Course Notes

Introduction to Abstract Algebra

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BSM Fall 2018

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Chapter 0

A Brief Introduction

0.1 The group $\mathbb{Z}_m$

To construct $\mathbb{Z}_m$, we define $\mathbb{Z}_m = \mathbb{Z}/\sim$ where $a \sim b$ if $a \cong b \pmod{m}$. Since we have a division algorithm in $\mathbb{Z}$, for any $d \in \mathbb{Z}$, we can write $d = tm + r$ with $0 \le r \le m-1$. Thus $\overline{d} = \overline{r}$, so we can represent $\mathbb{Z}_m = \{\overline{0}, \overline{1}, \dots, \overline{m-1}\}$. As a result we usually do not bother writing $\overline{\cdot}$. To show that this is a group, we must show that its operations are well defined.

Prop. 0.1.1 *We have* $\overline{a} + \overline{b} = \overline{a+b}$ *and* $\overline{a} \cdot \overline{b} = \overline{ab}$.

Proof Obvious. □

Thm. 0.1.2 $\mathbb{Z}_m^\times = \{\overline{a} \mid \gcd(a,m) = 1\}$.

Proof Assume $\overline{a} \in \mathbb{Z}_m^\times$ so there exists $\overline{x}$ with $\overline{x} \cdot \overline{a} = 1$. Then $\overline{xa} = \overline{1}$ so $xa \cong 1 \pmod{m}$ so $m|xa-1$. Let $d = \gcd(a,m)$ so $d|a$ and $d|m$. Thus $d|xa-1$ and $d|xa$ so $d|1$ and $\gcd(a,m) = 1$.

Conversely, suppose $\gcd(a,m) = 1$. Then by Bézout's Lemma, get x, y so that $xa + ym = 1$, so $xa \cong 1 \pmod{1}$ and $\overline{xa} = \overline{1}$ and $\overline{xa} = \overline{1}$ and we have our multiplicative inverse. □

We thus have $|\mathbb{Z}_m^\times| = \phi(m)$.

Chapter 1

Fundamentals of Groups

1.1 Basics of Groups

Def'n. 1.1.1 *We say that* $(G,*)$ *with* $*: G \times G \to G$ *is a* ***group*** *if for all* $a,b,c \in G$

1. $(a*b)*c = a*(b*c)$
2. $\exists e \in G: \quad a*e = a = e*a$
3. $\exists u \in G: \quad a*u = e = u*a$

We have our first basic proposition:

Prop. 1.1.2 *The identity and inverses are unique.*

Proof If e,f are both identities, then $e = e*f = f$. If u,v are both inverses of x, then $u*(x*v) = u*e = u$ and $(u*x)*v = e*v = v$ so $u = v$. □

Def'n. 1.1.3 *If* $ab = ba$ *for all* $a,b \in G$ *then we say that* G *is* ***commutative*** *or* ***abelian***.

1.1.1 Order of an Element

One of the most basic properties of an element in a group is its order.

Def'n. 1.1.4 *The* ***order of an element*** $g \in G$ *is* $o(g) := \left|\{g^d | d \in \mathbb{Z}\}\right|$. *The* ***order of a group*** G *is* $|G|$.

We certainly have $o(g) \leq |G|$ for any $g \in G$. Equality holds when $o(g) = \infty$ and G is countable, or $G = \{g^d : d \in \mathbb{Z}\}$. The second case is an example of a cyclic group.

Def'n. 1.1.5 *A collection* $H = \{g_1, g_2, \ldots, g_k\}$ ***generates*** G *if we can write any* $g \in G$ *as a product of elements in* H.

Def'n. 1.1.6 *We say that* G *is* ***cyclic*** *if* $G = \{g^d : d \in \mathbb{Z}\}$ *for some* $g \in G$. *Equivalently, it is generated by a set of cardinality one.*

Note that cyclic groups are always abelian. We can also determine the order of powers of elements:

Lemma 1.1.7 *If $o(g)$ is finite and $d \in \mathbb{Z}$, then*

$$o(g^d) = \frac{o(g)}{\gcd(o(g),d)}$$

Proof Let $o(g) = K$ and $t = \gcd(K,d)$ and write $K = tK_1$ and $d = td_1$ with K_1, d_1 coprime. Thus $o(g^d)$ is the smallest positive integer l with $(g^d)^l = 1$. But then

$$\begin{aligned}(g^d)^l = 1 &\Leftrightarrow g^{dl} = 1 \Leftrightarrow o(g)|dl\\ &\Leftrightarrow K|dl \Leftrightarrow tK_1|td_1l\\ &\Leftrightarrow K_1|d_1l\end{aligned}$$

Since K_1 and d_1 are coprime, we must have $K_1|l$. Thus by minimality of l, we have $K_1 = l$ and $o(g^d) = K_1 = \frac{o(g)}{\gcd(o(g),d)}$ as desired. □

1.1.2 Group Morphisms

Def'n. 1.1.8 *Let G be a group with $G = \{g_1, g_2, \dots, g_n\}$. Then the **Cayley Table** for G is the matrix $M \in M_n(G)$ where $M_{ij} = g_ig_j$.*

Prop. 1.1.9 *In each column or row, each element occurs exactly once. Furthermore, if $M_{ij} = e$, then $M_{ji} = e$.*

Proof This follows by left or right cancellation, and by commutativity of the elements with their inverse. □

Def'n. 1.1.10 *Let $(G,*)$, $(H,\star)$ be groups. A mapping $f : G \to H$ is called an **homomorphism** if*

$$f(u * v) = f(u) \star f(v)$$

*If f is also a a bijection, then we call f an **isomorphism**. If $(G,*) = (H,\star)$, then we call f an **endomorphism**. If f is a bijective endomorphism, then f is an **automorphism**.*

Note that G and H are isomorphic if and only if their Cayley tables are the same up to permutation of elements. Given a group G, define $\mathrm{Aut}(G)$ as the set of all automorphisms of a group with composition as an operation.

