

Groups, Rings and Fields

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Spring 2026

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1 Groups

Definition 1.1 (Group). A group is a set S together with a binary operation \circ such that the following properties hold:

1. Identity: There exists an element $e \in S$, satisfying

$$e \circ a = a \circ e = a$$

for every $a \in S$.

2. Inverses: For every $a \in S$ there exists $b \in S$ such that

$$a \circ b = b \circ a = e, \text{ the identity element}$$

We usually denote this element as a^{-1} or $-a$, depending on context.

3. Associativity: For any $a, b, c \in S$, we require

$$a \circ (b \circ c) = (a \circ b) \circ c$$

A group is then the tuple (S, \circ) . We will often just write the set to refer to the group, e.g. referring to the group $(\mathbb{Z}, +)$ as just \mathbb{Z} .

1.1 Basic Examples

Example 1.1 (Integers under addition). The set of integers \mathbb{Z} with the operation $+$ forms a group:

- Identity: 0 since $0 + n = n + 0 = n$ for all $n \in \mathbb{Z}$.
- Inverses: For $n \in \mathbb{Z}$, the inverse is $-n$.
- Associativity: Addition is associative.

Hence $(\mathbb{Z}, +)$ is a group.

Example 1.2 (Non-example: Natural numbers under addition). The set \mathbb{N} under $+$ is not a group since there is no inverse for $n > 0$.

1.2 Basic Properties

Theorem 1.1 (Uniqueness of identity). *The identity element in a group is unique.*

Proof. Suppose e and e' are both identities. Then

$$e = e \circ e' = e',$$

so the identity is unique. \square

Theorem 1.2 (Uniqueness of inverses). *Each element in a group has a unique inverse.*

Proof. Suppose b and c are inverses of a . Then

$$b = b \circ e = b \circ (a \circ c) = (b \circ a) \circ c = e \circ c = c.$$

\square

1.3 Example Problem

Problem 1.1. *Determine whether the set*

$$G = \{1, -1, i, -i\} \subset \mathbb{C}$$

with multiplication is a group.

Solution. We check the group axioms:

1. **Closure:** Multiplying any two elements of G yields another element in G . True.
2. **Identity:** The element 1 acts as identity. True.
3. **Inverses:** Each element has an inverse in G : $1^{-1} = 1$, $(-1)^{-1} = -1$, $i^{-1} = -i$, $(-i)^{-1} = i$. True.
4. **Associativity:** Multiplication of complex numbers is associative. True.

Hence (G, \cdot) is a group, in fact it is an abelian group which we shall describe below in definition 1.2. \square

1.4 Abelian Groups

Definition 1.2 (Abelian Group). A group (G, \circ) is abelian (or commutative) if

$$a \circ b = b \circ a \quad \forall a, b \in G.$$

Example 1.3. The group $(\mathbb{Z}, +)$ is abelian because $m + n = n + m$.

2 Important Groups

First let's define some often used notation.

For $g \in G$, define:

- $g^n = gg \dots g (n > 0)$
- $g^0 = e$
- $g^{-n} = (g^{-1})^n$

and recognize the following identities (which are provable by induction):

$$g^m g^n = g^{m+n}, \quad (g^m)^n = g^{mn}$$

Definition 2.1 (Roots of Unity).

$$U_n = \{e^{2\pi i k/n} : 0 \leq k < n\}$$

are called the n -th roots of unity.

Definition 2.2. An subset $\{g_1, \dots, g_k\} \subseteq G$ is a generating set if every $g \in G$ can be expressed as

$$g_1^{n_1} \dots g_k^{n_k}$$

If a singleton g' alone generates a group then it is called a generator of G and G is said to be cyclic.

The n -th roots of unity are finite, with exactly n elements. They are cyclic, with generator $e^{2i\pi/n}$.

Definition 2.3 (Symmetric Group). The symmetric group S_n is the set of all permutations of n elements under composition. In other words it is the set of all $\sigma : [n] \rightarrow [n]$ with composition as its operation.

The symmetric group is non-abelian for $n \geq 3$. The identity corresponds to the identity permutation (doing nothing) and inverses are undoing a permutation. We have the following notation for permutations in the symmetric Group (assume $n = 3$ for this example):

$$\begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix}$$

corresponds to $1 \mapsto 2, 2 \mapsto 3, 3 \mapsto 1$.

3 Subgroups

Definition 3.1 (Subgroup). Let G be a group under \star . A subgroup $H \leq G$ is a subset $H \subseteq G$ that is itself a group under \star .

Having to mechanically check if $H \subseteq G$ satisfies all the required axioms can be a bit tedious so next we introduce a powerful theorem which let's us easily determine whether some subset is a subgroup or not.

Theorem 3.1 (Subgroup Test). A nonempty subset $H \subseteq G$ is a subgroup if and only if

$$\forall x, y \in H, xy^{-1} \in H.$$

Proof Idea. If H is a subgroup the required conditions follows.
Conversely:

- Nonempty so some $h \in H$.
- $hh^{-1} = e \in H$.
- Closure under xy^{-1} will give inverses and closure.

□

We get some nice corollaries from this, as well as a nice and tidy way to prove whether or not a subset is a subgroup.

Corollary 3.1. The intersection of any collection of subgroups is a subgroup.
Given any subset $S \subseteq G$, there is a smallest subgroup containing it.

