. $f(a) = f(b) \Leftrightarrow f(ab^{-1}) = 1$

□

Definition 2.56. A subgroup K of a group G is called a **normal subgroup** if $k \in K$ and $g \in G$ imply $gkg^{-1} \in K$, denoted by $K \triangleleft G$

Definition 2.57. If G is a group and $a \in G$, then a **conjugate** of a is any element in G of the form

$$gag^{-1}$$

where $g \in G$

Definition 2.58. If G is a group and $g \in G$, define **conjugation** $\gamma_g : G \to G$ by

$$\gamma_g(a) = gag^{-1}$$

for all $a \in G$

Proposition 2.59. 1. *If G is a group and $g \in G$, then conjugation $\gamma_g : G \to G$ is an isomorphism*

2. *Conjugate elements have the same order*

Proof. 1. bijection: $\gamma_g \circ \gamma_{g^{-1}} = 1 = \gamma_{g^{-1}} \circ \gamma_g$.

□

Example 2.5. Define the **center** of a group G, denoted by $Z(G)$, to be

$$Z(G) = \{z \in G : zg = gz \text{ for all } g \in G\}$$

Example 2.6. If G is a group, then an **automorphism** of G is an isomorphism $f : G \to G$. For example, every conjugation γ_g is an automorphism of G (it is called an **inner automorphism**), for its inverse is conjugation by g^{-1}. The set $\mathrm{Aut}(G)$ of all the automorphism of G is itself a group.

$$\mathrm{Inn}(G) = \{\gamma_g : g \in G\}$$

is a subgroup of $\mathrm{Aut}(G)$

Proposition 2.60. 1. *If H is a subgroup of index 2 in a group G, then $g^2 \in H$ for every $g \in G$*

2. *If H is a subgroup of index 2 in a group G, then H is a normal subgroup of G*

Definition 2.61. The group of **quaternions** is the group **Q** of order 8 consisting of the following matrices in $GL(2, \mathbb{C})$

$$\mathbf{Q} = \{I, A, A^2, A^3, B, BA, BA^2, BA^3\}$$

where I is the identity matrix

$$A = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \text{ and } B = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$$

Example 2.7. **Q** is normal. By Lagrange's theorem the only possible orders of subgroups are 1,2,4 or 8. The only subgroup of order 2 is $\langle -I \rangle$ since $-I$ is the only element of order 2

Proposition 2.62. *The alternating group A_4 is a group of order 12 having no subgroup of order 6*

Exercise 2.4.1. Show that if there is a bijection $f : X \to Y$, then there is an isomorphism $\varphi : S_X \to S_Y$

Proof. If $\alpha \in S_X$, define $\varphi(\alpha) = f \circ \alpha \circ f^{-1}$. Since f, α, f^{-1} are bijections, $\varphi(\alpha)$ is an bijection. φ is a homomorphism. $\forall \beta \in S_Y$, we have $\alpha = f^{-1} \circ \beta \circ f$ □

2.5 Quotient group

$\mathcal{S}(G)$ is the set of all nonempty subsets of a group G. If $X, Y \in \mathcal{S}(G)$, define

$$XY = \{xy : x \in X \text{ and } y \in Y\}$$

Lemma 2.63. *$K \leq G$ is normal if and only if*

$$gK = Kg$$

A natural question is that whether HK is a subgroup when H and K are subgroups. The answer is no. Let $G = S_3, H = \langle(1\ 2)\rangle, K = \langle(1\ 3)\rangle$

Proposition 2.64.
1. *If H and K are subgroups of a group G, and if one of them is normal, then $HK \leq G$ and $HK = KH$*
2. *If $H, K \lhd G$, then $HK \lhd G$*

Theorem 2.65. *Let G/K denote the family of all the left cosets of a subgroup K of G. If $K \lhd G$, then*

$$aKbK = abK$$

for all $a, b \in G$ and G/K is a group under this operation

Proof. $aKbK = abKK = abK$ □

G/K is called the **quotient group** G mod K

Corollary 2.66. *Every $K \lhd G$ is the kernel of some homomorphism*

Proof. Define the **natural map** $\pi : G \to G/K$, $a \mapsto aK$ □

Theorem 2.67 (First Isomorphism Theorem)**.** *If $f : G \to H$ is a homomorphism, then*

$$\ker f \lhd G \quad \textit{and} \quad G/\ker f \cong \operatorname{im} f$$

If $\ker f = K$ and $\varphi : G/K \to \operatorname{im} f \leq H, aK \mapsto f(a)$, then φ is an isomorphism

Remark.

$$\begin{tikzcd} G \arrow[rr, "f"] \arrow[dr, "\pi"'] & & H \\ & G/K \arrow[ur, "\varphi"'] & \end{tikzcd}$$

Example 2.8. What's the quotient group $\mathbb{R}/\mathbb{Z}$? Define $f : \mathbb{R} \to S^1$ where S^1 is the circle group by

$$f : x \mapsto e^{2\pi i x}$$

$\mathbb{R}/\mathbb{Z} \cong S^1$

Proposition 2.68 (Product Formula). *If H and K are subgroups of a finite group G, then*

$$|HK||H \cap K| = |H||K|$$

Proof. Define a function $f : H \times K \to HK, (h,k) \mapsto hk$. Show that $\left|f^{-1}(x)\right| = |H \cap K|$.

Claim that if $x = hk$, then

$$f^{-1}(x) = \{(hd, d^{-1}k) : d \in H \cap K\}$$

□

Theorem 2.69 (Second Isomorphism Theorem). *If $H \triangleleft G, K \leq G$, then $HK \leq G, H \cap K \triangleleft G$ and*

$$K/(H \cap K) \cong HK/H$$

Proof. $hkH = kk^{-1}hkH = kh'H = kH$ □

Theorem 2.70 (Third Isomorphism Theorem). *If $H, K \triangleleft G$ with $K \leq H$, then $H/K \triangleleft G/K$ and*

$$(G/K)/(H/K) \cong G/H$$

Theorem 2.71 (Correspondence Theorem). *If $K \triangleleft G, \pi : G \to G/K$ is the natural map, then*

$$S \mapsto \pi(S) = S/K$$

is a bijection between $Sub(G;K)$, the family of all those subgroups S of G that contain K, and $Sub(G/K)$, the family of all the subgroups of G/K. If we denote S/K by S^*, then

1. *$T \leq S \leq G$ if and only if $T^* \leq S^*$, in which case $[S:T] = [S^* : T^*]$*
2. *$T \triangleleft S$ if and only if $T^* \triangleleft S^*$, in which case $S/T \cong S^*/T^*$*

$$\begin{tikzcd}
G \arrow[d, dash] \arrow[dr] & \\
S \arrow[d, dash] \arrow[dr] & G/K \arrow[d, dash] \\
T \arrow[d, dash] \arrow[dr] & S/K = S^* \arrow[d, dash] \\
K \arrow[dr] & T/K = T^* \arrow[d, dash] \\
& \{1\}
\end{tikzcd}$$

Proof. Use $\pi^{-1}\pi = 1$ and $\pi\pi^{-1} = 1$ to prove injectivity and surjectivity respectively.

For $[S : T] = [S^* : T^*]$, show there is a bijection between the family of all cosets of the form sT and the family of all the cosets of the form s^*T^*.

injective:

$$\begin{aligned}
\pi(m)T^* = \pi(n)T^* &\Leftrightarrow \pi(m)\pi(n)^{-1} \in T^* \\
&\Leftrightarrow mn^{-1}K \in T/K \\
&\Rightarrow mn^{-1}t^{-1} \in K \\
&\Rightarrow mn^{-1} = tk \in T \\
&\Leftrightarrow mT = nT
\end{aligned}$$

surjective:

If G is finite, then

$$\begin{aligned}
[S^* : T^*] &= \left|S^*\right| / \left|T^*\right| \\
&= \left|S/K\right| / \left|T/K\right| \\
&= (|S| / |K|) / (|T| / |K|) \\
&= |S| / |T| \\
&= [S : T]
\end{aligned}$$

If $T \lhd S$, by third isomorphism theorem, $T/S \cong (T/K)/(S/K) = T^*/S^*$

If $T^* \lhd S^*$,

$$\pi(sts^{-1}) \in \pi(s)T^*\pi(s)^{-1} = T^*$$

so that $sts^{-1} \in \pi^{-1}(T^*) = T$ □

Proposition 2.72. *If G is a finite abelian group and d is a divisor of $|G|$, then G contains a subgroup of order d*

Proof. Abelian group's subgroup is normal and hence we can build quotient groups. p90 for proof. Use the correspondence theorem □

Definition 2.73. If H and K are grops, then their **direct product**, denoted by $H \times K$, is the set of all ordered pairs (h, k) with the operation

$$(h, k)(h', k') = (hh', kk')$$

Proposition 2.74. *Let G and G' be groups and $K \lhd G$, $K' \lhd G'$. Then $K \times K' \lhd G \times G'$ and*

$$(G \times G')/(K \times K') \cong (G/K) \times (G'/K')$$

Proof. □

Proposition 2.75. *If G is a group containing normal subgroups H and K and $H \cap K = \{1\}$ and $HK = G$, then $G \cong H \times K$*

Proof. Note $|HK||H \cap K| = |H||K|$. Consider $\varphi : G \to H \times K$. Show it's homo and bijective. □

Theorem 2.76. *If m, n are relatively prime, then*

$$\mathbb{I}_{mn} \cong \mathbb{I}_m \times \mathbb{I}_n$$

Proof.

$$\begin{aligned} f :& \mathbb{Z} \to \mathbb{I}_m \times \mathbb{I}_n \\ & a \mapsto ([a]_m, [a]_n) \end{aligned}$$

is a homo. $\mathbb{Z}/\langle mn \rangle \cong \mathbb{I}_m \times \mathbb{I}_n$ □

Proposition 2.77. *Let G be a group, and $a, b \in G$ be commuting elements of orders m, n. If $(m, n) = 1$, then ab has order mn*

Corollary 2.78. *If $(m, n) = 1$, then $\phi(mn) = \phi(m)\phi(n)$*

Proof. Theorem 2.76 shows that $f : \mathbb{I}_{mn} \cong \mathbb{I}_m \times \mathbb{I}_n$. The result will follow if we prove that $f(U(\mathbb{I}_{mn})) = U(\mathbb{I}_m) \times U(\mathbb{I}_n)$, for then

$$\begin{aligned} \phi(mn) =& \left|U(\mathbb{I}_{mn})\right| = \left|f(U(\mathbb{I}_{mn}))\right| \\ =& \left|U(\mathbb{I}_m) \times U(\mathbb{I}_n)\right| = \left|U(\mathbb{I}_m)\right| \cdot \left|U(\mathbb{I}_n)\right| \end{aligned}$$

If $[a] \in U(\mathbb{I}_{mn})$, then $[a][b] = [1]$ for some $[b] \in \mathbb{I}_{mn}$ and

$$\begin{aligned} f([ab]) &= ([ab]_m, [ab]_n) = ([a]_m[b]_m, [a]_n[b]_n) \\ &= ([a]_m, [a]_n)([b]_m, [b]_n) = ([1]_m, [1]_n) \end{aligned}$$

Hence $f([a]) = ([a]_m, [a]_n) \in U(\mathbb{I}_m) \times U(\mathbb{I}_n)$

For the reverse inclusion, if $f([c]) = ([c]_m, [c]_n) \in U(\mathbb{I}_m) \times U(\mathbb{I}_n)$, then we must show that $[c] \in U(\mathbb{I}_{mn})$. There is $[d]_m \in \mathbb{I}_m$ with $[c]_m[d]_m = [1]_m$, and there is $[e]_n\mathbb{I}_n$ with $[c]_n[e]_n = [1]_n$. Since f is surjective, there is $b \in \mathbb{Z}$ with $([b]_m, [b]_n) = ([d]_m, [e]_n)$, so that

$$f([1]) = ([1]_m, [1]_n) = ([c]_m[b]_m, [c]_n[b]_n) = f([c][b])$$

Since f is an injection, $[1] = [c][b]$ and $[c] \in U(\mathbb{I}_{mn})$ □

Corollary 2.79. *1. If p is a prime, then $\phi(p^e) = p^e - p^{e-1} = p^e(1 - \frac{1}{p})$*

2. If $n = p_1^{e_1} \dots p_t^{e_t}$, then

$$\phi(n) = n(1 - \frac{1}{p_1}) \dots (1 - \frac{1}{p_t})$$

Lemma 2.80. *A cyclic group of order n has a unique subgroup of order d, for each divisor d of n, and this subgroup is cyclic.*

Define an equivalence relation on a group G by $x \equiv y$ if $\langle x \rangle = \langle y \rangle$. Denote the equivalence class containing x by $\operatorname{gen}(C)$, where $C = \langle x \rangle$. Equivalence classes form a partition and we get

$$G = \coprod_C \operatorname{gen}(C)$$

where C ranges over all cyclic subgroups of G. Note $\left|\operatorname{gen}(C)\right| = \phi(n)$

Theorem 2.81. *A group G of order n is cyclic if and only if for each divisor d of n, there is at most one cyclic subgroup of order d*

Theorem 2.82. *If G is an abelian group of order n having at most one cyclic subgroup of order p for each prime divisor p of n, then G is cyclic*

Exercise:

- 2.71 Suppose $H \leq G$,$|H| = |K|$. Since $|H| = [H : K]|K|$, $[H : K] = 1$. Hence $H = K$
- 2.67 1. $\operatorname{Inn}(S_3) \cong S_3/Z(S_3) \cong S_3$ and $\left|\operatorname{Aut}(S_3)\right| \leq 6$. Hence $\operatorname{Aut}(S_3) = \operatorname{Inn}(S_3)$

Exercise 2.5.1. Prove that if G is a group for which $G/Z(G)$ is cyclic, then G is abelian

Proof. Suppose $G/Z(G) = \langle a \rangle$, let $g = a^k z^{-1}, g' = a^{k'} z'^{-1}$, then $gg' = a^k z^{-1} z^{k'} z'^{-1} = a^{k+k'} z'^{-1} z^{-1} = g'g$. Hence G is abelian. □

2.6 Group Actions

Theorem 2.83 (Cayley). *Every group G is isomorphic to a subgroup of the symmetric group S_G. In particular, if $|G| = n$, then G is isomorphic to a subgroup of S_n*

Proof. For each $a \in G$, define $\tau_a(x) = ax$ for every $x \in G$. τ_a is a bijection for its inverse is $\tau_{a^{-1}}$

$$\tau_a \tau_{a^{-1}} = \tau_1 = \tau_{a^{-1}} \tau_a$$

□

Theorem 2.84 (Representation on Cosets)**.** *Let G be a group and $H \leq G$ having finite index n. Then there exists a homomorphism $\varphi : G \to S_n$ with $\ker \varphi \leq H$*

Proof. We still denote the family of all the cosets of H in G by G/H

For each $a \in G$, define "translation" $\tau_a : G/H \to G/H$ by $\tau_a(xH) = axH$ for every $x \in G$. For $a, b \in G$

$$(\tau_a \circ \tau_b)(xH) = a(bxH) = (ab)xH$$

so that

$$\tau_a \tau_b = \tau_{ab}$$

It follows that each τ_a is a bijection and so $\tau_a \in S_{G/H}$. Define $\varphi : G \to S_{G/H}$ by $\varphi(a) = \tau_a$. Rewriting

$$\varphi(a)\varphi(b) = \tau_a \tau_b = \tau_{ab} = \varphi(ab)$$

so that φ is a homomorphism. Finally if $a \in \ker \varphi$, then $\varphi(a) = 1_{G/H}$, so that $\tau_a(xH) = xH$, in particular, when $x = 1$, this gives $aH = H$ and $a \in H$. And $S_{G/H} \cong S_n$ □

When $H = \{1\}$, this is the Cayley theorem.