Prop. 1.1.11 $\mathrm{Aut}(G)$ *is a group.*

Proof
1. By properties of functions, composition is associative.
2. Consider the map $1(x) = x$. This map is an automorphism since $1(x*y) = x*y = 1(x)*1(y)$, and it is the identity function.
3. For any f, since f is bijective, it has an inverse f^{-1}. Let $x, y \in G$; then $x = f(u)$ and $y = f(v)$ by surjectivity. Thus $f^{-1}(x * y) = f^{-1}(f(u) * f(v)) = f^{-1}(f(u * v)) = u * v = f^{-1}(x) * f^{-1}(y)$ since f is an automorphism. □

Prop. 1.1.12 *Let G be a cyclic group and H be an arbitrary group. Then G and H are isomorphic if and only if H is cyclic and $|H| = |G|$.*

Proof First suppose G and H are isomorphic via f. We certainly have $|H| = |G|$ since f is a bijection and preserves cardinality. Let g be a generator G; I claim that $f(g)$ is a generator for H. Write $G = \{g^n \mid n \in \mathbb{N}\}$, and for any $x \in G$, there exists some n so $g^n = x$. Then for any $y \in H$, there exists some n so that $y = f(g^n) = f(g)^n$ since f preserves the group structure.

Conversely, suppose H is a cyclic group and $|H| = |G|$. Let g be a generator for G and h be a generator for H. For any $x \in G$, there exists a minimal n so $x = g^n$; and define $f(x) = h^n$. Such an n must be unique by minimality. Let's see that f is well-defined and injective. Let $x, y \in G$ be arbitrary; by uniqueness

$$\begin{aligned} x = y &\Leftrightarrow x = y = g^n \\ &\Leftrightarrow f(x) = f(y) = h^n \end{aligned}$$

as required. As well, f is surjective: if $x = h^n$, then $x = f(g^n)$; thus f is a bijection. To see that f respects the group structure, let $g^u, g^v \in G$ be arbitrary. Then $f(g^u g^v) = f(g^{u+v}) = h^{u+v} = h^u h^v = f(g^u)f(g^v)$ as desired. □

1.2 Subgroups

Def'n. 1.2.1 *A subset H of a group G is called a* ***subgroup*** *if H is also a group with the same operation. We write $H \leq G$.*

For example, $(\mathbb{Z},+) \leq (\mathbb{Q},+) \leq (\mathbb{R},+) \leq (\mathbb{C},+)$. Note that associativity automatically holds since every element of H is an element of G. Furthermore, $1_H = 1_G$ since $1_H 1_G = 1_H = 1_H 1_H$ where the first equality holds since 1_G is an identity, and the second since 1_H is an identity. As a result, inverses in H are inverses in G.

1.2.1 Subgroup Tests

Prop. 1.2.2 (First Subgroup Test) *A subset H of a group G is a subgroup if and only if*

1. $H \neq \emptyset$
2. $x, y \in H \Rightarrow xy \in H$
3. $x \in H \Rightarrow x^{-1} \in H$

If G is finite, it suffices to verify (1) and (2).

Proof Associativity follows since elements of H are elements of G. Since $H \neq \emptyset$, $x \in H$, so $x^{-1} \in H$ and $1 = xx^{-1} \in H$, so H contains the identity (which, by uniqueness, is the identity in G). It is clearly closed under multiplication by (2), and contains inverses by (3). In the finite case, for any $x \in H$, there exists some n so $x^n = 1$ and $x^{n-1}x = xx^{n-1} = 1$, so $x^{-1} = x^{n-1}$ can be obtained by closure under multiplication. □

Prop. 1.2.3 (Second Subgroup Test) *A subset H of a group G is a subgroup*

1. $H \neq \emptyset$
2. $x, y \in H \Rightarrow xy^{-1} \in H$

That the first subgroup test implies the second is obvious. Coversely, the identity is in H since $xx^{-1} \in H$. Thus get closure under inversion by choosing x as the identity to get inverses. Then if $x, y \in H$, $x, y^{-1} \in H$ so $x(y^{-1})^{-1} = xy \in H$.

We have the following proposition. The proof is straightforward but it is a good illustration of the first subgroup test.

Prop. 1.2.4 *Arbitrary intersections of subgroups are also subgroups.*

Proof Let $\{H_i\}_{i\in I}$, $H_i \leq G$ be an arbitrary collection of subgroups of G, and define $H = \bigcap\limits_{i\in I} H_i$. We certainly have $1 \in H$, so $H \neq \emptyset$. If $x \in H$, then $x \in H_i$ for all i, so $x^{-1} \in H_i$ for all i, so $x^{-1} \in H$. If $x, y \in H$, then $x, y \in H_i$ for all i and $xy \in H_i$, so $xy \in H$. □

Thm. 1.2.5 *Any subgroup of a cyclic group is also cyclic.*

Proof Let $G = \langle g \rangle$ be a cyclic group, $H \leq G$. If $H = \{1\}$, then $H = \langle 1 \rangle$ is cyclic. Since G is cyclic, there exists some minimal $k \neq 0$ so that $g^k \in H$. We will see that $H = \langle g^k \rangle$. It is clear that $\langle g^k \rangle \subseteq H$; we show the reverse inclusion.