Definition 3.2 (Cyclic Subgroups). Let G be a group.
For any $g \in G$, define:

$$\langle g \rangle = \{g^n : n \in \mathbb{Z}\}.$$

$\langle g \rangle$ is called the cyclic subgroup generated by g .

It is very straightforward to show that the cyclic subgroup generated by some $g \in G$ is indeed a subgroup with the use of theorem 3.1.

On page 6 we say that a group is cyclic if it has a single element which generates it, but now we can simply say that a group G is cyclic if $G = \langle g \rangle$ for some $g \in G$.

Theorem 3.2. Suppose a group G is cyclic, i.e. $G = \langle g \rangle$ for some $g \in G$.

Then it is isomorphic to one of the following:

- $(\mathbb{Z}, +)$, or
- $(\mathbb{Z}/n\mathbb{Z}, +)$ for some $n \geq 1$.

3.1 Structure of Cyclic Subgroups

Definition 3.3 (Order). The order of an element $g \in G$ is

$$\text{ord}(g) = |\langle g \rangle|$$

Furthermore, if $\text{ord}(g) = n < \infty$, then $g^n = e$ and n is minimal, otherwise we say g has infinite order.

If $\text{ord}(g) = n$, then:

$$\langle g \rangle = \{e, g, g^2, \dots, g^{n-1}\}$$

Moreover:

- $g^k = e \Leftrightarrow n \mid k$
- $\langle g^k \rangle = \langle g \rangle \Leftrightarrow \gcd(k, n) = 1$

Theorem 3.3. Every subgroup of a cyclic group is cyclic.

More precisely:

- Subgroups of \mathbb{Z} are exactly $n\mathbb{Z}$.
- Subgroups of $\mathbb{Z}/n\mathbb{Z}$ correspond to the divisors of n .

With all of this machinery we can approach group theory with geometric and algebraic intuition. Cyclic groups are like repeated motion, finite cyclic groups corresponding to rotations by rational angles and infinite ones corresponding to translations.

4 Cosets and Lagrange's Theorem

Definition 4.1 (Left and Right Cosets). Let $H \leq G$, and let $g \in G$. The left- and right cosets are:

$$gH = \{gh : h \in H\} \quad Hg = \{hg : h \in H\}$$

respectively.

A key intuition is that a coset is like a copy of H shifted by g . We may also recognize that the cosets are the same size as H by identifying $h \mapsto gh$ to be a bijection and so forth.

The next natural question is when are two cosets equal? Like with showing when a subset is a subgroup we have a little trick for this problem.

Theorem 4.1. Let G be a group.
For $g_1, g_2 \in G$, the following are equivalent:

$$\begin{aligned} g_1H &= g_2H \\ \Updownarrow \\ g_2^{-1}g_1 &\in H \\ \Updownarrow \\ g_1 &\in g_2H \end{aligned}$$

Theorem 4.2. The set of all left cosets of $H \leq G$ forms a partition of G .
That is,

- Every element of G is in exactly one coset.
- Two cosets are either the same or disjoint.

Definition 4.2. Let G be a group with $H \leq G$.
The index of H in G , written $[G : H]$, is the number of left cosets of H .

If G is finite we get $|G| = [G : H] \cdot |H|$.

Theorem 4.3 (Lagrange's Theorem). *Let G be a group with $H \leq G$. Then:*

$$|H| \mid |G|$$

Proof. Let G be a group with $H \leq G$.

Recall that by theorem 4.2 we have that the set of left cosets of H , g_1H, g_2H, \dots, g_kH (this set is finite since G is finite) are pairwise disjoint, satisfying

$$G = \bigcup_{i=1}^k g_iH$$

meaning

$$|G| = \sum_{i=1}^k |g_iH|$$

Recall also that $|H| = |g_iH|, \forall i \in [k]$. Thus

$$|G| = \sum_{i=1}^k |H| = k|H|$$

In other words $|G|$ is $|H|$ times some integer k , therefore $|H|$ divides $|G|$. \square

Theorem 4.3 has the following immediate consequences:

- The order of any element divides $|G|$.
- $g^{|G|} = e$ for every $g \in G$.

Beware that it does not follow from Lagrange's Theorem that there exists a subgroup with the order of a divisor of $|G|$ for every divisor of G . The alternating group of order 12, A_4 , has no subgroup of order 6 for example.

Proposition 4.1. *A group of order p where p is prime, is cyclic.*

Proof Sketch. Let G be a group with $|G| = p$ (prime).

Let $g \in G \setminus \{1\}$. Consider it's generated subgroup $\langle g \rangle$. By Lagrange's Theorem the order of this subgroup divides p so $|\langle g \rangle|$ is 1 or p , but it can't be 1 as $g \neq 1$ so it's order is p , i.e. g generates the entirety of G . \square

4.1 Problems relating to subgroups

Problem 4.1. Let G be a group and $g \in G$ with $\text{ord}(g) = 12$.

- List all distinct subgroups of $\langle g \rangle$.
- For which integers k does g^k generate $\langle g \rangle$?

Solution. Recalling that $\langle g \rangle = \{g^k : k \in \mathbb{Z}\}$, we want to find all the distinct subgroups of $\langle g \rangle$. In other words, which subsets of $\langle g \rangle$ are also groups with respect to the operation of G ?