Four-group $\mathbf{V} = \{1, (12)(34), (13)(24), (14)(23)\}$

Proposition 2.85. *Every group G of order 4 is isomorphic to either $\mathbb{I}_4$ or the four-group $\boldsymbol{V}$. And $\mathbb{I}_4 \ncong \boldsymbol{V}$*

Proof. By lagrange's theorem, every element in G other than 1 has order 2 or 4. If 4, then G is cyclic.

Suppose $x, y \neq 1$, then $xy \neq x, y$. Hence $G = \{1, x, y, xy\}$. □

Proposition 2.86. *If G is a group of order 6, then G is isomorphic to either $\mathbb{I}_6$ or S_3. Moreover $\mathbb{I}_6 \ncong S_3$*

Proof. If G is not cyclic, since $|G|$ is even, it has some elements having order 2, say t by exercise 2.2.2

If G is abelian. Suppose it has another different element a with order 2. Then $H = \{1, a, t, at\}$ is a subgroup which contradict. Hence it must contain an element b of order 3. Then bt has order 6 and G is cyclic.

If G is not abelian. If G doesn't have elements of order 3, then it's abelian. Hence G has an element s of order 3.

Now $\left|\langle s \rangle\right| = 3$, so $[G : \langle s \rangle] = |G| / \left|\langle s \rangle\right| = 2$ and $\langle s \rangle$ is normal. Since $t = t^{-1}$, $tst \in \langle s \rangle$. If $tst = s^0 = 1$, $s = 1$. If $tst = s$, $\left|\langle st \rangle\right| = 6$. Therefore $tst = s^2 = s^{-1}$.

Let $H = \langle t \rangle$, $\varphi : G \to S_{G/\langle t \rangle}$ given by

$$\varphi(g) : x\langle t \rangle \mapsto gx\langle t \rangle$$

By representation on cosets, $\ker \varphi \leq \langle t \rangle$. Hence $\ker \varphi = \{1\}$ or $\ker \varphi = \langle t \rangle$. Since

$$\varphi(t) = \begin{pmatrix} \langle t \rangle & s\langle t \rangle & s^2\langle t \rangle \\ t\langle t \rangle & ts\langle t \rangle & ts^2\langle t \rangle \end{pmatrix}$$

If $\varphi(t)$ is the identity permutation, then $ts\langle t \rangle = s\langle t \rangle$, so that $s^{-1}ts \in \langle t \rangle = \{1, t\}$. But now $s^{-1}ts = t$. Therefore $t \notin \ker \varphi$ and $\ker \varphi = \{1\}$. Therefore φ is injective. Because $|G| = |S_3|$, $G \cong S_3$ $\square$

Definition 2.87. If X is a set and G is a group, then G **acts** on X if there is a function $G \times X \to X$, denoted by $(g, x) \to gx$ s.t.

1. (gh)x=g(hx) for all $g, h \in G$ and $x \in X$
2. $1x = x$ for all $x \in X$

X is a G-**set** if G acts on X

If a group G acts on a set X, then fixing the first variable, say g, gives a function $\alpha_g : X \to X$, namely, $\alpha_g : x \mapsto gx$. This function is a permutation of X, for its inverse is $\alpha_{g^{-1}}$

$$\alpha_g \alpha_{g^{-1}} = 1 = \alpha_{g^{-1}} \alpha_g$$

If's easy to see that $\alpha : G \to S_X$ defined by $\alpha : g \mapsto \alpha_g$ is a homomorphism. Conversely, given any homomorphism $\varphi : G \to S_X$, define $gx = \varphi(g)(x)$. Thus an action of a group G on a set X is another way of viewing a homomorphism.

Definition 2.88. If G acts on X and $x \in X$, then the **orbit** of x, denoted by $\mathcal{O}(x)$, is the subset of X

$$\mathcal{O}(x) = \{gx : g \in G\} \subseteq X$$

the **stabilizer** of x, denoted by G_x, is the subgroup

$$G_x = \{g \in G : gx = x\} \leq G$$

Example 2.9.
1. Caylay's theorem says that G acts on itself by translation: $\tau_g : a \mapsto ga$. We say G acts **transitively** on X if there is only one orbit.
2. When G acts on G/H by translation $\tau_g : aH \mapsto gaH$, then the orbit $\mathcal{O}(aH) = G/H$

3. When a group G acts on itself by conjugation, then the orbit $\mathcal{O}(x)$ is

$$\{y \in G : y = axa^{-1} \text{ for some } a \in G\}$$

in this case, $\mathcal{O}(x)$ is called the **conjugacy class** of x, and it is commonly denoted by x^G.
centralizer $C_G(x) = \{g \in G : gxg^{-1} = x\}$
4. Let $X = \{1, 2, \dots, n\}$, let $\alpha \in S_n$ and regard the cyclic group $G = \langle \alpha \rangle$ as acting on X. If $i \in X$, then

$$\mathcal{O}(i) = \{\alpha^k(i) : k \in \mathbb{Z}\}$$

Let the complete factorization of α be $\alpha = \beta_1 \dots \beta_{t(\alpha)}$, and let $i = i_1$ be moved by α. If the cycle involving i_1 is $\beta_j = (i_1 i_2 \dots i_r)$,

$$\mathcal{O}(i) = \{i_1, \dots, i_r\}$$

where $i = i_1$. It follows that $\left|\mathcal{O}(i)\right| = r$. The stabilizer G_l of a number l is G if α fixes l

Normalizer

$$N_G(H) = \{g \in G : gHg^{-1} = H\}$$

Proposition 2.89. *If G acts on a set X, then X is the disjoint union of the orbits. If X is finite, then*

$$|X| = \sum_i \left|\mathcal{O}(x_i)\right|$$

where x_i is chosen from each orbit

Proof. $x \equiv y \Leftrightarrow$ there exists $g \in G$ with $y = gx$ is an equivalence relation □

Theorem 2.90. *If G acts on a set X and $x \in X$ then*

$$\left|\mathcal{O}(x)\right| = [G : G_x]$$

Proof. Let G/G_x denote the family of cosets. Construct a bijection $\varphi : G/G_x \to \mathcal{O}(x)$ □

Corollary 2.91. *If a finite group G acts on a set X, then the number of elements in any orbit is a divisor of $|G|$.*

Corollary 2.92. *If x lies in a finite group G, then the number of conjugates of x is the index of its centralizer*

$$\left|x^G\right| = [G : C_G(x)]$$

and hence it's a divisor of G

Proof. x^G is the orbit, $C_G(x)$ is the stabilizer $\square$

Proposition 2.93. *If H is a subgroup of a finite group G, then the number of conjugates of H in G is $[G : N_G(H)]$*

Proof. Similar to theorem 2.90 $\square$

Theorem 2.94 (Cauchy). *If G is a finite group whose order is divisible by a prime p, then G contains an element of order p*

Proof. Prove by induction on $m \geq 1$, where $|G| = mp$. If $m = 1$, it's obvious.

If $x \in G$, then $\left|x^G\right| = [G : C_G(x)]$. If $x \notin Z(G)$, then x^G has more than one element, so $\left|C_G(x)\right| < |G|$. If $p \mid \left|C_G(x)\right|$, by inductive hypothesis, we are done. Else if $p \nmid \left|C_G(x)\right|$ for all noncentral x and $|G| = [G : C_G(x)]\left|C_G(x)\right|$, we have

$$p \mid [G : C_G(x)]$$

$Z(G)$ consists of all those elements with $\left|X^G\right| = 1$, we have

$$|G| = \left|Z(G)\right| + \sum_i [G : C_G(x_i)]$$

Hence $p \mid \left|Z(G)\right|$ and by proposition 2.72 $\square$

Definition 2.95. The **class equation** of a finite group G is

$$|G| = \left|Z(G)\right| + \sum_i [G : C_G(x_i)]$$

where each x_i is selected from each conjugacy class having more than one element

Definition 2.96. If p is a prime, then a finite group G is called a **p-group** if $|G| = p^n$ for some $n \geq 0$

Theorem 2.97. *If p is a prime and G is a p-group, then $Z(G) \neq \{1\}$*

Proof. Consider

$$|G| = \left|Z(G)\right| + \sum_i [G : C_G(x_i)]$$

$\square$

Corollary 2.98. *If p is a prime, then every group G of order p^2 is abelian*

Proof. If G is not abelian, then $Z(G)$ has order p. The center is always normal, and so $G/Z(G)$ is defined; it has order p and is cyclic by Lagrange's theorem. This contradicts Exercise 2.5.1 $\square$

Example 2.10. Cauchy's theorem and Fermat's theorem are special cases of some common theorem.

If G is a finite group and p is a prime, define

$$X = \{(a_0, a_1, \ldots, a_{p-1}) \in G^p : a_0 a_1 \ldots a_{p-1} = 1\}$$

Note that $|X| = |G|^{p-1}$, for having chosen the last $p-1$ entries arbitrarily, the 0th entry must equal $(a_1 a_2 \ldots a_{p-1})^{-1}$. Introduce an action of $\mathbb{I}_p$ on X by defining, for $0 \leq i \leq p-1$,

$$[i](a_0, \ldots, a_{p-1}) = (a_{i+1}, \ldots, a_{p-1}, a_0, \ldots, a_i)$$

The product of the new p-tuple is a conjugate of $a_0 a_1 \ldots a_{p-1}$

$$a_{i+1} \ldots a_{p-1} a_0 \ldots a_i = (a_0 \ldots a_i)^{-1}(a_0 \ldots a_{p-1})(a_0 \ldots a_i)$$

This conjugate is 1 for $g^{-1}1g = 1$, and so $[i](a_0, \ldots, a_{p-1}) \in X$. By Corollary 2.91, the size of every orbit of X is a divisor of $|\mathbb{I}_p| = p$. Now orbits with just one element consists of a p-tuple all of whose entries a_i are equal, for all cyclic permutations of the p-tuple are the same. In other words, such an orbit corresponds to an element $a \in G$ with $a^p = 1$. Clearly $(1, 1, \ldots, 1)$ is such an orbit; if it were the only such , then we would have

$$|G|^{p-1} = |X| = 1 + kp$$

That is, $|G|^{p-1} \equiv 1 \mod p$. If p is a divisor of $|G|$, then we have a contradiction and thus proved Cauchy's theorem.

Proposition 2.99. *If G is a group of order $|G| = p^e$ then G has a normal subgroup of order p^k for every $k \leq e$*

Proof. We prove the result by induction on $e \geq 0$.

By Theorem 2.97, $Z(G) \neq \{1\}$. Let $Z \leq Z(G)$ be a subgroup of order p and Z is normal. If $k \leq e$, then $p^{k-1} \leq p^{e-1} = |G/Z|$. By induction, G/Z has a normal subgroup H^* of order p^{k-1}. The correspondence theorem says there is a subgroup H of G containing Z with $H^* = H/Z$; moreover $H^* \lhd G/Z$ implies $H \lhd G$. But $|H/Z| = p^{k-1}$ implies $|H| = p^k$ as desired. $\square$

Definition 2.100. A group $G \neq \{1\}$ is called **simple** if G has no normal subgroups other than $\{1\}$ and G itself.

Proposition 2.101. *An abelian group G is simple if and only if it is finite and of prime order*

Proof. Assume G is simple. Since G is abelian, every subgroup is normal, and so G has no subgroups otherthan $\{1\}$ and G. Choose $x \in G$ with $x \neq 1$. Since $\langle x \rangle \leq G$, we have $\langle x \rangle = G$. If x has infinite order, then all the powers of x are distinct, and so $\langle x^2 \rangle < \langle x \rangle$ is a forbidden subgroup of $\langle x \rangle$, a contradiction. Therefore every $x \in G$ has finite order. If x has order m and if m is composite, say $m = kl$, then $\langle x^k \rangle$ is a proper subgroup of $\langle x \rangle$, a contradiction. Therefore $G = \langle x \rangle$ has prime order. □

Suppose that an element $x \in G$ has k conjugates, that is

$$\left| x^G \right| = \left| \{gxg^{-1} : g \in G\} \right| = k$$

If there is a subgroup $H \leq G$ with $x \in H \leq G$, how many conjugates does $x $ have in H?

Since

$$x^H = \{hxh^{-1} : h \in H\} \subseteq x^G$$

we have $\left| x^H \right| \leq \left| x^G \right|$. It is possible that there is a strict inequality $\left| x^H \right| < \left| x^G \right|$. For example, take $G = S_3, x = (1\ 2)$, and $H = \langle x \rangle$. Now let us consider this question, in particular, for $G = S_5, x = (1\ 2\ 3), H = A_5$

Lemma 2.102. *All 3-cycles are conjugate in A_5*

Proof. Let $G = S_5, \alpha = (1\ 2\ 3), H = A_5$. We know that $\left| \alpha^{S_5} \right| = 20$, for there are 20 3-cycles in S_5. Therefore, $20 = |S_5| / \left| C_{S_5}(\alpha) \right|$ by Corollary 2.92 , so that $\left| C_{S_5}(\alpha) \right| = 6$. Here they are

$$(1),\ (1\ 2\ 3),\ (1\ 3\ 2),\ (4\ 5),\ (4\ 5)(1\ 2\ 3),\ (4\ 5\ )(1\ 3\ 2)$$

The last there of these are odd permutations, so that $\left| C_{A_5}(\alpha) \right| = 3$. We conclude that

$$\left| \alpha^{A_5} \right| = |A_5| / \left| C_{A_5}(\alpha) \right| = 20$$

that is all 3-cycles are conjugate to α in A_5 □

Lemma 2.103. *If $n \geq 3$, every element in A_n is a 3-cycle or a product of 3-cycles*

Proof. Since each β equals $\tau_1 \dots \tau_{2q}$ □

Theorem 2.104. *A_5 is a simple group*

Proof. If $H \triangleleft A_5$ and $H \neq \{(1)\}$. Now if H contains a 3-cycle, then normality forces H to contain all its conjugates. Therefore it suffices to prove that H contains 3-cycle.