Let $x \in H$ so $x = g^d$ for some d. Then division with remainder yields $d = tk + r$ with $0 \leq r \leq k-1$ so that $g^d = g^{tk+r}$ and $x = (g^k)^t g^r$ so $g^r = x(g^k)^{-t} \in H$. Minimality of k forces $r = 0$, so $d = tk$, $x = g^d = (g^k)^t \in \langle g^k \rangle$. □

1.2.2 Cosets of Subgroups

Def'n. 1.2.6 *Let $H \leq G$, $g \in G$. Then the* ***right coset*** *of H by g is the set $Hg := \{hg : h \in H\}$. Similarly, the* ***left coset*** *of H by g is the set $gH := \{gh : h \in H\}$.*

We have the following theorem about cosets:

Thm. 1.2.7 *Let $H \leq G$. Then*

1. *$|Hg| = |H|$*
2. *$Hg = H \Leftrightarrow g \in H$*
3. *For any $x, y \in G$, either $Hx = Hy$ or $Hx \cap Hy = \emptyset$*
4. *$Hx = Hy \Leftrightarrow xy^{-1} \in H$*

Proof

1. The map $\cdot g : H \to Hg$ is bijective since it has an inverse.

2. This is a special case of (4) with $x = g$, $y = 1$.

3. Suppose $Hx \cap Hy \neq \emptyset$. Thus let $z \in Hx \cap Hy$ so we can write $z = h_1 x = h_2 y$. Then for any $hx \in Hx$, $hx = hh_1^{-1}h_1 x = hh_1^{-1}h_2 y \in Hy$ so $Hx \subseteq Hy$. The identical argument works in reverse, so equality holds.

4. Assume $Hx = Hy$, and let $x \in Hx$. Then $x \in Hy$ as well so $x = hy$ and $xy^{-1} = h \in H$. Conversely, suppose $xy^{-1} \in H$; then $xy^{-1}y \in Hy$ so $x \in Hy$. Also, $x \in Hx$ so $x \in Hx \cap Hy \neq \emptyset$ so by (3), $Hx = Hy$. □

Thus all the cosets of H have the same size as H, and cosets with different elements are disjoint. Therefore the following definition makes sense:

Def'n. 1.2.8 *The **index** of a subgroup H in a group G is denoted $[G:H]$ and denotes the number of distinct right cosets of H.*

Thus G is a disjoint union of $[G:H]$ right cosets of H, each of size $|H|$. Therefore we have

Cor. 1.2.9 $|G| = |G:H| \cdot |H|$

We also have the following theorem:

Prop. 1.2.10 *$Hx \mapsto x^{-1}H$ is a one-to-one correspondence between right cosets and left cosets.*

As an application of the previous results, we have the following theorem.

Thm. 1.2.11 (Lagrange) *Suppose G is a finite group. Then*

1. *For any $H \leq G$, $|H| \mid |G|$.*
2. *For any $g \in G$, $o(g) \| |G|$.*

Proof
1. This follows since $|G| = |G:H| \cdot |H|$ and $|G:H|$ is a positive integer.
2. $o(g) = |\langle g \rangle|$ and it follows by (1). □

1.3 Factor Groups

1.3.1 Normal Subgroups

Def'n. 1.3.1 *Let $H \leq G$. Then we say H is a **normal subgroup** of G and write HG if $Hx = xH$ for all $x \in G$.*

Def'n. 1.3.2 *The **normalizer** of a subgroup H in G is*

$$N_G(H) = \{x \in G : Hx = xH\} = \{x \in G : x^{-1}Hx = H\} \leq G$$

First note that $H \leq N_G(H)$. For any $x \in H$, $Hx = xH$ since H is a subgroup Here are some properties of normal subgroups and normalizers.

Prop. 1.3.3
1. *$H \leq N_G(H)$.*
2. *$N_G(H) = G$ iff H is normal.*

Proof
1. For any $x \in H$, $Hx = xH$ since H is a subgroup, so $H \subseteq N_G(H)$. Since they are both groups, we have $H \leq N_G(H)$.
2. This follows directly from the definition. □

We have the following characterization of normality for subgroups of G.

Prop. 1.3.4 *A subgroup H in G is normal if and only if*

1. *$Hx = xH$ for all $x \in G$.*

2. *$x^{-1}Hx = H$ for all $x \in G$.*
3. *$N_G(H) = G$.*
4. *For any $h \in H$, $x \in G$, $x^{-1}hx \in H$.*
5. *H is a union of some conjugacy classes.*

Proof We only see (4) $\Leftrightarrow$ (5). We have

$$\forall h \in H \forall x \in G x^{-1}hx \in H \Leftrightarrow \forall h \in H C_h \subseteq H$$

which means that all conjugacy classes are either disjoint from H, or in H. □

We will most commonly use condition (4) to check normality.

1.4 Group Actions

1.4.1 Center of a Group

Def'n. 1.4.1 *For any $g \in G$, define*

$$C_G(g) = \{x \in G : gx = xg\}$$

*the **centralizer** of g in G. Then define the **center** of a group G*

$$Z(G) = \bigcap_{g \in G} C_G(g) \leq G$$

Note that the center of a group is the set of elements which commute with everything in the group. These are indeed groups: We certainly have $1 \in C_G(g)$. Also, if $x, y \in G$, then $gx = xg$ and $gy = yg$ so that $gxy = xgy = xyg$. If $x \in C_G(g)$, then $gx = xg$ so $g = xgx^{-1}$ and $x^{-1}g = gx^{-1}$.

1.5 Conjugacy Classes

This definition inspires the following definition:

Def'n. 1.5.1 *We say that f is a **conjugate** of g if and only if there exists $x \in G$ such that $x^{-1}gx = f$.*

Denote the binary relation by $\sim$: we will show that this is an equivalence relation:
1. Reflexive: $g \sim g$ by $x = 1$
2. Symmetric: If $g \sim f$, then $x^{-1}gx = f$ so $g = xfx^{-1} = (x^{-1})^{-1}fx^{-1}$
3. Transitive: If $f \sim g$ and $g \sim h$, get x, y so $x^{-1}gx = f$ and $y^{-1}fy = h$ so

$$h = y^{-1}x^{-1}gxy = (xy)^{-1}g(xy)$$

Def'n. 1.5.2 *These equivalence classes are called the **conjugacy classes** of G.*

We denote the conjugacy class of $g \in G$ by $C_g = \{x^{-1}gx : x \in G\}$. Note that $|C_g| = 1$ if and only if $C_g = \{g\}$ if and only if $x^{-1}gx = g$ for any $x \in G$ if and only if $gx = xg$ and $g \in Z(G)$.