$\text{ord}(g) = |\langle g \rangle| = 12$ hence $\langle g \rangle = \{g^0, g^1, \dots, g^{11}\}$. We know that there are two trivial subgroups of $\langle g \rangle$, namely $\{g^0\}$ and $\langle g \rangle$. Otherwise, we know that every cyclic subgroup of a cyclic group (which $\langle g \rangle$ is) is itself cyclic, so we can find the subgroups by looking at the generated groups of each element of $\langle g \rangle$. Otherwise, we could use the fact that $\langle g \rangle$ is isomorphic to $\mathbb{Z}/12\mathbb{Z}$ together with realizing that the number of subgroups is then the same as the number of positive divisors of 12.

Using the first approach we get:

$$\begin{aligned}\langle g^2 \rangle &= \{g^n : n = 2k, k \in \mathbb{Z}\} \\ &= \{e, g^2, \dots, g^{10}\} = \langle g^2 \rangle \\ \langle g^3 \rangle &= \{e, g^3, g^6, g^9\} = \langle g^3 \rangle \\ \langle g^4 \rangle &= \{e, g^4, g^8\} = \langle g^4 \rangle \\ \langle g^6 \rangle &= \{e, g^6\}\end{aligned}$$

Those integers which are coprime to 12, like 1, 5, 7, 11, will generate $\langle g \rangle$. Thus we have 6 distinct subgroups, exactly the same as the number of positive divisors of 12, as expected. \square

Problem 4.2. Let G be any group $H = \langle g \rangle$ where $\text{ord}(g) < \infty$. Prove that if $g^m \in H$, then $\langle g^m \rangle \leq H$.

Proof. Assume, for contradiction, that $g^m \in H$, but $\langle g^m \rangle$ is not a subgroup of H .

Let $s = m \bmod \text{ord}(g)$. Then $\langle g^m \rangle = \{g^{sk} : k \in \mathbb{Z}\} \neq \emptyset$. It is clear that this is a subset of $\langle g \rangle = H$, since $\langle g \rangle$ is closed under the group operation and $g^m \in H$. Then the only way our assumption is true is if there exists some $x, y \in \langle g^m \rangle$ such that $xy^{-1} \notin \langle g^m \rangle$.

Every element $x, y \in \langle g^m \rangle$ is of the form $x = g^{sn}, y = g^{st}$ for some $n, t \in \mathbb{N}$. By assumption, $xy^{-1} = g^{s(n-t)} \notin \langle g^m \rangle$ which would necessarily mean that $n - t \notin \mathbb{Z}$, impossible. \square

The above argument can be made more rigorous by considering the isomorphism between $\langle g^m \rangle$ and $\mathbb{Z}/s\mathbb{Z}$, or by proving the claim directly (I am an idiot, and this was a bad approach).

5 Normal subgroups

Definition 5.1 (Normal subgroup). A subgroup $H \leq G$ is normal, written $H \trianglelefteq G$, if:

$$gH = Hg, \forall g \in G$$

with the equivalent characterization:

$$H \trianglelefteq G \Leftrightarrow gHg^{-1} = H, \forall g \in G$$

A few things to tick off immediately;

1. Every subgroup of an abelian group is normal.
2. $\{e\}$ and G are always normal.
3. The alternating group $A_n \trianglelefteq S_n$.
4. Subgroups of index 2 are always normal.

If you consider the map (conjugation)

$$x \mapsto gxg^{-1},$$

which constitutes an automorphism of G we can say the following.

Normal subgroups are precisely those subgroups which are fixed under every conjugation.

Definition 5.2 (Quotient Group). If $H \trianglelefteq G$, define:

$$G/H := \{gH : g \in G\}$$

with an operation we'll call multiplication by:

$$(gH)(kH) = (gk)H$$

Theorem 5.1. The quotient group with multiplication, as defined above, is a well-defined group.

Definition 5.3. We define the **canonical projection** as

$$\pi : G \rightarrow G/H, \pi(g) = gH.$$

Notably, the projection π constitutes a homomorphism with kernel $\ker \pi = H$. Notice that this claim of the kernel being H itself should be immediately obvious as hH for some $h \in H$ is itself H as it's closed.

6 Exercises for Week 1

Problem 6.1 (29, p.48). Show that if G is a finite group with identity e and an even number of elements, then there is $a \neq e$ in the group such that $a * a = e$.

Proof. We are being asked to show that in a finite group with even order, there exists some element other than the identity which is its own inverse.

Recall uniqueness of inverses and that for $g \in G$, $(g^{-1})^{-1} = g$. Thus for every element there exists one and only one element which is its inverse. $e^{-1} = e$ is covered. In $G \setminus \{e\}$ there are an odd number of elements. Each of these have exactly one unique inverse meaning that there is one element "left" over which then necessarily has itself as its inverse. \square

Problem 6.2 (33, p.49). Let G be an abelian group and let $c^n = c * c * \dots * c$ for n factors c , where $c \in G$ and $n \in \mathbb{Z}^+$. Give a proof by mathematical induction that $(a * b)^n = a^n * b^n$ for all $a, b \in G$.

Proof. Let $a, b \in G$. The base case where $n = 1$ is trivial so we proceed to our assumption that for any $k \in \mathbb{Z}^+$ we have $(a * b)^k = a^k * b^k$.