Since $\sigma \in H$, we may assume, after a harmless relabeling, that either $\sigma = (1\ \ 2\ 3), \sigma = (1\ 2)(3\ 4)$ or $\sigma = (1\ 2\ 3\ 4\ 5x)$

If $\sigma = (1\ 2)(3\ 4)$, define $\tau = (1\ 2)(3\ 5)$. Now $(3\ 5\ 4) = (\tau\sigma\tau^{-1})\sigma^{-1} \in H$. If $\sigma = (1\ 2\ 3\ 4\ 5)$, define $\rho = (1\ 3\ 2)$ and $(1\ 3\ 4) = \rho\sigma\rho^{-1}\sigma^{-1} \in H$ $\square$

A_4 is not simple for $\mathbf{V} \triangleleft A_4$.

Lemma 2.105. *A_6 is a simple group*

Proof. Let $\{1\} \neq H \triangleleft A_6$; we must show that $H = A_6$. Assume that there is some $\alpha \in H$ with $\alpha \neq (1)$ that fixes some i, where $1 \leq i \leq 6$. Define

$$F = \{\sigma \in A_6 : \sigma(i) = i\}$$

Note that $\alpha \in H \cap F$, so that $H \cap F \neq \{(1)\}$. The second isomorphism theorem gives $H \cap F \triangleleft F$. But F is simple for $F \cong A_5$, we have $H \cap F = F$: that is $F \leq H$. It follows that H contains a 3-cycle, and so $H = A_6$ by Exercise 2.6.2.

If there is no $\alpha \in H$ with $\alpha \neq \{1\}$ that fixes some i with $1 \leq i \leq 6$. If we consider the cycle structures of permutations in A_6, however, any such α must have cycle structure $(1\ 2)(3\ 4\ 5\ 6)$ or $(1\ 2\ 3)(4\ 5\ 6)$. In the first case $\alpha^2 \in H$, $\alpha^2 \in H$ fixes 1. In the second case $\alpha(\beta\alpha^{-1}\beta^{-1})$ where $\beta = (2\ 3\ 4)$ fixes 1. $\square$

Theorem 2.106. *A_n is a simple group for all $n \geq 5$*

Proof. If H is a nontrivial normal subgroup of A_n, then we must show that $H = A_n$. By Exercise 2.6.2 it suffices to prove that H contains a 3-cycle. If $\beta \in H$ is nontrivial, then there exists some i that β moves: say, $\beta(i) = j \neq i$. Choose a 3-cycle α that fixes i and moves j. The permutations α and β do not commute. It follows that $\gamma = (\alpha\beta\alpha^{-1})\beta^{-1}$ is a nontrivial element of H. But $\beta\alpha^{-1}\beta^{-1}$ is a 3-cycle, and so $\gamma = \alpha(\beta\alpha^{-1}\beta^{-1})$ is a product of two 3-cycles. Hence γ moves at most 6 symbols, say $i_1, \ldots, i_6$. Define

$$F = \{\sigma \in A_n : \sigma \text{ fixes all } i \neq i_1, \ldots, i_6\}$$

Now $F \cong A_6$ and $\gamma \in H \cap F$. Hence $H \cap F \triangleleft F$. But F is simple, and so $H \cap F = F$; that is $F \leq H$. Therefore H contains a 3-cycle $\square$

Theorem 2.107 (Burnside's Lemma)**.** *Let G act on a finite set X. If N is the number of orbits, then*

$$N = \frac{1}{|G|} \sum_{\tau \in G} Fix(\tau)$$

where $Fix(\tau)$ is the number of $x \in X$ fixed by τ

Proof. List the elements of X as follows: Choose $x_1 \in X$ and then list all the elements $x_1, \ldots, x_r$ in the orbit $\mathcal{O}(x_1)$; then choose $x_{r+1} \notin \mathcal{O}(x_1)$, and so on until all the elements of X are listed. Now list the elements $\tau_1, \ldots, \tau_n$ of G and form the following array, where

$$f_{i,j} = \begin{cases} 1 & \text{if } \tau_i \text{ fixes } x_j \\ 0 & \text{if } \tau_i \text{ moves } x_j \end{cases}$$

$$\begin{array}{c|cccccc} & x_1 & x_2 & \cdots & x_{r+1} & x_{r+2} & \cdots \\ \hline \tau_1 & f_{1,1} & f_{1,2} & \cdots & f_{1,r+1} & f_{1,r+2} & \cdots \\ \vdots & & & & & & \\ \tau_n & f_{n,1} & f_{n,2} & \cdots & f_{n,r+1} & f_{n,r+2} & \cdots \end{array}$$

Now $Fix(\tau_i)$ is the number of 1's in the ith row. therefore $\sum_{\tau \in G} Fix(\tau)$ is the total number of 1's in the array. The number of 1's in column 1 is $\left|G_{x_1}\right|$. By Exercise 2.6.3 $\left|G_{x_1}\right| = \left|G_{x_2}\right|$. By Theorem 2.90 the number of 1's in the r columns labels by the $x_i \in \mathcal{O}(x_i)$ is thus

$$r\left|G_{x_1}\right| = \left|\mathcal{O}(x_1)\right| \cdot \left|G_{x_1}\right| = (|G| / \left|G_{x_1}\right|)\left|G_{x_1}\right| = |G|$$

Therefore

$$\sum_{\tau \in G} Fix(\tau) = N|G|$$

□

We are going to use Burnside's lemma to solve problems of the following sort. How many striped flags are there having six stripes each of which can be colored red, white or blue?

r	w	b	r	w	b

b	w	r	b	w	r

Let X be the set of all 6-tuples of colors: if $x \in X$, then

$$x = (c_1, c_2, c_3, c_4, c_5, c_6)$$

Let τ be the permutation that reserves all the indices:

$$\tau = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 6 & 5 & 4 & 3 & 2 & 1 \end{pmatrix} = (1\ 6)(2\ 5)(3\ 4)$$

(thus τ turns over each 6-tuple x of colored stripes). The cyclic group $G = \langle \tau \rangle$ acts on X; since $|G| = 2$, the orbit of any 6-tuple x consists of either 1 or 2 elements. Since a flag is unchanged by turning it over, it is reasonable to identify a flag with an orbit of 6-tuple. For example, the orbit consisting of the 6-tuples

$$(r, w, b, r, w, b) \text{ and } (b, w, r, b, w, r)$$

above. The number of flags is thus the number N of orbits; by Burnside's lemma, $N = \frac{1}{2}[Fix((1)) + Fix(\tau)]$. The identity permutation (1) fixes every $x \in X$, and so $Fix((1)) = 3^6$. Now τ fixes a 6-tuple x if it's a "palindrome". It follows that $Fix(x) = 3^3$. The number of flags is thus

$$N = \frac{1}{2}(3^6 + 3^3) = 378$$

Definition 2.108. If a group G acts on $X = \{1, \dots, n\}$ and if $\mathcal{C}$ is a set of q colors, then G acts on the set $\mathcal{C}^n$ of all n-tuples of colors by

$$\tau(c_1, \dots, c_n) = (c_{\tau 1}, \dots, c_{\tau n}) \text{ for all } \tau \in G$$

An orbit of $(c_1, \dots, c_n) \in \mathcal{C}^n$ is called a (q, G)**-coloring** of X.

Example 2.11. Color each square in a 4×4 grid red or black.

If X consists of the 16 squares in the grid and if $\mathcal{C}$ consists of the two colors red and black, then the cyclic group $G = \langle R \rangle$ or order 4 acts on X, where R is a clockwise rotation by $90°$;

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

13	9	5	1
14	10	6	2
15	11	7	3
16	12	8	4

Figure shows how R acts: the right square is R)'s action on the left square. In cycle notation

$$R = (1,\ 4,\ 16,\ 13)(2,\ 8,\ 15,\ 9)(3,\ 12,\ 14,\ 5)(6,\ 7,\ 11,\ 10)$$
$$R^2 = (1,\ 16)(4,\ 13)(2,\ 15)(8,\ 9)(3,\ 14)(12,\ 5)(6,\ 11)(7,\ 10)$$
$$R^3 = (1,\ 13,\ 16,\ 4)(2,\ 9,\ 15,\ 8)(3,\ 5,\ 14,\ 12)(6,\ 10,\ 11,\ 7)$$

By Burnside's lemma, the number of chessboards is

$$\frac{1}{4}[Fix((1)) + Fix(R) + Fix(R^2) + Fix(R^3)]$$

Exercise 2.6.1. Prove that if p is a prime and G is a finite group in which every element has order a power of p, then G is a p-group. (A possibly infinite group G) is called a p**-group** if every element in G has order a power of p

Proof. By Cauchy's theorem 2.94 □

Exercise 2.6.2.
1. For all $n \geq 5$, prove that all 3-cycles are conjugate in A_n
2. Prove that if a normal subgroup $H \lhd A_n$ contains a 3-cycle, where $n \geq 5$, then $H = A_n$

Proof.
1. If $(1\ 2\ 3)$ and $(i\ j\ k)$ are not disjoint. As Example 2.1 illustrated, $\alpha \in S_5$
   If they are disjoint, simple
2. By lemma 2.103

□

Exercise 2.6.3.
1. Let a group G act on a set X, and suppose that $x, y \in X$ lie in the same orbit: y=gx for some $g \in G$. Prove that $G_y = gG_xg^{-1}$
2. Let G be a finite group acting on a set X; prove that if $$x,y∈ X lie in the same orbit, then $|G_x| = |G_y|$

Proof.
1. If $f \in G_x$, then $gfg^{-1}(y) = gfg^{-1}gx = gx = y$
2. There is a bijection.

□

3 Commuctative Rings I

3.1 First Properties

Definition 3.1. A **commutative ring** R is a set with two binary operations, addition and multiplication s.t.

1. R is an abelian group under addition
2. (**commutativity**) $ab = ba$ for all $a, b \in R$
3. (**associativity**) $a(bc) = (ab)c$ for every $a, b, c \in R$
4. there is an element $1 \in R$ with $1a = a$ for every $a \in R$
5. (**distributivity**) $a(b + c) = ab + ac$ for every $a, b, c \in R$

The element 1 in a ring R has several names: it is called **one**, the **unit** of R, or the **identity** in R

Example 3.1. 1. $\mathbb{Z}, \mathbb{Q}, \mathbb{R}$ and $\mathbb{C}$ are commutative rings with the usual addition and multiplication

2. Consider the set R of all real numbers x of the form

$$x = a + b\omega$$

where $a, b \in \mathbb{Q}$ and $\omega = \sqrt[3]{2}$. R is closed under ordinary addition. However, if R is closed under multiplication, then $\omega^2 \in R$ and there are rationals a and b with

$$\omega^2 = a + b\omega$$
$$2 = a\omega + b\omega^2$$
$$b\omega^2 = ab + b^2\omega$$

Hence $2 - a\omega = ab + b^2\omega$ and so

$$2 - ab = (b^2 + a)\omega$$

A contradiction.

Proposition 3.2. *Let R be a commutative ring.*

1. $0 \cdot a = 0$ *for every* $a \in R$
2. *If* $1 = 0$ *then* R *consists of the single element 0. In this case* R *is called the* ***zero ring***
3. *If* $-a$ *is the additive inverse of* a*, then* $(-1)(-a) = a$
4. $(-1)a = -a$ *for every* $a \in R$
5. *If* $n \in \mathbb{N}$ *and* $n1 = 0$*, then* $na = 0$ *for all* $a \in R$

6. *The binomial theorem holds: if $a, b \in R$, then*

$$(a+b)^n = \sum_{r=0}^{n} \binom{n}{r} a^r b^{n-r}$$

Proof. 6. $\binom{n+1}{r} = \binom{n}{r-1} + \binom{n}{r}$ $\square$

Definition 3.3. A subset S of a commutative ring R is a **subring** of R if

1. $1 \in S$
2. if $a, b \in S$ then $a - b \in S$
3. if $a, b \in S$, then $ab \in S$

Notation. The tradition in ring theory is to write $S \subseteq R$ for a subring

Proposition 3.4. *A subring S of a commutative ring R is itself a commutative ring.*

Definition 3.5. A **domain** (often called an **integral domain**) is a commutative ring R that satisfies two extra axioms: first

$$1 \neq 0$$

second, the **cancellation law** for multiplication: for all $a, b, c \in R$

$$\text{if } ca = cb \text{ and } c \neq 0, \text{ then } a = b$$

Proposition 3.6. *A nonzero commutative ring R is a domain if and only if the product of any two nonzero elements of R is nonzero*

Proof. $ab = ac$ if and only if $a(b-c) = 0$ $\square$

Proposition 3.7. *The commutative ring $\mathbb{I}_m$ is a domain if and only if m is a prime*

Proof. If $m = ab$, where $1 < a, b < m$, then $[a], [b] \neq [0]$ yet $[a][b] = [m] = [0]$

Conversely, if m is a prime and $[a][b] = [ab] = [0]$, then $m \mid ab$ $\square$

Example 3.2. 1. Let $\mathcal{F}(\mathbb{R})$ be the set of all the function $\mathbb{R} \to \mathbb{R}$ equipped with the operations of **point-wise addition** and **point-wise multiplication**: Given $f, g \in \mathcal{F}(\mathbb{R})$, define functions $f + g$ and fg by

$$f + g : a \mapsto f(a) + f(b) \quad \text{and} \quad fg : a \mapsto f(a)g(a)$$

We claim that $\mathcal{F}(\mathbb{R})$ with these operations is a commutative ring. The zero element is the constant function z with value 0. $\mathcal{F}(\mathbb{R})$ is not a domain by

$$f(a) = \begin{cases} a & \text{if } a \leq 0 \\ 0 & \end{cases} \quad g(a) = \begin{cases} 0 & \text{if } a \leq 0 \\ a & \end{cases}$$

Definition 3.8. Let a and b be elements of a commutative ring R. Then a **divides** b **in** R (or a is a **divisor** of b or b is a **multiple** of a), denoted by $a \mid b$, if there exists an element $c \in R$ with $b = ca$

Definition 3.9. An element u in a commutative ring R is called a **unit** if $u \mid 1$ in R.