Thm. 1.5.3 *For any $g \in G$, $|C_g| \cdot |C_G(g)| = |G|$.*

Proof Consider $\alpha : \{\text{Right cosets of } D_G(g)\} \longrightarrow C_g$ defined by $C_G(g) \cdot x \mapsto x^{-1}gx$. This is well defined and injective:

$$\begin{aligned} C_G(g)x = C_G(g)y &\Leftrightarrow xy^{-1} \in C_G(g) \\ &\Leftrightarrow g(xy^{-1}) \\ &\Leftrightarrow (xy^{-1})g \end{aligned}$$

so it suffices to show the map is surjective. In fact, any element of C_g is of the form $x^{-1}gx = \alpha(C_G(g)x)$. Thus α is bijective, so $|G : C_G(x)| = |C_g|$ and

$$|G| = |G : C_G(g)| \cdot |C_G(g)| = |C_g| \cdot |C_G(g)|$$

□

Cor. 1.5.4 *If G is finite, $g \in G$, then $|C_g| \mid |G|$.*

We have the following nice application:

Thm. 1.5.5 *If $|G| = p^2$ for p prime, then G is commutative.*

Proof For any $g \in G$, $|C_g| \mid |G| = p^2$ so $|C_g|$ there are three cases. Note that $|C_g| = p^2$ is impossible, since $C_1 = \{1\}$ and the remainder has fewer elements. Thus let a denote the number of conjugacy classes of size 1 by a, and the number of conjugacy classes of size p by b. Since G is a disjoint union of conjugacy classes, we have $|G| = p^2 = a + bp$ so that $p|a$. Furthermore, $a \neq 0$ since $|C_1| = 1$, so $a \geq p$. Furthermore, $|C_g| = 1$ if and only if $g \in Z(G)$, so $a = |Z(G)| \geq p$. Since $Z(G) \leq G$, by Lagrance, $|Z(G)| \mid |G| = p^2$, so $|Z(G)| = p$ or $|Z(G)| = p^2$. If $|Z(G)| = p$, pick any $x \in G$ with $x \notin Z(G)$ and consider $C_G(x)$. Since $Z(G) \leq C_G(x)$, we must have $p + 1 \leq |C_G(x)|$ and $|C_G(x)| = p^2$ so $C_G(x) = G$ and $x \in Z(G)$, a contradiction. Thus $Z(G) = p^2$ and the group is commutative. □

Note that if $|G| = p$ prime, then G is cyclic. Since $o(g)||G| = p$, and $o(g) \neq 1$ if $g \neq 1$; we must have $o(g) = p$ and $\langle g \rangle = G$.

Now if $H \leq G$, then $x^{-1}Hx = \{x^{-1}hx : h \in H\} \leq G$, as can be verified.

Def'n. 1.5.6 *A subgroup K of G is **conjugate** to H in G if and only if there exists $x \in G$ with $x^{-1}Hx = K$. We write $H \sim K$, and the equivalence classes are called **conjugacy classes** of subgroups.*

Thm. 1.5.7
1. *Conjugate elements are of the same order.*
2. *Conjugate subgroups are isomorphic.*

Proof
1. We have

$$\begin{aligned} (x^{-1}gx)^k = 1 &\Leftrightarrow (x^{-1}gx)(x^{-1}gx)\cdots(x^{-1}gx) = 1 \\ &\Leftrightarrow x^{-1}g^K x = 1 \\ &\Leftrightarrow g^k x = x \\ &\Leftrightarrow g^k = 1 \end{aligned}$$

2. I claim that the map $\alpha : H \to x^{-1}Hx$ by $h \mapsto x^{-1}hx$ is an isomorphism. We have $\alpha(h_1h_2) = x^{-1}h_1h_2x = x^{-1}h)1xx^{-1}h_2x = \alpha(h_1)\alpha(h_2)$, and bijectivity can be verified easily. □

For any group G, we always have $C_{\{}1\} = \{\{1\}\}$ and $C_G = \{G\}$. A particularly nice type of conjugacy class are the ones with only 1 element. We have

$$|C_H| = 1 \Leftrightarrow C_H = \{H\} \Leftrightarrow x^{-1}Hx = H(\forall x \in G) \Leftrightarrow Hx = xH(\forall x \in G)$$

Def'n. 1.5.8 *A subgroup H which satisfies $Hx = xH$ for all $x \in G$ is called a **normal** subgroup. We say $H \triangleleft G$.*

Def'n. 1.5.9 *The **centralizer** of a subgroup H in G is*

$$C_G(H) = \{x \in G : hx = xh(\forall h \in H)\} = \bigcap_{h \in H} C_G(h) \leq G$$

Note that intersections of subgroups are subgroups.

Def'n. 1.5.10 *The **normalizer** of a subgroup H in G is*

$$N_G(H) = \{x \in G : Hx = xH\} = \{x \in G : x^{-1}Hx = H\} \leq G$$

It is easy to verify this is a subgroup. We thus have $H \triangleleft G$ if and only if $N_G(H) = G$. We have some properties:

Ex. 1.5.11 For example, fix $G = GL_n(\mathbb{R})$, so $SL_n(\mathbb{R}) = \{A \in M_n(\mathbb{R}) : \det(A) = 1\}$. This is indeed a subgroup: let's also verify that it is a normal subgroup. Also, if $h \in SL_n(\mathbb{R})$ and $x \in GL_n(\mathbb{R})$, then $\det(x^{-1}hx) = \det(x^{-1})\det(h)\det(x) = \det(h) = 1$ so $x^{-1}hx \in SL_n(\mathbb{R})$.