Let $n = k + 1$.

$$\begin{aligned}
 (a * b)^n &= (a * b)^{k+1} \\
 &= (a * b)^k * (a * b) \\
 &= a^k * b^k * (a * b) && \text{by hypothesis} \\
 &= a^k * (b^k * a) * b && \text{by associativity} \\
 &= a^k * (a * b^k) * b && \text{by commutativity} \\
 &= (a^k * a) * (b^k * b) \\
 &= (a^{k+1}) * (b^{k+1}) \\
 &= a^n * b^n
 \end{aligned}$$

By the principle of mathematical induction we have that

$$(a * b)^n = a^n * b^n, \forall n \in \mathbb{Z}^+$$

\square

Problem 6.3 (35, p. 49). Show that if $(a * b)^2 = a^2 * b^2$ for a, b in a group, then $a * b = b * a$.

Proof.

$$\begin{aligned}(a * b)^2 &= (a * b) * (a * b) \\ a^2 * b^2 &= (a * a) * (b * b) \\ \Rightarrow (a * b) * (a * b) &= (a * a) * (b * b) \\ a * (b * a) * b &= a * (a * b) * b\end{aligned}$$

By one application each of left- and right cancellation we have

$$a * b = b * a$$

□

Problem 6.4 (41, p. 49). Let G be a group and fix $g \in G$. Show that the map i_g , s.t. $i_g(x) = gxg^{-1}$ for $x \in G$. Show that i_g is an automorphism on G .

Proof. Let $i_g : G \rightarrow G$ be defined as above. We need to show that it satisfies all the properties of an isomorphism.

It is clear, through left- and right cancellation, that i_g is injective.

Notice also that for any $x \in G$ we have the pre-image $g^{-1}xg$ since $i_g(g^{-1}xg) = gg^{-1}xgg^{-1} = x$, hence i_g is surjective.

Lastly we verify the homomorphism property:

$$\begin{aligned}i_g(xy) &= gxyg^{-1} \\ &= gxeyg^{-1} \\ &= gxg^{-1}gyg^{-1} \\ &= i_g(x)i_g(y)\end{aligned}$$

completing the proof.

□

7 Problems for week of Jan 26

Problem 7.1 (Problem 44 Fraleigh's p.67). Let $G = \langle a \rangle$ be a cyclic group isomorphic to a group G' . If $\phi: G \rightarrow G'$ is an isomorphism, show that for every $x \in G$, $\phi(x)$ is uniquely determined by $\phi(a)$. That is, if ϕ and ψ constitutes isomorphisms from $G \rightarrow G'$ with $\phi(a) = \psi(a)$, then $\phi(x) = \psi(x)$ for every $x \in G$.

Proof. Let G be generated by a , isomorphic to G' via ϕ and ψ , satisfying

$$\phi(a) = \psi(a)$$

Let $x \in G$. Then $x = a^n$ for some $n \in \mathbb{Z}$, as $G = \langle a \rangle$. Observe the following:

$$\begin{aligned}\phi(x) &= \phi(a^n) \\ &= \phi(a)^n \\ &= \psi(a)^n \\ &= \psi(a^n) = \psi(x)\end{aligned}$$

This completes the proof. □

Problem 7.2 (Problem 6 Fraleigh's p.83). Compute $|\sigma|$ for

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 3 & 1 & 4 & 5 & 6 & 2 \end{pmatrix}$$

Solution. Observe that σ is the permutation which sends

$$\begin{aligned}1 &\rightarrow 3 \\ 2 &\rightarrow 1 \\ &\vdots \\ 6 &\rightarrow 2\end{aligned}$$

so σ^2 is

$$\begin{aligned}1 &\rightarrow 4 \\ 2 &\rightarrow 3 \\ &\vdots \\ 6 &\rightarrow 1\end{aligned}$$

We want to find $n \in \mathbb{N}$ such that $\sigma^n =$ the identity permutation. It's easy to see that performing the permutation 6 times gives $1 \rightarrow 1$ which we would require. We also see that $2 \rightarrow 2$, $3 \rightarrow 3$ and so on.

We could also write the permutation in compact form and see that σ is a cycle of length 6, so the order is 6. □

Problem 7.3 (Problem 7 Fraleigh's p.83). Compute $|\tau|$ for

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

Solution. Note that τ in compact notation is

$$\tau = (1\ 2\ 4\ 3)(5\ 6)$$

so τ is the composition of a 2- and 4-cycle.

$$|\tau| = \text{lcm}(4, 2) = 4$$

□

Problem 7.4 (Problem 49 Fraleigh's p.86). If A is a set, then a subgroup $H \leq S_A$ is transitive on A if for each $a, b \in A$ there exists $\sigma \in H$ such that $\sigma(a) = b$. Show that if A is a nonempty finite set, then there exists a finite cyclic subgroup H of S_A with $|H| = |A|$ that is transitive on A .

Proof. Let $A = \{a_1, a_2, \dots, a_n\}$ with S_A being the permutations on A . Let $\sigma \in S_A$ be the permutation which sends $a_i \rightarrow a_{i+1}$ (take i modulo n). It is clear that σ^k is the permutation which sends a_i to a_{i+k} and furthermore $|\sigma| = n = |A|$. It is not hard to see that $\langle \sigma \rangle$ forms a subgroup where each permutation shifts all elements of A .