Proposition 3.10. *Let R be a domain, and let $a, b \in R$ be nonzero. Then $a \mid b$ and $b \mid a$ if and only if $b = ua$ for some unit $u \in R$*

Proposition 3.11. *If a is an integer, then $[a]$ is a unit in $\mathbb{I}_m$ if and only if a and m are relatively prime.*

Corollary 3.12. *If p is a prime, then every nonzero $[a]$ in $\mathbb{I}_p$ is a unit.*

Definition 3.13. If R is a commutative ring, then the **group of units** of R is

$$U(R) = \{\text{all units in } R\}$$

Definition 3.14. A **field** F is a commutative ring in which $1 \neq 0$ and every nonzero element a is a unit; that is, there is $a^{-1} \in F$ with $a^{-1}a = 1$

A commutative ring R is a field if and only if $U(R) = R^{\times}$, the nonzero elements of R.

Proposition 3.15. *Every field F is a domain*

Proof. $ab = ac, b = a^{-1}ab = a^{-1}(ac) = c$ □

Proposition 3.16. *The commutative ring $\mathbb{I}_m$ is a field if and only if m is prime*

Theorem 3.17. *If R is a domain then there is a field F containing R as a subring. Moreover, F can be chosen so that for each $f \in F$, there are $a, b \in R$ with $b \neq 0$ and $f = ab^{-1}$*

Proof. Let $X = \{(a, b) \in R \times R : b \neq 0\}$ and define a relation $\equiv$ on X by $(a, b) \equiv (c, d)$ if $ad = bc$. We claim that $\equiv$ is an equivalence relation. If $(a, b) \equiv (c, d)$ and $(c, d) \equiv (e, f)$, then $ad = bc, cf = de$ and $adf = b(cf) = bde$, gives $af = be$

Denote the equivalence class of (a,b) by $[a, b]$, define F as the set of all equivalence classes $[a, b]$ and equip F with the following addition and multiplication

$$
\begin{aligned}
[a, b] + [c, d] &= [ad + bc, bd] \\
[a, b][c, d] &= [ac, bd]
\end{aligned}
$$

Show addition and multiplication are well-defined. □

Definition 3.18. The field F constructed from R in Theorem 3.17 is called the **fraction field** of R, denoted by $\mathrm{Frac}(R)$, and we denote $[a, b] \in \mathrm{Frac}(R)$ by a/b

Note that $\mathrm{Frac}(\mathbb{Z}) = \mathbb{Q}$

3.2 Polynomials

Definition 3.19. If R is a commutative ring, then a **sequence** σ in R is

$$\sigma = (s_0, s_1, \dots, s_i, \dots)$$

the entries $s_i \in R$ for all $i \geq 0$ are called the **coefficients** of σ

Definition 3.20. A sequence $\sigma = (s_0, \dots, s_i, \dots)$ in a commutative ring R is called a **polynomial** if there is some integer $m \geq 0$ with $s_i = 0$ for all $i > m$; that is

$$\sigma = (s_0, \dots, s_m, 0, \dots)$$

A polynomial has only finitely many nonzero coefficients. The **zero polynomial**, denoted by $\sigma = 0$

Definition 3.21. If $\sigma(s_0, \dots, s_n, 0, \dots) \neq 0$ is a polynomial, we call s_n the **leading coefficient** of σ, we call n the **degree** of σ, an we denote n by $\deg(\sigma)$

Notation. If R is a commutative ring, then the set of all polynomials with coefficients in R is denoted by $R[x]$

Proposition 3.22. *If R is a commutative ring, then $R[x]$ is a commutative ring that contains R as a subring*

Proof. $\sigma = (s_0, s_1, \dots), \tau = (t_0, t_1, \dots)$

$$\sigma + \tau = (s_0 + t_0, s_1 + t_1, \dots)$$
$$\sigma\tau = (c_0, c_1, \dots)$$

where $c_k = \sum_{i+j=k} s_i t_j = \sum_{i=0}^{k} s_i t_{k-i}$. □

Lemma 3.23. *Let R be a commutative ring and let $\sigma, \tau \in R[x]$ be nonzero polynomials.*

1. *Either $\sigma\tau = 0$ or deg$(\sigma\tau) \le$ deg$(\sigma) +$ deg(τ)*
2. *If R is a domain, then $\sigma\tau \neq 0$ and*

$$\textit{deg}(\sigma\tau) = \textit{deg}(\sigma) + \textit{deg}(\tau)$$

3. *If R is a domain, then $R[x]$ is a domain*

Proof. $\sigma = (s_0, s_1, \dots), \tau = (t_0, t_1, \dots)$ have degrees m and n respectively.

1. if $k > m + n$, then each term in $\sum_i s_i t_{k-i}$ is 0
2. Each term in $\sum_i s_i t_{m+n-i}$ is 0 with the possible exception of $s_m t_n$. Since R is a domain, $s_m \neq 0$ and $t_n \neq 0$ imply $s_m t_n \neq 0$.

□

Definition 3.24. If R is a commutative ring, then $R[x]$ is called the **ring of polynomials over** R

Definition 3.25. Define the element $x \in R[x]$ by

$$x = (0, 1, 0, 0, \dots)$$

Lemma 3.26.

1. *IF $\sigma = (s_0, \dots)$, then*

$$x\sigma = (0, s_0, s_1, \dots)$$

2. *If $n \geq 1$, then x^n is the polynomial having 0 everywhere except for 1 in the nth coordinate*
3. *If $r \in R$, then*

$$(r, 0, \dots)(s_0, s_1, \dots, s_j, \dots) = (rs_0, rs_1, \dots, rs_j, \dots)$$

Proposition 3.27. *If $\sigma = (s_0, \dots, s_n, 0, \dots)$, then*

$$\sigma = s_0 + s_1 x + s_2 x^2 + \cdots + s_n x^n$$

where each element $s \in R$ is identified with the polynomial $(s, 0, \dots)$

As a customary, we shall write

$$f(x) = s_0 + s_1x + \cdots + s_nx^n$$

instead of σ. s_0 is called its **constant term**. If $s_n = 1$, then $f(x)$ is called **monic**.

Corollary 3.28. *Polynomials $f(x) = s_0+\cdots+s_nx^n$ and $g(x) = t_0+\cdots+t_mx^m$ are equal if and only if $n = m$ and $s_i = t_i$ for all i.*

If R is a commutative ring, each polynomial $f(x) = s_0 + \cdots + s_nx^n$ defines a **polynomial function** $f : R \to R$ by evaluation: If $a \in R$, define $f(a) = s_0 + \cdots + s_na^n \in R$.

Definition 3.29. Let k be a field. The fraction field of $k[x]$, denoted by $k(x)$, is called the **field of rational function** over k

Proposition 3.30. *If k is a field, then the elements of $k(x)$ have the form $f(x)/g(x)$ where $f(x), g(x) \in k[x]$ and $g(x) \neq 0$*

Proposition 3.31. *If p is a prime, then the field of rational functions $\mathbb{I}_p(x)$ is a n infinite field containing $\mathbb{I}_p$ as a subfield.*

Proof. By Lemma 3.23 (3), $\mathbb{I}_p[x]$ is an infinite domain for the powers x^n for $n \in \mathbb{N}$ are distinct. Thus its fraction filed $\mathbb{I}_p(x)$ is an infinite field containing $\mathbb{I}_p[x]$ as a subring. But $\mathbb{I}_p[x]$ contains $\mathbb{I}_p$ as a subring, by Proposition 3.22. $\square$

$R[x]$ is often called the ring of all **polynomials over R in one variable**. If we write $A = R[x]$, then $A[y]$ is called the ring of all **polynomials over R in two variables x and y**, and it is denoted by $R[x, y]$.

Exercise 3.2.1. Show that if R is a commutative ring, then $R[x]$ is never a field

Proof. If $R[x]$ is a field, then $x^{-1} \in R[x]$ and $x^{-1} = \sum_i c_ix^i$. However

$$\deg(xx^{-1}) = \deg(1) = 1 = \deg(x) + \deg(x^{-1})$$

A contradiction. $\square$

Exercise 3.2.2. Show that the polynomial function defined by $f(x) = x^p - x \in \mathbb{I}_p[x]$ is identically zero.

Proof. By Fermat's theorem 2.49, $a^p \equiv a \mod p$ $\square$

3.3 Greatest Common Divisors

Theorem 3.32 (Division Algorithm)**.** *Assume that k is a field and that $f(x), g(x) \in k[x]$ with $f(x) \neq 0$. Then there are unique polynomials $q(x), r(x) \in k[x]$ with*

$$g(x) = q(x)f(x) + r(x)$$

and either $r(x) = 0$ or deg$(r) <$ deg(f)

Proof. We first prove the existence of such q and r. If $f \mid g$, then $g = qf$ for some q; define the remainder $r = 0$. If $f \nmid g$, then consider all polynomials of the form $g - qf$ as q varies over $k[x]$. The least integer axiom provides a polynomial $r = g - qf$ having least degree among all such polynomials. Since $g = qf + r$, it suffices to show that deg$(r) <$ deg(f). Write $f(x) = s_n x^n + \cdots + s_1 x + s_0$ and $r(x) = t^m x^m + \ldots t_0$. Now $s_n \neq 0$ implies that s_n is a unit because k is a field and so $s_n^{-1} \in k$. If deg$(r) \geq$ deg(f), define

$$h(x) = r(x) - t_m s_n^{-1} x^{m-n} f(x)$$

that is, if $\mathrm{LT}(f) = s_n x^n$, where LT abbreviates **leading term**, then

$$h = r - \frac{\mathrm{LT}(r)}{\mathrm{LT}(f)} f$$

note that $h = 0$ or deg$(h) <$ deg(r). If $h = 0$, then $r = [\mathrm{LT}(r)/\,\mathrm{LT}(f)]f$ and

$$\begin{aligned} g = qf + r &= qf + \frac{\mathrm{LT}(r)}{\mathrm{LT}(f)} f \\ &= \left[q + \frac{\mathrm{LT}(r)}{\mathrm{LT}(f)} \right] f \end{aligned}$$

contradicting $f \nmid g$. If $h \neq 0$, then deg$(h) <$ deg(r) and

$$g - qf = r = h + \frac{\mathrm{LT}(r)}{\mathrm{LT}(f)} f$$

Thus $g - [q + \mathrm{LT}(r)/\,\mathrm{LT}(f)]f = h$, contradicting r being a polynomial of least degree having this form. Therefore deg$(r) <$ deg(f)

To prove uniqueness of $q(x)$ and $r(x)$ assume that $g = q'f + r'$, where deg$(r') <$ deg(f). Then

$$(q - q')f = r' - r$$

If $r' \neq r$, then each side has a degree. But deg$((q - q')f) =$ deg$(q - q') +$ deg$(f) \geq$ deg(f), while deg$(r' - r) \leq \max\{$deg$(r'),$ deg$(r)\} < deg(f)$, a contradiction. Hence $r' = r$ and $(q - q')f = 0$. As $k[x]$ is a domain and $f \neq 0$, it follows that $q - q' = 0$ and $q = q'$ $\square$

Definition 3.33. If $f(x)$ and $g(x)$ are polynomials in $k[x]$, where k is a field, then the polynomials $q(x)$ and $r(x)$ occurring in the division algorithm are called the **quotient** and the **remainder** after dividing $g(x)$ by $f(x)$

The hypothesis that k is a filed is much too strong: long division can be carried out in $R[x]$ for every commutative ring R as long as the leading coefficient of $f(x)$ is a unit in R; in particular, long division is always possible when $f(x)$ is monic.

Corollary 3.34. *Let R be a commutative ring and let $f(x) \in R[x]$ be a monic polynomial. If $g(x) \in R[x]$, then there exists $q(x), r(x) \in R[x]$ with*

$$g(x) = q(x)f(x) + r(x)$$

where either $r(x) = 0$ or $deg(r) < deg(f)$

Proof. Note that $\mathrm{LT}(r)/\mathrm{LT}(f) \in R$ because $f(x)$ is monic ☐

Definition 3.35. If $f(x) \in k[x]$, where k is a field, then a **root** of $f(x)$ **in** k is an element $a \in k$ with $f(a) = 0$

Lemma 3.36. *Let $f(x) \in k[x]$, where k is a field, and let $u \in k$. Then there is $q(x) \in k[x]$ with*

$$f(x) = q(x)(x-u) + f(u)$$

Proof. The division algorithm gives

$$f(x) = q(x)(x-u) + r$$

Now evaluate

$$f(u) = q(u)(u-u) + r$$

and so $r = f(u)$ ☐

Proposition 3.37. *If $f(x) \in k[x]$, where k is a field, then a is a root of $f(x)$ in k if and only if $x - a$ divides $f(x)$ in $k[x]$*

Proof. If a is a root of $f(x)$ in k, then $f(a) = 0$ and the lemma gives $f(x) = q(x)(x-a)$. ☐

Theorem 3.38. *Let k be a field and let $f(x) \in k[x]$. If $f(x)$ has degree n, then $f(x)$ has at most n roots in k*

Proof. We prove the statement by induction on $n \geq 0$. If $n = 0$, then $f(x)$ is a nonzero constant, and so the number of its roots in k is zero. Now let $n > 0$. If $f(x)$ has no roots in k, then we are done. Otherwise we may assume that there is $a \in k$ with a a root of $f(x)$; hence by Proposition 3.37

$$f(x) = q(x)(x - a)$$

moreover, $q(x) \in k[x]$ has degree $n - 1$. □

Example 3.3. Theorem 3.38 is not true for polynomials with coefficients in an arbitrary commutative ring R. For example, if $R = \mathbb{I}_8$, then the quadratic polynomial $x^2 - 1$ has 4 roots: $[1], [3], [5], [7]$

Corollary 3.39. *Every nth root of unity in $\mathbb{C}$ is equal to*

$$e^{2\pi ik/n} = \cos\left(\frac{2\pi k}{n}\right) + i \sin\left(\frac{2\pi k}{n}\right)$$

where $k = 0, 1, \ldots, n - 1$

Corollary 3.40. *Let k be an infinite field and let $f(x)$ and $g(x)$ be polynomials in $k[x]$. If $f(x)$ and $g(x)$ determine the same polynomial function, then $f(x) = g(x)$*

Proof. If $f(x) \neq g(x)$, then the polynomial $h(x) = f(x) - g(x)$ is nonzero, so that it has some degree, say n. Now every element of k is a root of $h(x)$; since k is infinite, $h(x)$ has more than n roots, a contradiction. □

Theorem 3.41. *If k is a field and G is a finite subgroup of the multiplicative group $k^\times$., then G is cyclic. In particular, if k itself is finite, then $k^\times$ is cyclic.*

Proof. Let d be a divisor of$|G|$. If there are two subgroups of G of order d, say S and T, then$|S \cup T| > d$. But each $a \in S \cup T$ satisfies $a^d = 1$ and hence it's a root of $x^d - 1$, a contradiction. Thus G is cyclic, by Theorem 2.81. □

Definition 3.42. If k is a finite field, a generator of the cyclic group $k^\times$ is called a **primitive element** of k