Why are normal subgroups nice? If $H \triangleleft G$, and $x, y \in G$, then $(Hx)(Hy) = Hxy$. We thus have an operation on cosets of H. Furthermore, this action satisfies the properties of the group. Thus $\{Hx : x \in G\}$ with the operation $HxHy = Hxy$ is a group, called the factor group or quotient group of G by H.

Ex. 1.5.12 Consider $G = \mathbb{Z}_{13}^{\times}$, $H = \langle 3 \rangle$. Then $H2 = \{256\}$, $H4 = \{4, 10, 12\}$, $H7 = \{7, 8, 11\}$. We have

	H	H2	H4	H7
H	H	H2	H4	H7
H2	H2	H4	H7	H
H4	H4	H7	H	H2
H7	H7	H	H2	H4

Prop. 1.5.13
1. *Index 2 subgroups are normal.*
2. *Any subgroup of a commutative group is normal.*
3. *Any subgroup of the center is normal.*
4. *If $H \leq G$, $|H| = K$ and H is the only subgroup of G of size K, then $H \triangleleft G$.*

Proof
1. If $H \leq G$ with $[G : H] = 2$, we know $g^2 \in H$ for all $g \in G$. Then for $h \in H$, $x \in G$, $x^{-1}hx = x^{-2}xhxhh^{-1} = (x^{-1})^2(xh)^2h^{-1} \in H$.
2. If $H \leq G$, G commutative, if $h \in H$ and $x \in G$, then $hx = xh$ and $x^{-1}hx = h \in H$.
3. Elements of the center commute with everything.
4. For any $x \in G$, $x^{-1}Hx \leq G$ and $|x^{-1}Hx| = |H|$ so $x^{-1}Hx = H$ □

1.5.1 Group Homomorphisms

Def'n. 1.5.14 *A map $\alpha : G \to H$ is called a* ***homomorphism*** *(of groups) iff $\alpha(xy) = \alpha(x)\alpha(y)$ for every $x, y \in G$.*

Homomorphisms are isomorphisms that are not (necessarily) bijective.

Ex. 1.5.15

1. The identity map ($g \mapsto g$), the constant identity map ($g \mapsto 1$).
2. The map $\alpha : \mathbb{C}^\times \to \mathbb{R}^\times$ given by $z \mapsto |z|$.
3. The map $\alpha : \mathrm{GL}_n(\mathbb{R}) \to \mathbb{R}^\times$ by $A \mapsto \det(A)$, since $\det(AB) = \det(A)\det(B)$.
4. If $H \triangleleft G$, the map $\alpha : G \to G/H$ by $x \mapsto Hx$.

For a homomorphism $\alpha : G \to H$ of groups, we have the following properties.

Prop. 1.5.16

1. *$\alpha(1_G) = 1_H$*
2. *$\alpha(g^{-1}) = \alpha(g)^{-1}$*
3. *$\alpha(g^k) = \alpha(g)^k$ for any $k \in \mathbb{Z}$.*

Proof

1. $1_H\alpha(1_G) = \alpha(1_G) = \alpha(1_G 1_G) = \alpha(1_G)\alpha(1_G)$
2. $\alpha(g)\alpha(g^{-1}) = \alpha(gg^{-1}) = \alpha(1_G) = 1_H$, so they are inverses.
3. Follows directly by above and induction. □

Def'n. 1.5.17 *The* ***image*** *of α is given by $\mathrm{im}(\alpha) = \{\alpha(g) : g \in G\} \leq H$.*

The image of α is a subgroup since it is a subgroup. We also define

Def'n. 1.5.18 *The* ***kernel*** *of α is given by $\ker(\alpha) = \{x \in G : \alpha(x) = 1_H\} \trianglelefteq G$.*

To see it is a normal subgroup, we have $1_G \in \ker(\alpha)$, and it is certainly a subgroup. Then by the normality test, if $x \in \ker(\alpha)$ and $g \in G$, then

$$\begin{aligned}\alpha(g^{-1}xg) &= \alpha(g^{-1})\alpha(x)\alpha(g) \\ &= \alpha(g^{-1})\alpha(g) \\ &= \alpha(1_G) \\ &= 1_U\end{aligned}$$

so $g^{-1}xg \in \ker(\alpha)$ as well.

Thm. 1.5.19 (First Isomorphism) *For a homomorphism $\alpha : G \to H$, $G/\ker(\alpha) \cong \mathrm{im}(\alpha)$.*

Proof Consider the map $\beta : G/\ker(\alpha) \to \mathrm{im}(\alpha)$ given by $\ker(\alpha)x \mapsto \alpha(x)$.

This map is well defined and injective: we have

$$\begin{aligned} \ker(\alpha)x = \ker(\alpha)y &\Leftrightarrow xy^{-1} \in \ker(\alpha) \\ &\Leftrightarrow \alpha(xy^{-1}) = 1 \\ &\Leftrightarrow \alpha(x)\alpha(y)^{-1} = 1 \\ &\Leftrightarrow \alpha(x) = \alpha(y) \end{aligned}$$

It is also surjective since any element if $\mathrm{im}(\alpha)$ is of the form $\alpha(x)$, which is the image of $\beta(\ker(\alpha)x)$. Finally,

$$\begin{aligned} \beta((\ker(\alpha)x)(\ker(\alpha)x)) &= \beta(\ker(\alpha)xy) \\ &= \alpha(xy) \\ &= \alpha(x)\alpha(y) \\ &= \beta(\ker(\alpha)x)\beta(\ker(\alpha)y) \end{aligned}$$

so β is a bijective homomorphism, which is an isomorphism. □

Ex. 1.5.20 Consider the map $\alpha\, \mathrm{GL}_n(\mathbb{R}) \to \mathbb{R}^\times$ given by $A \mapsto \det(A)$. We have $\mathrm{im}(\alpha) = \mathbb{R}^\times$ and $\ker(\alpha) =_n (\mathbb{R})$, so $_n(\mathbb{R}) \trianglelefteq \mathrm{GL}_n(\mathbb{R})$.