It is clear that for any $a_i, a_j \in A$ we can find a permutation which sends one to the other. Suppose, without loss of generality, $i < j$. Then $\sigma^{j-i}(a_i) = a_j$, and the inverse of said permutation sends a_j to a_i .

A bit inelegantly written, but I digress. □

Problem 7.5 (Problem 1 Fraleigh's p.94). Find the orbit of

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 5 & 1 & 3 & 6 & 2 & 4 \end{pmatrix}$$

Solution. We are looking at $\sigma \in S_6$ acting on $[6]$ (I assume) so we want to find

$$\{\text{Orb}_\sigma(n) = \{\sigma^k(x) : k \in \mathbb{Z}\} \mid n = 1, 2, \dots, 6\}$$

Let us rewrite σ more compactly.

$$1 \rightarrow 5 \rightarrow 2 \rightarrow 1$$

$$3 \rightarrow 3$$

$$4 \rightarrow 6 \rightarrow 4$$

so

$$\sigma = (1 \ 5 \ 2)(4 \ 6)$$

Thus we have the following orbits:

$$\begin{aligned} \text{Orb}_\sigma(1) &= \text{Orb}_\sigma(2) = \text{Orb}_\sigma(5) = \{1, 2, 5\} \\ \text{Orb}_\sigma(4) &= \text{Orb}_\sigma(6) = \{4, 6\} \\ \text{Orb}_\sigma(3) &= \{3\} \end{aligned}$$

□

Problem 7.6 (Problem 7 Fraleigh's p.94). *Compute:*

$$(1 \ 4 \ 5)(7 \ 8)(2 \ 5 \ 7)$$

Solution.

$$\begin{aligned} (1 \ 4 \ 5)(7 \ 8)(2 \ 5 \ 7) &= (1 \ 4 \ 5) \circ ((7 \ 8)(2 \ 5 \ 7)) \\ &= (1 \ 4 \ 5)(2 \ 5 \ 8 \ 7) \\ &= (2 \ 1 \ 4 \ 5 \ 8 \ 7) \end{aligned}$$

□

Problem 7.7 (Problem 29 Fraleigh's p.96). *Show that for every subgroup H of S_n for $n \geq 2$, either all permutations in H are even or exactly half are.*

Proof. Recall that an even permutation is a permutation which can be expressed as an even number of transpositions (swaps of 2 elements).

Let $\text{sgn}(\sigma) = 1$ if σ is even, $\text{sgn}(\sigma) = -1$ otherwise for all $\sigma \in S_n$. $\text{sgn} : S_n \rightarrow \{1, -1\}$ is a homomorphism. Restrict this map to H . Then, the image:

$$\text{sgn}[H] = \begin{cases} \{+1\} \\ \{+1, -1\} \end{cases}$$

In the first case it is clear that every element of H must be even.

In the other case where sgn is surjective, the kernel

$$\ker(\text{sgn}[H]) = H \cap A_n,$$

the set of even permutations in H . By the first isomorphism theorem,

$$H/(H \cap A_n) \cong \{+1, -1\}$$

so

$$[H : H \cap A_n] = 2$$

8 External- and Internal Direct Products

Definition 8.1. Let $H, K \leq G$,

$$G' = H \times K = \{(h, k) \mid h \in H, k \in K\}$$

$$G = H \oplus K = \{hk \mid h \in H, k \in K\}$$

The internal direct product $H \oplus K$ presupposes that $H, K \trianglelefteq G$, and $H \cap K = \{e\}$.

We really want to be able to say that $H \times K \cong H \oplus K$.

Example 8.1. Consider the dihedral group $D_3 = \{1, x, x^2, y, xy, x^2y\}$. Let $H = \langle x \rangle$ and $K = \langle y \rangle$. It's easy to see that $H \cap K = \{e\} = \{1\}$, and $H \trianglelefteq D_3$. However $xK = \{x, xy\}$, but $Kx = \{x, yx\} = \{x, x^2y\}$. Hence

$$D_3 \neq H \oplus K$$

Lemma 8.1. $H, K \trianglelefteq G$ and $H \cap K = \{e\}$.

1. if $ab = a'b'$ where $a, a' \in H$ and $b, b' \in K$ then $a = a'$ and $b = b'$.
2. if $a \in H$ and $b \in K$ then $ab = ba$.

Theorem 8.1. Assuming H, K normal subgroups of G with trivial intersection, then

$$H \times K \cong H \oplus K$$

Proof. Define a map

$$\varphi : H \times K \rightarrow HK, \quad \varphi(h, k) = hk.$$

This map is well-defined since $h \in H, k \in K$ implies $hk \in HK$.

Define a second map

$$\psi : HK \rightarrow H \times K$$

by sending $g \in HK$ to the unique pair (h, k) such that $g = hk$. Such a decomposition exists since $HK = G$, and is unique because $H \cap K = \{e\}$.

We now verify that these maps are inverse to one another. For all $(h, k) \in H \times K$,

$$(\psi \circ \varphi)(h, k) = \psi(hk) = (h, k),$$

and for all $g \in HK$,

$$(\varphi \circ \psi)(g) = g.$$

Thus φ is bijective with inverse ψ .