Definition 3.43. If $f(x)$ and $g(x)$ are polynomials in $k[x]$, where k is a field, then a **common divisor** is a polynomial $c(x) \in k[x]$ with $c(x) \mid f(x)$ and $c(x) \mid g(x)$. If $f(x)$ and $g(x)$ in $k[x]$ are not both 0, define their **greatest common divisor**, abbreviated gcd, to be the monic common divisor having largest degree. If $f(x) = 0 = g(x)$, define their $\gcd = 0$. The gcd of $f(x)$ and $g(x)$ is often denoted by (f, g)

Theorem 3.44. *If k is a field and $f(x), g(x) \in k[x]$, then their* $\gcd d(x)$ *is a nonlinear combination of $f(x)$ and $g(x)$; that is there are $s(x), t(x) \in k[x]$ with*

$$d(x) = s(x)f(x) + t(x)g(x)$$

Corollary 3.45. *Let k be a field and let $f(x), g(x) \in k[x]$. A monic common divisor $d(x)$ is the gcd if and only if $d(x)$ is divisible by every common divisor*

Definition 3.46. An element p in a domain R is **irreducible** if p is neither 0 nor a unit and in any factorization $p = uv$ in R, either u or v is a unit. Elements $a, b \in R$ are **associates** if there is a unit $u \in R$ with $b = ua$

For example, a prime p is irreducible in $\mathbb{Z}$

Proposition 3.47. *If k is a field, then a polynomial $p(x) \in k[x]$ is irreducible if and only if deg$(p) = n \geq 1$ and there is no factorization in $k[x]$ of the form $p(x) = g(x)h(x)$ in which both factors have degree smaller than n*

Proof. We show fist that $h(x) \in k[x]$ is a unit if and only if $\deg(h) = 0$. If $h(x)u(x) = 1$, then $\deg(h) + \deg(u) = \deg(1) = 0$, we have $\deg(h) = 0$. Conversely if $\deg(h) = 0$, then $h(x)$ is a nonzero constant; that is, $h \in k$; since k is a field, h has an inverse

If $p(x)$ is irreducible, then its only factorization are of the form $p(x) = g(x)h(x)$ where $g(x)$ or $h(x)$ is a unit; that is, either $\deg(g) = 0$ or $\deg(h) = 0$.

Conversely, if $p(x)$ is reducible, then it has factorization $p(x) = g(x)h(x)$ where neither $g(x)$ nor $h(x)$ is a unit; □

Corollary 3.48. *Let k be a field and let $f(x) \in k[x]$ be a quadratic or cubic polynomial. Then $f(x)$ is irreducible in $k[x]$ if and only if $f(x)$ does not have a root in k*

Proof. If $f(x) = g(x)h(x)$, then $\deg(f) = \deg(g) + \deg(h)$ □

Example 3.4. 1. We determine the irreducible polynomials in $\mathbb{I}_2[x]$ of small degree.
As always, the linear polynomials x and $x + 1$ are irreducible
There are four quadratics: $x^2, x^2 + x, x^2 + 1, x^2 + x + 1$

Lemma 3.49. *Let k be a field, let $p(x), f(x) \in k[x]$, and let $d(x) = (p, f)$. If $p(x)$ is a monic irreducible polynomial, then*

$$d(x) = \begin{cases} 1 & \text{if } p(x) \nmid f(x) \\ p(x) & \text{if } p(x) \mid f(x) \end{cases}$$

Theorem 3.50 (Euclid's Lemma)**.** *Let k be a field and let $f(x), g(x) \in k[x]$. If $p(x)$ is an irreducible polynomial in $k[x]$, and $p(x) \mid f(x)g(x)$, then either*

$$p(x) \mid f(x) \quad \textit{or} \quad p(x) \mid g(x)$$

More generally, if $p(x) \mid f_1(x) \dots f_n(x))$, then $p(x) \mid f_i(x)$ for some i

Proof. Assume $p \mid fg$ but that $p \nmid f$. Since p is irreducible, $(p, f) = 1$, and so $1 = sp + tf$ for some polynomials s and t. Therefore

$$g = spg + tfg$$

and so $p \mid g$ □

Definition 3.51. Two polynomials $f(x), g(x) \in k[x]$ where k is a field, are called **relatively prime** if their gcd is 1

Corollary 3.52. *Let $f(x), g(x), h(x) \in k[x]$, where k is a field and let $h(x)$ and $f(x)$ be relatively prime. If $h(x) \mid f(x)g(x)$, then $h(x) \mid g(x)$*

Definition 3.53. If k is a field, then a rational function $f(x)/g(x) \in k(x)$ is in **lowest terms** if $f(x)$ and $g(x)$ are relatively prime

Proposition 3.54. *If k is a field, every nonzero $f(x)/g(x) \in k(x)$ can be put in lowest terms*

Theorem 3.55 (Euclidean Algorithm)**.** *If k is a field and $f(x), g(x) \in k[x]$, then there are algorithms for computing $\gcd(f, g)$ as well as for finding a pair of polynomials $s(x)$ and $t(x)$ with*

$$(f, g) = s(x)f(x) + t(x)g(x)$$

Proof.

$$\begin{aligned}
g &= q_1 f + r_1 \\
f &= q_2 r_1 + r_2 \\
r_1 &= q_3 r_2 + r_3 \\
&\vdots \\
r_{n-4} &= q_{n-2} r_{n-3} + r_{n-2} \\
r_{n-3} &= q_{n-1} r_{n-2} + r_{n-1} \\
r_{n-2} &= q_n r_{n-1} + r_n \\
r_{n-1} &= q_{n+1} r_n
\end{aligned}$$

Since the degrees of the remainders are strictly decreasing, this procedure must stop after a finite number of steps. The claim is that $d = r_n$ is the gcd. If c is any common divisor of f and g, then $c \mid r_i$ for every i. Also

$$\begin{aligned}
r_n &= r_{n-2} - q_n r_{n-1} \\
&= r_{n-2} - q_n(r_{n-3} - q_{n-1}r_{n-2}) \\
&= (1 + q_{n-1})r_{n-2} - q_n r_{n-3} \\
&= (1 + q_{n-1})(r_{n-4} - q_{n-2}r_{n-3}) - q_n r_{n-3} \\
&= (1 + q_{n-1})r_{n-4} - [(1 + q_{n-1})q_{n-2} + q_n]r_{n-3} \\
&\vdots \\
&= sf + tg
\end{aligned}$$

□

Corollary 3.56. *Let k be a subfield of a field K, so that $k[x]$ is a subring of $K[x]$. If $f(x), g(x) \in k[x]$, then their gcd in $k[x]$ is equal to their gcd in $K[x]$*

Proof. The division algorithm in $K[x]$ gives

$$g(x) = Q(x)f(x) + R(x)$$

$k[x]$ gives

$$g(x) = q(x)f(x) + r(x)$$

and this also holds in $K[x]$. So that uniqueness of quotient and remainder gives $Q(x) = q(x), R(x) = r(x)$. □

Theorem 3.57 (Unique Factorization)**.** *If k is a field, then every polynomial $f(x) \in k[x]$ of degree ≥ 1 is a product of a nonzero constant and monic irreducibles. Moreover, if $f(x)$ has two such factorizations*

$$f(x) = ap_1(x) \dots p_m(x) \quad \textit{and} \quad f(x) = bq_1(x) \dots q_n(x)$$

then $a = b, m = n$ and the q's may be reindexed so that $q_i = p_i$ for all i

Proof. We prove the existence of a factorization for a polynomial $f(x)$ by induction on $\deg(f) \geq 1$. If $\deg(f) = 1 =$, then $f(x) = ax + c = a(x + a^{-1}c)$. As every linear polynomial, $x + a^{-1}c$ is irreducible.

Assume now that $\deg(f) \geq 1$. If $f(x)$ is irreducible and its leading coefficient is a, write $f(x) = a(a^{-1}f(x))$; we are done. If $f(x)$ is not irreducible, then $f(x) = g(x)h(x)$, where $\deg(g) < \deg(f)$ and $\deg(h) < \deg(f)$. By the

inductive hypothesis, $g(x) = bp_1(x) \dots p_m(x)$ and $h(x) = cq_1(x) \dots q_n(x)$. It follows that
$$f(x) = (bc)p_1(x) \dots p_m(x)q_x(x) \dots q_n(x)$$

We now prove by induction on $M = \max\{m, n\} \geq 1$ if there is an equation
$$ap_1(x) \dots p_m(x) = bq_1(x) \dots q_n(x)$$
where a and b are nonzero constants and the p's and q's are monic irreducibles. For the inductive step, $p_m(x) \mid q_1(x) \dots q_n(x)$. By Euclid's lemma, there is i with $p_m(x) \mid q_i(x)$. But $q_i(x)$ are monic irreducible, so that $q_i(x) = p_m(x)$. Canceling this factor we will use inductive hypothesis $\square$

Let k be a field and assume that there are $a, r_1, \dots, r_n \in k$ with
$$f(x) = a \prod_{i=1}^{n} (x - r_i)$$

If $r_1, \dots, r_s$ where $s \leq n$ are the distinct roots of $f(x)$, then collecting terms gives
$$f(x) = a(x - r_1)^{e_1} \dots (x - r_s)^{e_s}$$
where r_j are distinct and $e_j \geq 1$. We call e_j the **multiplicity** of the root r_j.

Theorem 3.58. *Let $f(x) = a_0 + a_1 x + \dots + a_n x^n \in \mathbb{Z}[x] \subseteq \mathbb{Q}[x]$. Every rational root r of $f(x)$ has the form b/c, where $b \mid a_0$ and $c \mid a_n$*

Proof. We may assume that $r = b/c$ is in lowest form.
$$0 = f(b/c) = a_0 + a_1(b/c) + \dots + a_n(b/c)^n$$
$$0 = a_0 c^n + a_1 b c^{n-1} + \dots + a_n b^n$$
Hence $a_0 c^n = b(-a_1 c^{n-1} - \dots - a_n b^{n-1})$, that is $b \mid a_0 c^n$. $\square$

Definition 3.59. A complex number α is called an **algebraic integer** if α is a root of a monic $f(x) \in \mathbb{Z}[x]$

Corollary 3.60. *A rational number z that is an algebraic integer must lie in $\mathbb{Z}$. More precisely, if $f(x) \in \mathbb{Z}[x] \subseteq \mathbb{Q}[x]$ is a monic polynomial, then every rational root of $f(x)$ is an integer that divides the constant term*

Proof. $a_n = 1$ in Theorem 3.58 $\square$

For example, consider $f(x) = x^3 + 4x^2 - 2x - 1 \in \mathbb{Q}[x]$. By Corollary 3.48, this cubic is irreducible if and only if it has no rational root. As $f(x)$ is monic, the candidates for rational roots are ± 1, for these are the only divisor of -1 in $\mathbb{Z}$. Thus $f(x)$ has no roots in $\mathbb{Q}$ and hence $f(x)$ is irreducible in $\mathbb{Q}[x]$

3.4 Homomorphisms

Definition 3.61. If A and R are (commutative) rings, a **(ring) homomorphism** is a function $f : A \to R$ s.t.

1. $f(1) = 1$
2. $f(a + a') = f(a) + f(a')$
3. $f(aa') = f(a)f(a')$

Example 3.5.
1. Let R be a domain and let $F = \mathrm{Frac}(R)$. $R' = \{[a, 1] : a \in R\} \subseteq F$, then the function $f : R \to R'$ given by $f(a) = [a, 1]$, is an isomorphism
2. Complex conjugation $z = a + ib \mapsto \overline{z} = a - ib$ is an isomorphism $\mathbb{C} \to \mathbb{C}$.
3. Let R be a commutative ring, and let $a \in R$. Define the **evaluation homomorphism** $e_a : R[x] \to R$ by $e_a(f(x)) = f(a)$.

Lemma 3.62. *If $f : A \to R$ is a ring homomorphism, then for all $a \in A$*

1. $f(a^n) = f(a)^n$
2. *if a is a unit, then $f(a)$ is a unit and $f(a^{-1}) = f(a)^{-1}$*
3. *if $f : A \to R$ is a ring homomorphism, then*

$$f(U(A)) \leq U(R)$$

where $U(A)$ is the group of units of A; if f is an isomorphism, then

$$U(A) \cong U(R)$$

Proposition 3.63. *If R and S are commutative rings and $\varphi : R \to S$ is a ring homomorphism, then there is a ring homomorphism $\varphi^* : R[x] \to S[x]$ given by*

$$\varphi^* : r_0 + r_1 x + r_2 x^2 + \dots \mapsto \varphi(r_0) + \varphi(r_1)x + \varphi(r_2)x^2 + \dots$$

Definition 3.64. If $f : A \to R$ is a ring homomorphism, then its **kernel** is

$$\ker f = \{a \in A : f(a) = 0\}$$

and its **image** is

$$\mathrm{im}\, f = \{r \in R : \exists a \in R \;\; r = f(a)\}$$

The kernel of a group homomorphism is not merely a subgroup; it is a **normal** subgroup. Similarly, the kernel of a ring homomorphism is almost a subring ($1 \notin \ker f$) and is closed under multiplication.

Definition 3.65. An **ideal** in a commutative ring R is a subset I of R s.t.

1. $0 \in I$
2. if $a, b \in I$, then $a + b \in I$
3. if $a \in I$ and $r \in R$, then $ra \in I$

An ideal $I \neq R$ is called a **proper ideal**

Example 3.6. If $b_1, \ldots, b_n \in R$, then the set of all linear combinations

$$I = \{r_1 b_1 + \cdots + r_n b_n : r_i \in R\}$$

is an ideal in R. We write $I = (b_1, \ldots, b_n)$ in this case and we call I the **ideal generated by** $b_1, \ldots, b_n$. In particular, if $n = 1$, then

$$I = (b) = \{rb : r \in R\}$$

is an ideal in R; (b) consists of all the multiplies of b and it is called the **principal ideal** generated by b. Notice that R and $\{0\}$ are always principal ideals: $R = (1), \{0\} = (0)$

Proposition 3.66. *If $f : A \to R$ is a ring homomorphism, then $\ker f$ is an ideal in A and $\operatorname{im} f$ is a subring of R. Moreover, if A and R are not zero rings, then $\ker f$ is a proper ideal.*

Example 3.7.
1. If an ideal I in a commutative ring R contains 1, then $I = R$
2. it follows from 1 that if R is a field, then the only ideals are $\{0\}$ and R

Proposition 3.67. *A ring homomorphism $f : A \to R$ is an injection if and only if $\ker f = \{0\}$*

Corollary 3.68. *If $f : k \to R$ is a ring homomorphism, where k is a field and R is not the zero ring, then f is an injection*

Proof. the only proper ideal in k is $\{0\}$ □

Theorem 3.69. *If k is a field, then every ideal I in $k[x]$ is a principal ideal. Moreover, if $I \neq \{0\}$, there is a monic polynomial that generates I*

Proof. If k is a field, then $k[x]$ is an example of a **euclidean ring**. Follows Theorem 3.75 □

Definition 3.70. A domain R is a **principal ideal domain** (PID) if every ideal in R is a principal ideal.