Thm. 1.5.21 *Let $\mathcal{N}$ denote the set of normal subgroups of G. For any group G, the set of normal subgroups of G is equal to the collection of kernels of homomorphisms of G, and the factor gr Noral subgroups of G =kernels of homomorphisms of G Factor groups of G = images of homomorphisms of G*

Proof We know $\ker(\alpha) \trianglelefteq G$ for all homomorphisms $\alpha : G \to H$. Conversely, for $N \trianglelefteq G$, consider $\alpha : G \to G/N$ by $g \mapsto Ng$. Then $\mathrm{im}(\alpha) = \{Ng : g \in G\} = G/N$, and $\ker(\alpha) = \{g \in G : Ng = N\} = N$. This also show that any factor group is the image of a homomorphism. Converselty, for any $\alpha : G \to H$, and $\mathrm{im}(\alpha) \cong G/\ker(\alpha)$ by the first isomorphism theorem. □

1.6 Direct Products of Groups

Def'n. 1.6.1 *For groups A, B, the* ***direct product group*** *is the group with set $A \times B$ and operation $(a_1, b_1)(a_2, b_2) = (a_1 a_2, b_1 b_2)$.*

Define an operation $(a_1, b_1) \cdot (a_2, b_2) = (a_1 a_2, b_1 b_2)$. We have some obvious basic properties:

1. $1_{A\times B} = (1_A, 1_B)$
2. $(a, b)^{-1} = (a^{-1}, b^{-1})$
3. $|A \times B| = |A| \cdot |B|$.
4. $o(a, b) = (o(a), o(b))$
5. A, B are commutative if and only if $A \times B$ is commutative

6. $A \times B$ is cyclic if and only if A, B are both cyclic with coprime order. Note that $A \times B$ is cyclic if and only if there exists (a,b) generates $A \times B$, so $|A \times B| = o(a,b)$. But also $|A| \cdot |B| = |A \times B| = o(a,b) = (o(a), o(b))) \leq o(a) \cdot o(b) \leq |A| \cdot |B|$, so equality must hold. Thus $(o(a), o(b)) = o(a)o(b)$; and $o(a) = |A|$, $o(b) = |B|$.
7. $C_k \times C_l \cong C_{kl} \iff \gcd(k,l) = 1$.
8. $\overline{A} = \{(a,1) | a \in A\} \leq A \times B$; $A \cong \overline{A}$. $\overline{B} = \{(1,b) | b \in B\} \leq A \times B$; $B \cong \overline{B}$. Then $\overline{A} \cdot \overline{B} = A \times B$ since $\overline{A} \cap \overline{B} = \{1_{A \times B}\}$.
9. Define projection maps π_A, π_B by $(a,b) \mapsto a$ and $(a,b) \mapsto b$ respectively. Then $\operatorname{im}(\pi_A) = A$, $\ker(\pi_A) = \overline{B}$, $\operatorname{im}(\pi_B) = B$, $\ker(\pi_B) = \overline{A}$. Thus $\overline{A}, \overline{B} \trianglelefteq A \times B$.

Thm. 1.6.2 *Suppose $M, N G$ with $M \cap N = \{1\}$ and $M \cdot N = G$. Then $G \cong M \times N$.*

Proof We first see that $mn = nm$ for all $m \in M, n \in N$. Consider $[m,n] = (m^{-1}n^{-1}m)n \in N$ since N is normal. As well, $[m,n] = m^{-1}(n^{-1}mn) \in M$ since M is normal. Thus $m^{-1}n^{-1}mn = 1$ so m, n commute.

Now consider $\alpha : M \times N \to G$ by $(m,n) \mapsto mn$. α is onto since $\operatorname{im}(\alpha) = MN = G$, and injective since if $m_1 n_1 = m_2 n_2$, then $m_2^{-1} m_1 = n_2 n_1^{-1} = 1$ so $m_1 = m_2$ and $n_1 = n_2$. Finally, we have

$$\begin{aligned}
\alpha((m_1, n_1)(m_2, n_2)) &= \alpha(m_1 m_2, n_1 n_2) \\
&= m_1 m_2 n_1 n_2 \\
&= m_1 n_1 m_2 n_2 \\
&= \alpha((m_1, n_1))\alpha((m_2, n_2))
\end{aligned}$$

so α is an isomorphism. □

Furthermore, if G is finite, it suffices to require $|M| \cdot |N| = |G|$. This follows since $|M \cdot N| = \{m \cdot n | m \in M, n \in N\}$ must have distinct elements. Then $|M \cdot N| = |G|$, so $MN = G$.

Thm. 1.6.3 *If $|G| = p^2$, p prime, then*

Proof Suppose $|G| = p^2$. Then for any $g \in G$, by Lagrange, $o(g) \in \{1, p, p^2\}$. If $o(g) = p^2$ then G is cyclic. Pick any $1 \neq x \in G$, and let $M = \langle x \rangle$. Similarly, get $N = \langle y \rangle$ for $y \notin M$. Then $M \cap N \not\leq N$, so by Lagrange, $M \cap N = \{1\}$. Furthermore, M, N are normal subgroups, so $G \cong M \times N \cong C_p \times C_p$. □

Thm. 1.6.4 (Fundamental Theorem of Finite Abelian Groups) *Any finite commutative group is isomorphic to a direct product of cyclic groups.*

Thm. 1.6.5 *If G is finite, p prime, and $p \| G|$, then there eists $g \in G$ with $o(g) = p$.*