Finally, φ is a homomorphism, since for $(h_1, k_1), (h_2, k_2) \in H \times K$,

$$\begin{aligned}\varphi((h_1, k_1)(h_2, k_2)) &= \varphi(h_1 h_2, k_1 k_2) \\ &= h_1 h_2 k_1 k_2 \\ &= h_1 k_1 h_2 k_2 \\ &= \varphi(h_1, k_1) \varphi(h_2, k_2),\end{aligned}$$

where we use that elements of H and K commute.

Therefore φ is an isomorphism, and $HK \cong H \times K$. □

Theorem 8.2. *If $|x|, |y| < \infty$ and $(x, y) \in G \times H$ then $|(x, y)| = \text{lcm}(|x|, |y|)$.*

9 Problems from week of 8 Feb

Problem 9.1 (Problem 47 Fraleigh's p.113). Let G be an abelian group. Let $H \subseteq G$ consisting of the identity and all elements of H with order 2. Show that $H \leq G$.

Proof. Let $H = \{e\} \cup \{g \in G \mid |g| = 2\} \subseteq G$. Let $x, y \in H$, and for the sake of simplicity assume they are nontrivial, i.e. $x \neq e \neq y$. To show that H constitutes a subgroup of G it suffices to show that $xy^{-1} \in H$ (we already know it is nonempty).

$$\begin{aligned} (xy^{-1})^2 &= xy^{-1}xy^{-1} \\ &= xxy^{-1}y^{-1} && (G \text{ abelian}) \\ &= x^2(y^2)^{-1} \\ &= e(e) \\ &= e \end{aligned}$$

Hence $|xy^{-1}| = 2$, so $xy^{-1} \in H$. Thus H is a subgroup of G . \square

Problem 9.2 (Problem 52 Fraleigh's p.113). Show that a finite abelian group is not cyclic if and only if it contains a subgroup isomorphic to $\mathbb{Z}_p \times \mathbb{Z}_p$ for some prime p .

Proof. Let G be a finite abelian group.

We begin by proving the right-to-left implication. Assume then that there is some $H \leq G$ with $H \cong \mathbb{Z}_p \times \mathbb{Z}_p$. Suppose, for a contradiction, that $G = \langle g \rangle$ (cyclic) for some $g \in G$. Let $\phi : H \rightarrow \mathbb{Z}_p \times \mathbb{Z}_p$ be an isomorphism.

Recall that as G is cyclic, generated by g , we have that there is some $k \in \mathbb{Z}$, for every $h \in H$, such that $h = k \cdot g$. As G is finite, $k \cdot g = (|G| - k) \cdot g$, so we can safely assume $k \geq 0$ without any loss of generality.

Since ϕ is bijective we know that, for every $y \in \mathbb{Z}_p \times \mathbb{Z}_p$, there is some $h \in H$ such that

$$\phi(h) = y$$

Using the homomorphism property, and the fact that $h = kg$, $k \in \mathbb{N}$, we

get that:

$$\begin{aligned}
y &= \phi(h) \\
&= \phi(k \cdot g) \\
&= \phi\left(\sum_{i=1}^k g\right) \\
&= \sum_{i=1}^k \phi(g) \\
&= k \cdot \phi(g)
\end{aligned}$$

As y was chosen arbitrarily we now see that $\mathbb{Z}_p \times \mathbb{Z}_p = \langle \phi(g) \rangle$, i.e. cyclic. Being cyclic, together with the fact that $|\mathbb{Z}_p \times \mathbb{Z}_p| = p^2$, it is the case that there must be some element with order p^2 , but no such element exists so $\mathbb{Z}_p \times \mathbb{Z}_p$ is not cyclic. We have arrived at a contradiction so our assumption that G is cyclic must be false.

Now we prove the other direction. We now assume that we have a finite abelian group G which is not cyclic. As G is finite we know that G is finitely generated. Thus by the fundamental theorem of finitely generated abelian groups we know that G is isomorphic to a direct product of cyclic groups of the form

$$\mathbb{Z}_{(p_1)^{\gamma_1}} \times \mathbb{Z}_{(p_2)^{\gamma_2}} \times \cdots \times \mathbb{Z}_{(p_n)^{\gamma_n}} \times \mathbb{Z} \times \mathbb{Z} \times \cdots \times \mathbb{Z}$$

As G is finite, the direct product does not include \mathbb{Z} . Furthermore as G is not cyclic we know that

$$G \not\cong \mathbb{Z}_{p^\gamma}$$

Hence G must be the direct product of at least 2 $\mathbb{Z}_{(p_i)^{\gamma_i}}$. As $\gamma_i \in \mathbb{N} \setminus \{0\}$ and distinct from γ_j for $j \neq i$ there must be some $\mathbb{Z}_{(p_i)^{\gamma_i}}$ with $\gamma_i \geq 2$. Notice that this group necessarily has

$$H = \{0\} \times \cdots \times \{0\} \times \mathbb{Z}_{p_i} \times \{0\} \times \cdots \times \{0\} \times \mathbb{Z}_{p_i} \times \{0\} \times \cdots \times \{0\}$$

as a subgroup, which itself is isomorphic to $\mathbb{Z}_{p_i} \times \mathbb{Z}_{p_i}$. Then $\phi^{-1}[H]$ is a subgroup of G , which is isomorphic to $\mathbb{Z}_{p_i} \times \mathbb{Z}_{p_i}$. \square

Problem 9.3 (Problem 46 Fraleigh's p.135). Let a group G be generated by $\{a_i \mid i \in I\}$, where I is some indexing set and $a_i \in G$ for all $i \in I$. Let ϕ, μ be two homomorphisms from G into a group G' , such that $\phi(a_i) = \mu(a_i)$ for every $i \in I$. Prove that $\phi = \mu$.