Example 3.8. 1. The ring of integers is a PID

2. Every field is a PID
3. If k is a field, then the polynomial ring $k[x]$ is a PID
4. There are rings other than $\mathbb{Z}$ and $k[x]$ where k is a field that have a division algorithm; they are called **euclidean rings**.

Example 3.9. Let $R = \mathbb{Z}[x]$. The set of all polynomials with even constant term is an ideal in $\mathbb{Z}[x]$. We show that I is not a principal ideal.

Suppose there is $d(x) \in \mathbb{Z}[x]$ with $I = (d(x))$. The constant $2 \in I$, so that there is $f(x) \in \mathbb{Z}[x]$ with $2 = d(x)f(x)$. We have $0 = \deg(2) = \deg(d) + \deg(f)$. The candidates for $d(x)$ are ± 1 and ± 2. Suppose $d(x) = \pm 2$; since $x \in I$, there is $g(x) \in \mathbb{Z}[x]$ with $x = d(x)g(x) = \pm 2g(x)$. But every coefficients on the right side is even. This contradiction gives $d(x) = \pm 1$. Hence $I = \mathbb{Z}[x]$, another contradiction. Therefore I is not a principal ideal.

Definition 3.71. An element δ in a commutative ring R is a **greatest commmon divisor**, gcd, of elements $\alpha, \beta \in R$ if

1. δ is a common divisor of α and β
2. if γ is any common divisor of α and β, then $\gamma \mid \delta$

Remark. Let R be a PID and let $\pi, \alpha \in R$ with π irreducible. A gcd δ of π and α is a divisor of π. Hence $\pi = \delta\epsilon$. And irreducibility of π forces either δ or ϵ to be a unit. Now $\alpha = \delta\beta$. If δ is not a unit, then ϵ is a unit and so

$$\alpha = \delta\beta = \pi\epsilon^{-1}\beta$$

that is $\pi \mid \alpha$. We conclude that if $\pi \nmid \alpha$ then δ is a unit; that is 1 is a gcd of π and α

Theorem 3.72. *Let R be a PID*

1. *Every $\alpha, \beta \in R$ has a gcd, δ, which is a linear combination of α and β*

$$\delta = \sigma\alpha + \tau\beta$$

2. *If an irreducible element $\pi \in R$ divides a product $\alpha\beta$, then either $\pi \mid \alpha$ or $\pi \mid \beta$*

Proof. 1. We may assume that at least one of α and β is not zero. Consider the set I of all the linear combinations

$$I = \{\sigma\alpha + \tau\beta : \sigma, \tau \in R\}$$

I is an ideal and so there is $\delta \in I$ with $I = (\delta)$; we claim that δ is gcd of α and β

2. If $\pi \nmid \alpha$, then the remark says that 1 is a gcd of π and α. Thus $1 = \sigma\pi + \tau\alpha$ and so
$$\beta = \sigma\pi\beta + \tau\alpha\beta$$
Since $\pi \mid \alpha\beta$, it follows that $\pi \mid \beta$

□

Definition 3.73. If f and g are elements in a commutative ring R, then a **common multiple** is an element $m \in R$ with $f \mid m$ and $g \mid m$. If f and g in R are not both 0, define their **least common multiple**, abbreviated lcm.

Exercise 3.4.1.

1. If A and R are domains and $\varphi : A \to R$ is a ring homomorphism, prove that
$$[a, b] \to [\varphi(a), \varphi(b)]$$
is a ring homomorphism $\mathrm{Frac}(A) \to \mathrm{Frac}(B)$
2. Prove that if a field k contains an isomorphic copy of $\mathbb{Z}$ as a subring, then k must contain an isomorphic copy of $\mathbb{Q}$
3. Let R be a domain and let $\varphi : R \to k$ be an injective ring homomorphism, where k is a field. Prove that there exists a unique ring homomorphism $\Phi : \mathrm{Frac}(R) \to k$ extending φ ; that is, $\Phi|R = \varphi$

Proof.

1.
$$\begin{aligned} f([1,1]) &= [1,1] \\ f([a,b]+[c,d]) &= f([ad+bc, bd]) = [\varphi(ad+bc), \varphi(bd)] \\ &= [\varphi(a)\varphi(d) + \varphi(b)\varphi(c), \varphi(b)\varphi(d)] \\ &= [\varphi(a), \varphi(b)] + [\varphi(c), \varphi(d)] \\ &= f([a,b]) + f([c,d]) \\ f([a,b][c,d]) &= f([ac, bd]) = [\varphi(ac), \varphi(bd)] = [\varphi(a)\varphi(c), \varphi(b)\varphi(d)] \\ &= f([a,b])f([c,d]) \end{aligned}$$
2. Suppose $k' \leq k$ and $k' \cong \mathbb{Z}$, then $\mathrm{Frac}(k') \cong \mathrm{Frac}(\mathbb{Z})$. Obviously.
3. k is a field and has inverse.

□

3.5 Euclidean Rings

Definition 3.74. A **euclidean ring** is a domain that is equipped with a function

$$\partial : R - \{0\} \to \mathbb{N}$$

called a **degree function**, s.t.

1. $\partial(f) \leq \partial(fg)$ for all $f, g \in R$ with $f, g \neq 0$
2. for all $f, g \in R$ with $f \neq 0$, there exists $q, r \in R$ with

$$g = qf + r$$

where either $r = 0$ or $\partial(r) < \partial(f)$

Example 3.10.

1. The integers $\mathbb{Z}$ is a euclidean ring with the degree function $\partial(m) = |m|$. In $\mathbb{Z}$ we have

$$\partial(mn) = |mn| = |m||n| = \partial(m)\partial(n)$$

2. when k is a field, the domain $k[x]$ is a euclidean ring with degree function the usual degree of a nonzero polynomial. In $k[x]$, we have

$$\partial(fg) = \deg(fg) = \deg(f) + \deg(g) = \partial(f) + \partial(g)$$

If a degree function is multiplicative, then ∂ is called a **norm**

3. The Gaussian integers $\mathbb{Z}[i]$ form a euclidean ring whose degree function

$$\partial(a + bi) = a^2 + b^2$$

is a norm. One reason to show that $\mathbb{Z}[i]$ is a euclidean ring is that it is a PID, and hence it has unique factorization of its elements of into products of irreducibles.

∂ is a multiplicative degree function for

$$\partial(\alpha\beta) = \alpha\beta\overline{\alpha\beta} = \alpha\beta\overline{\alpha}\overline{\beta} = \alpha\overline{\alpha}\beta\overline{\beta} = \partial(\alpha)\partial(\beta)$$

Let us show that ∂ satisfies the second desired property. Given $\alpha, \beta \in \mathbb{Z}[i]$ with $\beta \neq 0$, regard α/β as an element of $\mathbb{C}$. Rationalizing the denominator gives $\alpha/\beta = \alpha\overline{\beta}/\beta\overline{\beta} = \alpha\overline{\beta}/\partial\beta$, so that

$$a/\beta = x + yi$$

where $x, y \in \mathbb{Q}$. Write $x = a + u$ and $y = b + v$, where $a, b \in \mathbb{Z}$are integers closest to x and y, respectively; thus $|u|, |v| \leq 1/2$. It follows that

$$\alpha = \beta(a + bi) + \beta(u + vi)$$

Notice that $\beta(u+vi) \in \mathbb{Z}[i]$. Finally we have

$$\partial(\beta(u+vi)) = \partial(\beta)\partial(u+vi) < \partial(\beta)$$

And so $\mathbb{Z}[i]$ is a euclidean ring whose degree function is a norm
Note that quotients and remainders are not unique because of the choice

Theorem 3.75. *Every euclidean ring R is a PID*

Proof. Let I be an ideal in R. If $I \neq \{0\}$, by the least integer axiom, the set of all degrees of nonzero elements in I has a smallest element, say n; choose $d \in I$ with $\partial(d) = n$. Clearly $(d) \subseteq I$. For any $a \in I$, then there are $q, r \in R$ with $a = qd + r$, where either $r = 0$ or $\partial(r) < \partial(a)$. But $r = a - qd \in I$ and so d having the least degree implies that $r = 0$. Hence $a = qd \in (d)$. □

Corollary 3.76. *The ring of Gaussian integers $\mathbb{Z}[i]$ is a PID*

Definition 3.77. An element u in a domain R is a **universal side divisor** if u is not a unit and for every $x \in R$, either $u \mid x$ or there is a unit $z \in R$ with $u \mid (x+z)$

Proposition 3.78. *If R is a euclidean ring but not a field, then R has a universal side divisor*

Proof. Define

$$S = \{\partial(v) : v \neq 0 \text{ and } v \text{ is not a unit}\}$$

where ∂ is the degree function on R. Since R is not a field, S is a nonempty subset of the natural number. By the least integer axiom, S has a smallest element, say, $\partial(u)$. We claim that u is a universal side divisor. If $x \in R$, then there are q, r with $x = qu + r$. □

Proposition 3.79.
1. *Let R be a euclidean ring R that is not a field. If the degree function ∂ is a norm, then α is a unit if and only if $\partial(\alpha) = 1$*
2. *Let R be a euclidean ring R that is not a field. If the degree function ∂ is a norm and if $\partial(a) = p$, where p is a prime, then α is not irreducible*
3. *The only units in the ring $\mathbb{Z}[i]$ of Gaussian integers are ± 1 and $\pm i$*

Proof.
1. Since $1^2 = 1$, we have $\partial(1)^2 = \partial(1)$, so that $\partial(1) = 0$ or $\partial(1) = 1$. If $\partial(1) = 0$, then $\partial(a) = \partial(1a) = 0$. But R is not a field, and so ∂ is not identically zero. We conclude that $\partial(1) = 1$
   If $a \in R$ is a unit, then there is $\beta \in R$ with $\alpha\beta = 1$. Therefore $\partial(\alpha)\partial(\beta) = 1$ and hence $\partial(\alpha) = 1$

For the converse, we begin by showing that there is no element $\beta \in R$ with $\partial(\beta) = 0$. If such an element exists, the division algorithms gives $1 = q\beta + r$ and so $\partial(r) = 0$. That is β is a unit, then $\partial(\beta) = 1$, a contradiction

Assume now that $\partial(\alpha) = 1$. The division algorithm gives

$$\alpha = q\alpha^2 + r$$

As $\partial(\alpha^2) = \partial(\alpha)^2 = 1$, $r = 0$ or $\partial(r) = 0$, which would not occur. Hence $r = 0$ and $\alpha = q\alpha^2$. It follows that $1 = q\alpha$, and so α is a unit

2. If on the contrary, $\alpha = \beta\gamma$, where neither β or γ is a unit, then $p = \partial(\alpha) = \partial(\beta)\partial(\gamma)$.
3. If $\alpha = a + bi \in \mathbb{Z}[i]$ is a unit, then $1 = \partial(\alpha) = a^2 + b^2$.

□

Lemma 3.80. *If p is a prime and $p \equiv 1 \mod 4$, then there is an integer m with*

$$m^2 \equiv -1 \mod p$$

Proof. If $G = (\mathbb{I}_p)^\times$ is the multiplicative group of nonzero elements in $\mathbb{I}_p$, then $|G| = p - 1 \equiv 0 \mod 4$. By Proposition 2.72, G contains a subgroup S of order 4. By Exercise 2.3.1 either S is cyclic or $a^2 = 1$ for all $a \in S$. Since $\mathbb{I}_p$ is a field, however, it cannot contain four roots of the quadratic $x^2 - 1$. Therefore, S is cyclic, say $S = \langle [m] \rangle$ where $[m]$ is the congruence class of m mod p. Since $[m]$ has order 4, we have $[m^4] = [1], [m^2] \neq 1$, and so $[m^2] = [-1]$ for $[-1]$ is the unique element in S of order 2. Therefore, $m^2 \equiv -1 \mod p$ □

Theorem 3.81 (Fermat's Two-Squares Theorem)**.** *An odd prime p is a sum of two squares,*

$$p = a^2 + b^2$$

where a and b are integers if and only if $p \equiv 1 \mod 4$

Proof. Assume that $p = a^2 + b^2$. Since p is odd, a and b have different parity; say, a is even and b is odd. Hence $a = 2m$ and $b = 2n + 1$ and

$$p = a^2 + b^2 = 4m^2 + 4n^2 + 4n + 1 \equiv 1 \mod 4$$

Conversely, assume that $p \equiv 1 \mod 4$. By the lemma, there is an integer m s.t.

$$p \mid (m^2 + 1)$$

In $\mathbb{Z}[i]$, there is a factorization $m^2 + 1 = (m + i)(m - i)$ and so

$$p \mid (m + i)(m - i) \text{ in } \mathbb{Z}[i]$$

If $p \mid (m \pm i)$ in $\mathbb{Z}[i]$, then there are integers u and v with $m \pm i = p(u + iv)$. Comparing the imaginary parts gives $pv = 1$, a contradiction. We conclude that p does not satisfy the analog of Euclid's lemma in Theorem 3.72; it follows from Exercise 3.5.1 that p is not irreducible. Hence there is a factorization

$$p = \alpha\beta \in \mathbb{Z}[i]$$

Therefore, taking norms gives an equation in $\mathbb{Z}$

$$\begin{aligned} p^2 &= \partial(p) = \partial(\alpha\beta) \\ &= \partial(\alpha)\partial(\beta) = (a^2 + b^2)(c^2 + d^2) \end{aligned}$$

By Proposition 3.79, the only units in $\mathbb{Z}[i]$ are ± 1 and $\pm i$, so that any nonzero Gaussian integers that is not a unit has a norm > 1; therefore $a^2 + b^2 \neq 1$ and $c^2 + d^2 \neq 1$. Euclid's lemma now gives $p \mid a^2 + b^2$ or $p \mid c^2 + d^2$; then fundamental theorem of arithmetic gives $p = a^2 + b^2$. $\square$

Lemma 3.82. *If $\alpha \in \mathbb{Z}[i]$ is irreducible, then there is a unique prime number p with $a \mid p$ in $\mathbb{Z}[i]$*

Proof. Since $\partial(\alpha) = \alpha\overline{\alpha}$, we have $\alpha \mid \partial(\alpha)$. Now $\partial(\alpha) = p_1 \dots p_n$. If $\alpha \mid q$ for some prime $q \neq p_i$, then $\alpha \mid (q, p_i) = 1$, forcing α to be unit. A contradiction $\square$

Proposition 3.83. *Let $\alpha = a + bi \in \mathbb{Z}[i]$ be neither 0 nor a unit. Then α is irreducible if and only if*

1. *α is an associate of a prime p in $\mathbb{Z}$ of the form $p = 4m + 3$; or*
2. *α is an associate of $1 + i$ or its conjugate; or*
3. *$\partial(\alpha) = a^2 + b^2$ is a prime in $\mathbb{Z}$ of the form $4m + 1$*

Proof. By Lemma 3.82 there is a unique prime number p divides by α in $\mathbb{Z}[i]$. Since $\alpha \mid p$, we have $\partial(\alpha) \mid \partial(p) = p^2$ in $\mathbb{Z}$, so that $\partial(\alpha) = p$ or $\partial(\alpha) = p^2$.