Proof Consider $T = \{(g_1, g_2, \ldots, g_p) : g_1 g_2 \cdots g_p = 1\}$. Note that $|T| = |G|^{p-1}$ since we can choose $g_1, g_2, \ldots, g_{p-1}$ arbitrarily and g_p is uniquely determined. Thus $p \| T|$. Now define $\alpha : T \to T$ by $(g_1, g_2, \ldots, g_p) \mapsto (g_2, g_3, \ldots, g_p, g_1)$. Since α also has an inverse, it is a permutation $\alpha \in S_T$. As well, $\alpha^p = 1_T$, so $o(\alpha) | p$ and the cycle form of α is composed of fixed points and p–cycles. Thus $|T|$ is given by the number of fixed points of α plus p times the number of p–cycles of α. Then since $p \| T|$, p divides the number of fixed points of α. The fixed points of α are the elements of the form $(g, g, \ldots, g)$; plus there are a non-zero number of fixed points since $(1, 1, \ldots, 1)$ is a fixed point. Thus there exists some $(g, g, \ldots, g) \in T$ with $g \neq 1$, so $g^p = 1$ and $o(g) \neq$, so $o(g) = p$. □

In fact, this shows that $|\{g \in G : g^p = 1\}| = 0 \pmod{p}$.

Chapter 2

Examples of Finite Groups and Rings

2.1 Examples of Finite Groups

2.1.1 Cyclic Groups

Ex. 2.1.1 Consider $G = \mathbb{Z}_{13}^{\times} = \langle 2 \rangle$, $|\mathbb{Z}_{13}^{\times}| = 12 = o(2)$.

Divisor of 12	Subgroup of $\mathbb{Z}_{13}^{\times}$
1	$\langle 2^1 \rangle = \langle 2 \rangle = \mathbb{Z}_{13}^{\times}$
1	$\langle 2^2 \rangle = \langle 4 \rangle = \{1,4,3,12,9,10\}$
1	$\langle 2^3 \rangle = \langle 8 \rangle = \{1,8,12,5\}$
1	$\langle 2^4 \rangle = \langle 3 \rangle = \{1,3,9\}$
1	$\langle 2^6 \rangle = \langle 12 \rangle = \{1,12\}$
1	$\langle 2^{12} \rangle = \langle 1 \rangle = \{1\}$

2.1.2 Permutation Groups

Recall that S_n is the symmetric group of degree n, consisting of all permutations of $[n]$. Thus $|S_n| = n!$. Instead of using the matrix form, we can write the permutation group using the cycle form.

Ex. 2.1.2 Write

$$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 4 & 7 & 3 & 1 & 2 & 9 & 8 & 5 & 6 \end{pmatrix} = (14)(2785)(3)(69)$$

We can also write (14)(2785)(69), in other words excluding elements which map to themselves.

In general, a cycle $(a_1 a_2 \ldots a_k)$ indicates that $a_1 f = a_2$, $a_2 f = a_3, \ldots, a_k f = a_1$. In S_n, each permutation can be expressed in a cycle form (using disjoint cycles). The cycle form is unique up to ordering within the cycles, and ordering among the cycles.

Ex. 2.1.3 In S_5, the possible cycle structures are

$$I, (ab), (abc), (abcd), (abcde), (ab)(cd), (ab)(cde)$$

We then have

$$\begin{aligned} o(I) &= 1 \\ o((ab)) &= 2 \\ o((abc)) &= 3 \\ o((abcd)) &= 4 \\ o((abcde)) &= 5 \\ o((ab)(cd)) &= 2 \\ o((ab)(cde)) &= 6 \end{aligned}$$

For $f = (abc)$, $f^2 = (abc)(abc) = (acb)$, $f^3 = (abc)(acb) = abc$. For $f = (abcd)$, $f^2 = (ac)(bd)$, $f^3 = (abdc)(ac)(bd)(adcb)$, and $f^4 = (abcd)(adcb) = (abcd)$.

If $f = (a_1 a_2 \dots a_k)$, $o(f) = k$.

Prop. 2.1.4 *Suppose $f = \gamma_1\gamma_2\dots\gamma_i$ for disjoint cycles. Then $o(f) = lcm(o(\gamma_1), o(\gamma_2), \dots, o(\gamma_i))$.*

Proof Note that the γ_i commute, so that

$$\begin{aligned} f^d = I &\Leftrightarrow (\gamma_1\gamma_2\dots\gamma_i)^d = I \\ &\Leftrightarrow \gamma_1^d\gamma_2^d\dots\gamma_i^d = I \\ &\Leftrightarrow \gamma_i^d = I \quad \forall i \end{aligned}$$

The last line holds since the γ_i^d operates on disjoint sets. Thus we have our formula, as desired. □

Note that any finite permutation of $f \in S_n$ can be expressed as a composition of 2-cycles. For example, $(abc) = (ab)(ac)$ and in general $(a_1a_2\dots a_k) = (a_1a_2)(a_1a_3)\dots(a_1a_k)$. In general, any k–cycle can be replaced by a composition of $(k-1)$ 2-cycles. This motivates the following definition:

Def'n. 2.1.5 *A permutation $f \in S_n$ is **even** if it can be expressed as a composition of an even number of 2-cycles. Then $f \in S_n$ is **odd** if it can be expressed as a composition of an odd number of 2-cycles.*

For example, $(15362)(4798) = (15)(13)(16)(12)(47)(49)(48)$ can be written as a composition of 7 2-cycles. This is certainly not unique: for example $(26) = (21)(16)(21)$.

Lemma 2.1.6 *The identity permutation is not odd.*

Proof For contradiction, assume

$$I = \alpha_1\alpha_2\dots\alpha_k$$

and assume that such an odd k is a minimal counterxample. We certainly have $k \geq 3$. Say $\alpha_1 = (cd)$, so c must be involved in another α_i, or d is mapped to c. Let α_r be the last 2-cycle involving c, say $\alpha_r = (cx)$. Now we rewrite α_{r-1} without changing $\alpha_{r-1}\alpha_r$.