Proof. Let $G = \langle a_i \mid i \in I \rangle$ with homomorphisms $\phi, \mu : G \rightarrow G'$ which

coincide on a_i for all $i \in I$. Let $x \in G$.

$$\begin{aligned}
\phi(x) &= \phi\left(\prod_{i \in I} a_i^{k_i}\right), \quad k_i \in \mathbb{Z} \\
&= \prod_{i \in I} \phi(a_i^{k_i}) \\
&= \prod_{i \in I} \underbrace{\phi(a_i) \cdots \phi(a_i)}_{k_i \text{ times}} \\
&= \prod_{i \in I} \underbrace{\mu(a_i) \cdots \mu(a_i)}_{k_i \text{ times}} \\
&= \prod_{i \in I} \mu(a_i^{k_i}) \\
&= \mu\left(\prod_{i \in I} a_i^{k_i}\right) = \mu(x)
\end{aligned}$$

x was chosen arbitrarily hence ϕ and μ coincide on all $x \in G$. In other words, $\phi = \mu$. \square

Problem 9.4 (52 Fraleigh's p.135). Let $\phi : G \rightarrow G'$ be a homomorphism with kernel H and let $a \in G$. Prove the set equality $\{x \in G \mid \phi(x) = \phi(a)\} = Ha$.

Proof. We begin by proving that $Ha \subseteq \{x \in G \mid \phi(x) = \phi(a)\}$.

Suppose $ha \in Ha$. Then $h \in H$ so

$$\phi(ha) = \underbrace{\phi(h)}_{\in H} \phi(a) = e' \phi(a) = \phi(a)$$

Thus $ha \in \{x \in G \mid \phi(x) = \phi(a)\}$. As x was arbitrarily chosen, we conclude that

$$Ha \subseteq \{x \in G \mid \phi(x) = \phi(a)\}$$

Let $x \in \{x \in G \mid \phi(x) = \phi(a)\}$. Then

$$\begin{aligned}
\phi(x) &= \phi(a) \\
\phi(x)\phi(a)^{-1} &= e' \\
\phi(xa^{-1}) &= e'
\end{aligned}$$

hence $xa^{-1} \in H$ which implies $x \in Ha$. Once again x was arbitrarily chosen so

$$\{x \in G \mid \phi(x) = \phi(a)\} \subseteq Ha$$

Summing up we conclude that

$$Ha = \{x \in G \mid \phi(x) = \phi(a)\}$$

10 Problems week of 16 Feb, Quotient grps, simple grps

Problem 10.1 (Problem 3 Fraleigh's p.142). Find the order of the given factor group:

$$(\mathbb{Z}_4 \times \mathbb{Z}_2) / \langle (2, 1) \rangle$$

Solution. We first compute the subgroup generated by $(2, 1)$:

$$\langle (2, 1) \rangle = \{(0, 0), (2, 1)\},$$

since $(2, 1) + (2, 1) = (0, 0)$.

Because $\mathbb{Z}_4 \times \mathbb{Z}_2$ is abelian, every subgroup is normal, so the quotient group is well-defined.

The elements of the quotient

$$(\mathbb{Z}_4 \times \mathbb{Z}_2) / \langle (2, 1) \rangle$$

are the cosets

$$(x, y) + \langle (2, 1) \rangle = \{(x, y), (x + 2, y + 1)\}, \quad (x, y) \in \mathbb{Z}_4 \times \mathbb{Z}_2.$$

Each coset has exactly 2 elements. Since

$$|\mathbb{Z}_4 \times \mathbb{Z}_2| = 8,$$

the number of distinct cosets is

$$\frac{8}{2} = 4.$$

Hence the quotient group has order 4. □

Problem 10.2 (Problem 34 Fraleigh's p.143). Show that if a finite group G has exactly one subgroup H of a given order, then H is a normal subgroup of G .

Proof. Suppose G is a finite group with only one subgroup H of some order $k \in \mathbb{N}$. Recall that for the conjugacy of H is still a subgroup, furthermore

$$|gHg^{-1}| = |H| = k, \quad g \in G$$

However H is the only subgroup with order k so

$$gHg^{-1} = H, \quad \forall g \in G$$

which implies that H is normal. □

Problem 10.3 (Problem 35 Fraleigh's p.143). Show that if H and N are subgroups of a group G , and N is normal in G , then $H \cap N$ is normal in H .

Proof. Let G be a group with $H \leq G$ and $N \trianglelefteq G$. We take it for granted that $H \cap N$ is indeed a group (this is not hard to show).

Fix some arbitrary $h \in H$. We must show that $h(H \cap N)h^{-1} \subseteq H \cap N$.

Let $x \in H \cap N$. As $x, h \in H$ we certainly have $h x h^{-1} \in H$. As $x \in N$, N normal, we have that for any $h \in H \subseteq G$, $h x h^{-1} \in N$.