1. $p \equiv 3 \mod 4$
   By Theorem 3.81 $p^2 = a^2 + b^2$. We have $\alpha\beta = p$ and $\partial(\alpha)\partial(\beta) = \partial(p)$. Therefore, $p^2\partial(\beta) = p^2$ and $\partial(\beta) = 1$. Thus β is a unit by Proposition 3.79 and p is irreducible.
2. $p \equiv 2 \mod 4$
   $a^2 + b^2 = 2$

3. $p \equiv 1 \mod 4$ If $\partial(\alpha) = p^2$, β is a unit as case 1. Now $\alpha\overline{\alpha} = p^2 = (\alpha\beta)^2$, so that $\overline{\alpha} = \alpha\beta^2$ but $\beta^2 = \pm 1$ by Proposition 3.79

□

Exercise 3.5.1. If R is a euclidean ring and $\pi \in R$ is irreducible, prove that $\pi \mid \alpha\beta$ implies $\pi \mid \alpha$ or $\pi \mid \beta$

Proof. R is PID and follow Theorem 3.72. □

3.6 Linear Algebra

Vector Spaces

Definition 3.84. If k is a field, then a **vector space over** k is an (additive) abelian group V equipped with a **scalar multiplication**; there is a function $k \times V \to V$, denoted by $(a, v) \mapsto av$ s.t. for all $a, b, 1 \in k$ and all $u, v \in V$

1. $a(u + v) = au + av$
2. $(a + b)v = av + bv$
3. $(abv) = a(bv)$
4. $1v = v$

The elements of V are called **vectors** and the elements of k are called **scalars**

Example 3.11. 1. Euclidean space $V = \mathbb{R}^n$ is a vector space over $\mathbb{R}$

2. If R is a commutative ring and k is a subring that is a field, then R is a vector space over k
   For example, if k is a field, then the polynomial ring $R = k[x]$ is a vector space over k.

Definition 3.85. If V is a vector space over a field k, then a **subspace** of V is a subset U of V s.t.

1. $0 \in U$
2. $u, u' \in U$ imply $u + u' \in U$
3. $u \in U$ and $a \in k$ imply $au \in U$

Definition 3.86. Let V be a vector space over a field k. A k**-linear combination** of a list $v_1, \dots, v_n$ in V is a vector of v of the form

$$v = a_1 v_1 + \cdots + a_n v_n$$

where $a_i \in k$ for all i

Definition 3.87. If $X = v_1, \ldots, v_m$ is a list in a vector space V, then

$$\langle v_1, \ldots, v_m \rangle$$

the set of all the k-linear combinations of $v_1, \ldots, v_m$ is called the **subspace spanned by** X. We also say that $v_1, \ldots, v_m$ **spans** $\langle v_1, \ldots, v_m \rangle$

Lemma 3.88. *Let V be a vector space over a field k*

1. *Every intersection of subspaces of V is itself a subspace*
2. *If $X = v_1, \ldots, v_m$ is a list in V, then the intersection of all the subspaces of V containing X is $\langle v_1, \ldots, v_m \rangle$, and so $\langle v_1, \ldots, v_m \rangle$ is the* ***smallest subspace***

Example 3.12. Let $V = \mathbb{R}^2$, let $e_1 = (1, 0)$ and let $e_2 = (0, 1)$. then $V = \langle e_1, e_2 \rangle$

Definition 3.89. A vector space V is called **finite-dimensional** if it is spanned by a finite list; otherwise V is called **infinite-dimensional**

Notation. If $v_1, \ldots, v_m$ is a list, then $v_1, \ldots, \widehat{v_i}, \ldots, v_m$ is the shorter list with v_i deleted

Proposition 3.90. *If V is a vector space, then the following conditions on a list $X = v_1, \ldots, v_m$ spanning V are equivalent*

1. *X is not a shortest spanning list*
2. *some v_i is in the subspace spanned by the others; that is*

$$v_i \in \langle v_1, \ldots, \widehat{v_i}, \ldots, v_m \rangle$$

3. *there are scalars $a_1, \ldots, a_m$ not all zero with*

$$\sum_{l=1}^{m} a_l v_l = 0$$

Definition 3.91. A list $X = v_1, \ldots, v_m$ in a vector space V is **linearly dependent** if there are scalars $a_1, \ldots, a_m$ not all zero, with $\sum_{l=1}^{m} a_l v_l = 0$; otherwise X is called **linearly independent**

Corollary 3.92. *If $X = v_1, \ldots, v_m$ is a list spanning a vector space V, then X is a shortest spanning list if and only if X is linearly independent*

Definition 3.93. A **basis** of a vector space V is a linearly independent list that spans V

Proposition 3.94. *Let $X = v_1, \dots, v_n$ be a list in a vector space V over a field k. Then X is a basis if and only if each vector in V has a unique expression as a k-linear combination of vectors in X*

Proof. If a vector $v = \sum a_i v_i = \sum b_i v_i$, then $\sum (a_i - b_i) = 0$ □

Definition 3.95. If $X = v_1, \dots, v_n$ is a basis of a vector space V and if $v \in V$, then there are unique scalars $a_1, \dots, a_n$ with $v = \sum_{i=1}^{n} a_i v_i$. The n-tuple $(a_1, \dots, a_n)$ is called the **coordinate set** of a vector $v \in V$ relative to the basis X

Theorem 3.96. *Every finite-dimensional vector space V has a basis*

Proof. A finite spanning list X exists, since V is finite-dimensional. If it is linearly independent, it is a basis; if not, X can be shortened to a spanning list X' by Proposition 3.90 □

Lemma 3.97. *Let $u_1, \dots, u_n$ be elements in a vector space V, and let $v_1, \dots, v_m \in \langle u_1, \dots, u_n \rangle$. If $m > n$, then $v_1, \dots, v_m$ is a linearly dependent list*

Proof. Induction on $n \geq 1$

Base step. If $n = 1$

Inductive step. For $i = 1, \dots, m$

$$v_i = a_{i1} u_1 + \cdots + a_{in} u_n$$

We may assume that some $a_{i1} \neq 0$ otherwise $v_1, \dots, v_m \in \langle u_2, \dots, u_n \rangle$, and the inductive hypothesis applies. Changing notation if necessary we may assume $a_{11} \neq 0$. For each $i \geq 2$, define

$$v_i' = v_i - a_{i1} a_{11}^{-1} v_1 \in \langle u_2, \dots, u_n \rangle$$

Since $m - 1 > n - 1$ □

Corollary 3.98. *A homogeneous system of linear equations, over a field k, with more unknowns than equations has a nontrivial solution.*

Proof. An n-tuple $(\beta_1, \dots, \beta_n)$ is a solution of a system

$$\begin{gathered} \alpha_{11} x_1 + \cdots + \alpha_{1n} x_n = 0 \\ \vdots \quad \vdots \quad \vdots \\ \alpha_{m1} x_1 + \cdots + \alpha_{mn} x_n = 0 \end{gathered}$$

if $\alpha_{i1}\beta_1 + \cdots + \alpha_{in}\beta_n = 0$ for all i. In other words, if $c_1, \ldots, c_n$ are the columns of the $m \times n$ coefficient matrix $A = [\alpha_{ij}]$, then

$$\beta_1 c_1 + \cdots + \beta_n c_n = 0$$

Note that $c_i \in k^m$. Now k^m can be spanned by m vectors. Since $n > m$, $c_1, \ldots, c_n$ is linearly dependent □

Theorem 3.99 (Invariance of Dimension). *If $X = x_1, \ldots, x_n$ and $Y = y_1, \ldots, y_m$ are bases of a vector space V, then $m = n$*

Proof. Otherwise $n < m$ or $m < n$ □

Definition 3.100. If V is a finite-dimensional vector space over a field k, then its **dimension** denoted by $\dim_k(V)$ or $\dim(V)$, is the number of elements in a basis of V

Example 3.13. Let $X = \{x_1, \ldots, x_n\}$ be a finite set. Define

$$k^X = \{\text{functions } f : X \to k\}$$

Now k^X is a vector space if we define addition

$$f + f' : x \mapsto f(x) + f'(x)$$

and scalar multiplication for $a \in k$

$$af : x \mapsto af(x)$$

It's easy to check that the set of n functions of the form f_x, where $x \in X$ defined by

$$f_x(y) = \begin{cases} 1 & \text{if } y = x \\ 0 \end{cases}$$

form a basis.

An n-tuple $(a_1, \ldots, a_n)$ is really a function $f : \{1, \ldots, n\} \to k$ with $f(i) = a_i$

Lemma 3.101. *If $X = v_1, \ldots, v_n$ is a linearly dependent list of vectors in a vector space V, then there exists v_r with $r \geq 1$ with $v_r \in \langle v_1, \ldots, v_{r-1} \rangle$*

Lemma 3.102 (Exchange Lemma). *If $X = x_1, \ldots, x_m$ is a basis of a vector space V and $y_1, \ldots, y_n$ is a linearly independent subset of V, then $n \leq m$*

Proof. We begin by showing that one of the x's in X can be replaced by y_n so that the new list still spans V. Now $y_n \in \langle X \rangle$, so that the list

$$y_n, x_1, \dots, x_m$$

is linearly dependent. By Lemma 3.101 there is some i with $x_i = ay_n + \sum_{j<i} a_j x_j$. Throwing out x_i and replacing it by y_n gives a spanning list

$$X' = y_n, x_1, \dots, \widehat{x_i}, \dots, x_m$$

Now repeat this argument for the spanning list $y_{n-1}, y_n, x_1, \dots, \widehat{x_i}, \dots, x_m$. It follows that the disposable vector must be one of the remaining x's, say x_l. After throwing out x_l, we have a new spanning list X''. If $n > m$, then this procedure ends with a spanning list consisting of m y's and no x'. Thus a proper sublist of $Y = y_1, \dots, y_n$ spans V, a contradiction $\square$

Theorem 3.103 (Invariance of Dimension)**.** *If $X = x_1, \dots, x_n$ and $Y = y_1, \dots, y_m$ are bases of a vector space V, then $m = n$*

Proof. By Lemma 3.102, $n \leq m$ and $m \leq n$ $\square$

Definition 3.104. A **longest** (or a **maximal**) linearly independent list $u_1, \dots, u_m$ is a linearly independent list for which there is no vector $v \in V$ s.t. $u_1, \dots, u_m, v$ is linearly independent

Lemma 3.105. *If V is a finite-dimensional vector space, then a longest linearly independent list $v_1, \dots, v_n$ is a basis of V*

Proposition 3.106. *Let $Z = u_1, \dots, u_m$ be a linearly independent list in an n-dimensional vector space V. Then Z can be extended to a basis*

Corollary 3.107. *If $\dim(V) = n$, then any list of $n+1$ or more vectors is linearly dependent*

Corollary 3.108. *Let V be a vector space with $\dim(V) = n$*

1. *A list of n vectors that spans V must be linearly independent*
2. *Any linearly independent list of n vectors must span V*

Corollary 3.109. *Let U be a subspace of a vector space V of dimension n*

1. *U is finite-dimensional and $\dim(U) \leq \dim(V)$*
2. *If $\dim(U) = \dim(V)$, then $U = V$*

Linear Tranformations

Definition 3.110. If V and W are vector spaces over a field k, then a function $T : V \to W$ is a **linear transformation** if for all vectors $u, v \in V$, and all scalars $a \in k$

1. $T(u + v) = T(u) + T(v)$
2. $T(av) = aT(v)$

We say that a linear transformation T is **nonsingular** (or is an **isomorphism**) if T is a bijection.

Example 3.14.
1. If θ is an angle, then the rotation about the origin by θ is a linear transformation $R_\theta : \mathbb{R}^2 \to \mathbb{R}^2$
2. If V and W are vector spaces over a field k, write $\mathrm{Hom}_k(V, W)$ for the set of all linear transformations $V \to W$. It's a vector space

Definition 3.111. If V is a vector space over a field k, then the **general linear group**, denoted by $\mathrm{GL}(V)$, is the set of all nonsingular linear transformations $V \to V$

A composite ST of linear transformation S and T is again a linear transformation

Theorem 3.112. *Let $v_1, \dots, v_n$ be a basis of a vector space V over a field k. If W is a vector space over k and $u_1, \dots, u_n$ is a list in W, then there exists a unique linear transformation $T : V \to W$ with $T(v_i) = u_i$ for all i*

Proof. Each $v \in V$ has a unique expression of the form $v = \sum_i a_i v_i$ and so $T : V \to W$ given by $T(v) = \sum a_i u_i$ is a well-defined function

To prove the uniqueness of T, assume that $S : V \to W$ is a linear transformation with

$$S(v_i) = u_i = T(v_i)$$

Then

$$\begin{aligned} S(v) = S(\sum a_i v_i) &= \sum S(a_i v_i) \\ &= \sum a_i S(v_i) = \sum a_i T(v_i) = T(v) \end{aligned}$$

□

Corollary 3.113. *If two linear transformations $S, T : V \to W$ agree on a basis, then $S = T$*

Proposition 3.114. *If $T : k^n \to k^m$ is a linear transformation, then there exists an $m \times n$ matrix A s.t.*

$$T(y) = Ay$$

for all $y \in k^n$ (here y is an $n \times 1$ column matrix)

Proof. If $e_1, \ldots, e_n$ is the standard basis of k^n and $e'_1, \ldots, e'_m$ is the standard basis of k^m, define $A = [a_{ij}]$ to be the matrix whose jth column is the coordinate set of $T(e_j)$. If $S : k^n \to k^m$ is defined by $S(y) = Ay$, then $S = T$ since they agree on a basis: $T(e_j) = \sum_i a_{ij}e'_i = Ae_j$ □

Definition 3.115. Let $X = v_1, \ldots, v_n$ be a basis of V and let $Y = w_1, \ldots, w_m$ be a basis of W. If $T : V \to W$ is a linear transformation, then the **matrix of** T is the $m \times n$ matrix $A = [a_{ij}]$, whose jth column $a_{1j}, a_{2j}, \ldots, a_{mj}$ is the coordinate set of $T(v_j)$ determined by w's: $T(v_j) = \sum_{i=1}^{m} a_{ij}w_j$. The matrix A does depend on the choice of bases X and Y: we will write

$$A = {}_Y[T]_X$$

In case $V = W$, we often let the basis $X = v_1, \ldots, v_n$ and $w_1, \ldots, w_m$ coincide. If $1_V : V \to V$, given by $v \mapsto v$ is the identity linear transformation, then ${}_X[1_V]_X$ is the $n \times n$ **identity matrix** I_n, defined by

$$I = [\delta_{ij}]$$

where δ_{ij} is the Kronecker delta. A matrix is **nonsingular** if it has inverse.