1. If $\alpha_{r-1} = (yz)$ disjoint from $\alpha_r = (cx)$, then $(yz)(cx) = (cx)(yz)$.
2. If $\alpha_{r-1} = (cy)$ with $y \neq x$, then $(cy)(cx) = (xc)(xy)$.

3. If $\alpha_{r-1} = (xy)$, $y \neq c$, then $(xy)(cx) = (yc)(yx)$.
4. $\alpha_{r-1} = \alpha_r$ so $(cx)(cx) = I$, contradicting minimality.

We can repeat this process until the last 2-cycle involving c is α_1, a contradiction. □

Prop. 2.1.7 *A permutation cannot be both even and odd.*

Proof Suppose f can be written as an even and odd permutation:

$$f = \alpha_1 \alpha_2 \dots \alpha_m$$
$$f = \beta_1 \beta_2 \dots \beta_n$$

but then

$$I = \alpha_1 \alpha_2 \dots \alpha_m \alpha_m \dots \alpha_2 \alpha_1 = \beta_1 \beta_2 \dots \beta_n \alpha_m \alpha_{m-1} \dots \alpha_1$$

so I is odd, a contradiction. □

Def'n. 2.1.8 *We define the **signature** $\operatorname{sgn}(f)$ to be 1 of f is even, and -1 if f is odd.*

Prop. 2.1.9 *1.* $\operatorname{sgn}(f^{-1}) = \operatorname{sgn}(f)$
2. $\operatorname{sgn}(fg) = \operatorname{sgn}(f)\operatorname{sgn}(g)$

Proof Follows directly from the 2-cycle decomposition. □

Def'n. 2.1.10 *The **alternating group** of degree n is the group $A_n = \{f \in S_n : \operatorname{sgn}(f) = 1\} \leq S_n$.*

Thm. 2.1.11 $|A_n| = \frac{n!}{2}$.

Proof We see two separate proofs.

1. Consider $\phi : A_n \to S_n \setminus A_n$ by $f \mapsto f(12)$. This is injective since if $\phi(f) = \phi(g)$, then $f(12) = g(12)$ and $f = g$. It is surjective: if g is odd, then $g(12)$ is even that $\phi(g(12)) = g$. Thus ϕ is bijective and $|A_n| = |S \setminus A_n| = |A| - |A_n|$ so $|A_n| = |S_n|/2 = n!/2$.

2. We claim that $|S_n : A_n| = 2$. For $f \in S_n$ even, $f \in A_n$ so $A_n f = A_n$. For $f \in S_n$ odd, f^{-1} is odd and $(12)f^{-1}$ is even and $(12)f^{-1} \in A_n$. Thus $A_n(12) = A_n f$, so there are only two cosets of A_n: A_n and $A_n(12)$, and the result follows by Lagrange's Theorem. □

As well, we also have $A_n \triangleleft S_n$, and $S_n/A_n \cong C_2$.

Centralizers of Permutation Groups

Ex. 2.1.12 Consider $g = (12)(34) \in S_4$. Then

$$C_{S_4}(g) = \{x \in S_4 \mid gx = xg\} = \{I, (12)(34), (12), (34), (14)(23), (1324), (1423)\}$$

The key idea is to observe that $x^{-1}gx = g$, which is called the conjugate of g by x.

Ex. 2.1.13 Consider $f = (34)(1572)(86)(9)$, $g = (194)(368)(257)$.

$$\begin{aligned} g^{-1}fg &= (752)(863)(491)(34)(1572)(86)(194)(368)(257) \\ &= (16)(2597)(38)(4) \\ &= (3g)(4g)(1g5g7g2g)(8g6g)(9g) \end{aligned}$$

In general, if $f, g \in S_n$ and $(a_1 a_2, \ldots, a_k)$ is a cycle in the cycle form of f, then $(a_1 z a_2 z \ldots a_k z)$ is a cycle in the cycle form of $z^{-1} f z$. To see this, $a_1 z(z^{-1} f z) = a_1 f z = a_2 z$, so $a_1 z$ maps to $a_2 z$, and similarly for all the pairs of elements in the cycle.

If we now return to $(12)(34)x = x(12)(34)$, we have $x^{-1}(12)(34)x = (12)(34)$ so

$$(1x\,2x)(3x\,4x) = (12)(34)$$

Since the cycle form is unique up to rearranging within cycles, we have

LHS	$1x$	$2x$	$3x$	$4x$	x
(12)(34)	1	2	3	4	I
(21)(34)	2	1	3	4	(12)
(12)(43)	1	2	4	3	(34)
(21)(43)	2	1	4	3	(12)(34)
(34)(12)	3	4	1	2	(13)(24)
(34)(21)	3	4	2	1	(1324)
(43)(12)	4	3	1	2	(1423)
(43)(21)	4	3	2	1	(14)(23)

Let's now compute the conjugacy classes of S_n. Let's do S_3 first: The conjugacy classes are given by

$$\{1\}, \{(12), (13), (23)\}, \{(123)\}$$

In general, the conjugacy classes in S_n correspond to the possible cycle structures in S_n.None

2.1.3 Dihedral Groups

Fix a regular polygon with n vertices. Let D_n be the collection of rigid motions with map the regular n–polygon to itself. Since $r^n = 1$ and $s^2 = 1$, we have

$$D_n = \{1, r, r^2, \ldots, r^{n-1}, s, sr, sr^2, \ldots, sr^{n-1}\}$$

Thus $|D_n| = 2n$. We can compute the oprations on D_n:

$$\begin{aligned} r^a \cdot r^b &= r^{a+b} \\ sr^a \cdot r^b &= sr^{a+b} \\ r^a \cdot sr^b &= sr^{b-a} \\ sr^a \cdot sr^b &= r^{b-a} \end{aligned}$$

Thus $o(sr^a) = 2$ and $o(r^a)$ is given by the usual formula.