Example 3.15. Let $T : V \to W$ be a linear transformation, and let $X = v_1, \ldots, v_n$ and $Y = w_1, \ldots, w_n$ be bases of V and W ,respectively. The matrix for T is set up from the equation

$$T(v_j) = a_{1j}w_1 + \cdots + a_{mj}w_m$$

Example 3.16. 1. Let $T : \mathbb{R}^2 \to \mathbb{R}^2$ be rotation by 90°. The matrix of T related to the standard basis $X = (1, 0), (0, 1)$ is

$$ {}_X[T]_X = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} $$

However if $Y = (0, 1)(1, 0)$, then

$$ {}_Y[T]_Y = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} $$

2. Let k be a field, let $T : V \to V$ be a linear transformation on a two-dimensional vector space, and assume that there is some vector $v \in V$ with $T(v)$ not a scalar multiple of v. The assumption on v says that the list $X = v, T(v)$ is linearly independent, and hence it's a basis of V. Write $v_1 = v, v_2 = Tv$.
   We compute ${}_X[T]_X$

$$T(v_1) = v_2 \quad \text{and} \quad T(v_2) = av_1 + bv_2$$

   for some $a, b \in k$. We conclude that

$${}_X[T]_X = \begin{bmatrix} 0 & a \\ 1 & b \end{bmatrix}$$

Proposition 3.116. *Let V and W be a vector spaces over a field k, and let $X = v_1, \ldots, v_n$ and $Y = w_1, \ldots, w_m$ be bases of V and W, respectively. If $\mathrm{Hom}_k(V, W)$ denotes the set of all linear transformations $T : V \to W$ and $\mathrm{Mat}_{m \times n}\, k$ denotes the set of all $m \times n$ matrices with entries in k, then the function $T \mapsto {}_Y[T]_X$ is a bijection $\mathrm{Hom}_k(V, W) \to \mathrm{Mat}_{m \times n}(k)$*

Proof. Given a matrix A, its columns define vectors in W; in more detail, if the jth column of A is $a_{1j}, \ldots, a_{mj}$, define $z_j = \sum_{i=1}^{m} a_{ij} w_i$. By Theorem 3.112, there exists a linear transformation $T : V \to W$ with $T(v_j) = z_j$ and ${}_Y[T]_X = A$. □

Proposition 3.117. *Let $T : V \to W$ and $S : W \to U$ be linear transformations. Choose bases $X = x_1, \ldots, x_n$ of V, $Y = y_1, \ldots, y_m$ of W, and $Z = z_1, \ldots, z_l$ of U, then*

$${}_Z[S \circ T]_X = ({}_Z[S]_Y)({}_Y[T]_X)$$

Proof. Let ${}_Y[T]_X = [a_{ij}]$, so that $T(x_j) = \sum_p a_{pj} y_p$, and let ${}_Z[S]_Y = [b_{qp}]$, so that $S(y_p) = \sum_q b_{qp} z_q$. Then

$$\begin{aligned} ST(x_j) = S(T(x_j)) &= S(\sum_p a_{pj} y_p) \\ &= \sum_p a_{pj} S(y_p) = \sum_p \sum_q a_{pj} b_{qp} z_q = \sum_q c_{qj} z_q \end{aligned}$$

where $c_{qj} = \sum_p b_{qp} a_{pj}$. Therefore

$${}_Z[ST]_X = [c_{qj}] = {}_Z[S]_Y {}_Y[T]_X$$

□

Corollary 3.118. *Matrix multiplication is associative*

Proof. Let A be an $m \times n$ matrix, let B be an $n \times p$ matrix, and let C be a $p \times q$ matrix. By Theorem 3.112, there are linear transformations

$$k^q \xrightarrow{T} k^p \xrightarrow{S} k^n \xrightarrow{R} k^m$$

with $C = [T], B = [S], A = [R]$

Then

$$[R \circ (S \circ T)] = [R][S \circ T] = [R]([S][T]) = A(BC)$$

On the other hand

$$[(R \circ S) \circ T] = [R \circ S][T] = ([R][S])[T] = (AB)C$$

□

Corollary 3.119. *Let $T : V \to W$ be a linear transformation of vector space V over a field k, and let X and Y be bases of V and W, respectively. If T is nonsingular, then the matrix of T^{-1} is the inverse of the matrix of T*

$$_X[T^{-1}]_Y = (_Y[T]_X)^{-1}$$

Proof. $I = {_Y[1_W]_Y} = {_Y[T]_X}{_X[T^{-1}]_Y}$ and $I = {_X[1_V]_X} = {_X[T^{-1}]_Y}{_Y[T]_X}$ □

Corollary 3.120. *Let $T : V \to V$ be a linear transformation on a vector space V over a field k. If X and Y are bases of V, then there is a nonsingular matrix P with entries in k so that*

$$_Y[T]_Y = P(_X[T]_X)P^{-1}$$

Conversely, if $B = PAP^{-1}$, where B, A, P are $n \times n$ matrices with entries in k and P is nonsingular, then there is a linear transformation $T : k^n \to k^n$ and bases X and Y of k^n s.t. $B =_Y [T]_Y, A =_X [T]_X$

Proof. The first statement follows from Proposition 3.117 and associativity

$$_Y[T]_Y =_Y [1_V T 1_V]_Y = (_Y[1_V]_X)(_X[T]_X)(_X[1_V]_Y)$$

Set $P =_Y [1_V]_X$

For the converse, let $E = e_1, \ldots, e_n$ be the standard basis of k^n, and define $T : k^n \to k^n$ be $T(e_j) = Ae_j$. If follows that $A =_E [T]_E$. Now define a basis $Y = y_1, \dots, y_n$ by $y_j = P^{-1}e_j$. Y is a basis because P^{-1} is nonsingular. It suffices to prove that $B =_Y [T]_Y$; that is $T(y_j) = \sum_i b_{ij}y_i$, where $B = [b_{ij}]$

$$\begin{aligned} T(y_j) &= Ay_y = AP^{-1}e_j = P^{-1}Be_j \\ &= P^{-1}\sum_i b_{ij}e_i = \sum_i b_{ij}P^{-1}e_i \\ &= \sum_i b_{ij}y_i \end{aligned}$$

□

Definition 3.121. Two $n \times n$ matrices B and A with entries in field k are **similar** if there is a nonsingular matrix P with entries in k with $B = PAP^{-1}$

Corollary 3.120 says the two matrices arise from the same linear transformation on a vector space V if and only if they are similar

Definition 3.122. If $T : V \to W$ is a linear transformation, then the **kernel** (or the **null space**) of T is

$$\ker T = \{v \in V : T(v) = 0\}$$

and the **image** of T is

$$\operatorname{im} T = \{w \in W : w = T(v) \text{ for some } v \in V\}$$

Proposition 3.123. *Let $T : V \to W$ be a linear transformation*

1. $\ker T$ *is a subspace of V and* $\operatorname{im} T$ *is a subspace of W*
2. *T is injective if and only if* $\ker T = \{0\}$

Lemma 3.124. *Let $T : V \to W$ be a linear transformation*

1. *If T is nonsingular, then for every basis $X = v_1, \dots, v_n$ of V, we have $T(X) = T(v_1), \dots, T(v_n)$ a basis of W*
2. *Conversely, if there exists some basis $X = v_1, \dots, v_n$ of V for which $T(X)$ is a basis of W, then T is nonsingular*

Proof. 1. If $\sum c_i T(v_i) = 0$, then $T(\sum c_i v_i) = 0$ and so $\sum c_i v_i \in \ker T = \{0\}$. Hence each $c_i = 0$ because X is linearly independent. If $w \in W$, then the surjectivity of T provides $v \in V$ with $w = T(v)$. But $v = \sum a_i v_i$, and so $w = T(v) = T(\sum a_i v_i) = \sum a_i T(v_i)$. Therefore $T(X)$ is a basis of W

2. Let $w \in W$. Since $T(X)$ is a basis of W, we have $w = \sum c_i T(v_i) = T(\sum c_i v_i)$. Add so T is surjective. If $\sum c_i v_i \in \ker T$, then $\sum c_i T(v_i) = 0$ and so linear independence gives all $c_i = 0$; hence $\ker T = \{0\}$. Therefore T is nonsingular

$\square$

Theorem 3.125. *If V is an n-dimensional vector space over a field k, then V is isomorphic to k^n*

Proof. Choose a basis $v_1, \ldots, v_n$ of V. If $e_1, \ldots, e_n$ is the standard basis of k^n, then Theorem 3.112 says that there is a linear transformation $T : V \to k^n$ with $T(v_i) = e_i$; by Lemma 3.124 T is nonsingular $\square$

Corollary 3.126. *Two finite-dimensional vector space V and W over a field k are isomorphic if and only if* $\dim(V) = \dim(W)$

Proposition 3.127. *Let V be a finite-dimensional vector space with* $\dim(V) = n$, *and let $T : V \to V$ be a linear transformation. The following statements are equivalent*

1. *T is an isomorphism*
2. *T is surjective*
3. *T is injective*

Proof. $2 \to 3$. Let $v_1, \ldots, v_n$ be the basis of V. Since T is surjective, there are vectors $u_1, \ldots, u_n$ with $Tu_i = v_i$. We claim that $u_1, \ldots, u_n$ are linearly independent. To show that T is injective, it suffices to show that $\ker T = \{0\}$

$3 \to 1$. Let $v_1, \ldots, v_n$ be a basis of V. If $c_1, \ldots, c_n$ are scalars not all 0, then $\sum c_i v_i \neq 0$. Since T is injective, it follows that $\sum c_i T(v_i) \neq 0$ and so $Tv_1, \ldots, Tv_n$ are linearly independent. Therefore Lemma 3.124 shows that T is an isomorphism $\square$

Corollary 3.128. *If A and B are $n \times n$ matrices with $AB = I$, then $BA = I$. Therefore A is nonsingular with inverse B*

Proof. There are linear transformations $T, S : k^n \to k^n$ with $[T] = A, [S] = B$, and $AB = I$ gives

$$[TS] = [T][S] = [1_{k^n}]$$

Since $T \mapsto [T]$ is a bijection, by Proposition 3.116, it follows that $TS = 1_{k^n}$. Hence T is a surjection and S is an injection by Proposition **??**.. But Proposition 3.127 says taht T, S are both isomorphism, so that $S = T^{-1}$ and $TS = 1_{k^n} = ST$ $\square$

Definition 3.129. The set of all nonsingular $n \times n$ matrices with entries in k is denoted by $\mathrm{GL}(n, k)$

It's easy to prove that $\mathrm{GL}(n, k)$ is a group

Proposition 3.130. *Let V be an n-dimensional vector space over a field k, and let $X = v_1, \ldots, v_n$ be a basis of V. Then $\mu : GL(V) \to GL(n, k)$ defined by $T \mapsto [T] = {}_X[T]_X$ is an isomorphism*

Proof. By Proposition 3.116 the function $\mu' : T \mapsto [T]$ is a bijection

$$\mathrm{Hom}_k(V, V) \to \mathrm{Mat}_n(k)$$

If $T \in \mathrm{GL}(V)$, then $[T]$ is a nonsingular matrix by Corollary 3.119; that is, if μ is the restriction of μ', then $\mu : \mathrm{GL}(V) \to \mathrm{GL}(n, k)$ is an injective homomorphism.

If $A \in \mathrm{GL}(n, k)$, then $A = [T]$ for some $T : V \to V$. It suffices to show that T is an isomorphism; that is, $T \in \mathrm{GL}(V)$. Since $[T]$ is a nonsingular matrix, there is a matrix B with $[T]B = I$. Now $B = [S]$ for some $S : V \to V$ and

$$[TS] = [T][S] = I = [1_V]$$

□

Definition 3.131. A linear transformation $T : V \to V$ is a **scalar transformation** if there is $c \in k$ with $T(v) = cv$ for all $v \in V$; that is $T = c1_V$. A **scalar matrix** is a matrix of the form cI

Corollary 3.132.
1. *The center of the group $GL(V)$ consists of all the nonsingular scalar transformations*
2. *The center of the group $GL(n, k)$ consists of all the nonsingular scalar matrices*

3.7 Quotient Rings and Finite Fields

Theorem 3.133. *If I is an ideal in a commutative ring R, then the additive abelian group R/I can be made into a commutative ring in such a way that the natural map $\pi : R \to R/I$ is a surjective ring homomorphism*

Proof. Define multiplication on the additive abelian group R/I by

$$(a + I)(b + I) = ab + I$$

□

Definition 3.134. The commutative ring R/I constructed in Theorem 3.133 is called the **quotient ring** of R modulo I

Corollary 3.135. *If I is an ideal in a commutative ring R, then there are a commutative ring A and a ring homomorphism $\pi : R \to A$ with $I = \ker \pi$*

Proof. Natural map $\pi : R \to R/I$ □

Theorem 3.136 (First Isomorphism Theorem)**.** *If $f : R \to A$ is a homomorphism of rings, then $\ker f$ is an ideal in R, $\operatorname{im} f$ is a subring of A, and*

$$R/\ker f \cong \operatorname{im} f$$

Definition 3.137. If k is a field, the intersection of all the subfields of k is called the **prime field** of k

Every subfield of $\mathbb{C}$ contains $\mathbb{Q}$ and so the prime field of $\mathbb{C}$ and of $\mathbb{R}$ is $\mathbb{Q}$.
Notation. From now on, we will denote $\mathbb{I}_p$ by $\mathbb{F}_p$ when we are regarding it as a field.

Proposition 3.138. *If k is a field, then its prime field is isomorphic to $\mathbb{Q}$ or to $\mathbb{F}_p$ for some prime p*

Proof. Consider the ring homomorphism $\chi : \mathbb{Z} \to k$ defined by $\chi(n) = n\epsilon$, where we denote the **one** in k by ϵ. Since every ideal in $\mathbb{Z}$ is principal, there is an integer m with $\ker \chi = (m)$. If $m = 0$, then χ is an injection, and so there is an isomorphism copy of $\mathbb{Z}$ taht is a subring of k. By Exercise 3.4.1 □

aef.

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