Hence

$$h x h^{-1} \in H \cap N$$

□

Problem 10.4 (Problem 3 Fraleigh's p.151). Classify the groups according to the fundamental theorem of finitely generated abelian groups.

$$\begin{aligned} &(\mathbb{Z}_2 \times \mathbb{Z}_4) / \langle (1, 2) \rangle \\ &(\mathbb{Z}_4 \times \mathbb{Z}_8) / \langle (1, 2) \rangle \\ &(\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_8) / \langle (1, 2, 4) \rangle \end{aligned}$$

Solution. We begin with $(\mathbb{Z}_2 \times \mathbb{Z}_4) / \langle (1, 2) \rangle$.

$$\begin{aligned} \langle (1, 2) \rangle &= \{(0, 0), (1, 2)\} \\ (0, 0)\{(0, 0), (1, 2)\} &= \{(0, 0), (1, 2)\} = A \\ (1, 0)\{(0, 0), (1, 2)\} &= \{(1, 0), (0, 2)\} = B \\ (0, 1)\{(0, 0), (1, 2)\} &= \{(0, 1), (1, 3)\} = C \\ (1, 1)\{(0, 0), (1, 2)\} &= \{(1, 1), (0, 3)\} = D \\ (0, 2)\{(0, 0), (1, 2)\} &= \{(1, 0), (0, 2)\} = B \\ (1, 2)\{(0, 0), (1, 2)\} &= \{(1, 2), (0, 0)\} = A \\ (0, 3)\{(0, 0), (1, 2)\} &= \{(0, 3), (1, 1)\} = D \\ (1, 3)\{(0, 0), (1, 2)\} &= \{(1, 3), (0, 1)\} = C \end{aligned}$$

We get an abelian group with 4 distinct elements. Crucially, we can see that the coset of $(0, 1)$ has order 4 and is thus a generator. We conclude that $(\mathbb{Z}_2 \times \mathbb{Z}_4) / \langle (1, 2) \rangle \cong \mathbb{Z}_4$.

Now we look at $(\mathbb{Z}_4 \times \mathbb{Z}_8) / \langle (1, 2) \rangle$.

Notice that

$$(\mathbb{Z}_4 \times \mathbb{Z}_8) = \langle a, b \mid 4a = 0, 8b = 0, ab = ba \rangle$$

so quotienting with $\langle(1,2)\rangle$ only imposes the extra relation that

$$a + 2b = 0 \Leftrightarrow a = -2b$$

then $\text{ord}(1,2) = \text{lcm}(4,4) = 4$ so $\langle(1,2)\rangle$ has 4 elements. $|\mathbb{Z}_4 \times \mathbb{Z}_8| = 32$ so the quotient group has

$$\frac{32}{4} = 8$$

elements. Up to isomorphism there exist 3 abelian groups of order 8. The relation imposed by $\langle(1,2)\rangle$ changes nothing so we require $8b = 0$. Clearly

$$(\mathbb{Z}_4 \times \mathbb{Z}_8) / \langle(1,2)\rangle \cong \mathbb{Z}_8$$

Lastly we look at

$$(\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_8) / \langle(1,2,4)\rangle$$

Notice that

$$\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_8 = \{a, b, c \mid 4a = 0, 4b = 0, 8c = 0, ab = ba, ac = ca, bc = cb\}$$

with

$$\langle(1,2,4)\rangle$$

imposing $a + 2b + 4c = 0$ which then means that $a = -2b - 4c$. The order of $\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_8$ is 128. The order of the subgroup is $\text{lcm}(4,2,2)$ which is 4. Thus the order of the quotient group is

$$\frac{128}{4} = 32 = 2^5$$

There are precisely 7 abelian groups unique up to isomorphism. b has order 4 and c has 8 so we conclude that the quotient group is isomorphic to

$$\mathbb{Z}_4 \times \mathbb{Z}_8$$

□

Problem 10.5 (Problem 34 Fraleigh's p.153). Let G be finite, containing a nontrivial subgroup of index 2 in G . Show that G is not simple.

Proof. There exists a subgroup $H \leq G$ with 2 left cosets. Since H is always a left coset of H there must be one more left coset gH for any $g \notin H$. Since the number of right cosets is the same we have right cosets H and Hg . There are only 2 cosets so the non- H cosets must be the same

$$gH = Hg$$

Thus left and right cosets coincide. Therefore

$$H \trianglelefteq G$$

H is nontrivial, and crucially $H \neq G$ (since the index is 2). Hence G has a nontrivial proper subgroup. In other words, G is not simple. □

11 Group Actions

Definition 11.1. Let X be a set, and G a group. A (left) action of G on X is a map

$$\begin{aligned} G \times X &\rightarrow X \\ (g, x) &\mapsto gx \end{aligned}$$

such that $ex = x$ and $g_1(g_2x) = (g_1g_2)x$ for all $x \in X$ and $g_1, g_2 \in G$.

The right action is similarly defined, and in the case where G is abelian the actions coincide.

Example 11.1. The following constitute group actions when considering matrix-vector multiplication.

1. $GL_2(\mathbb{R})$ and its subgroups on \mathbb{R}^2 .
2. same for $GL_n(\mathbb{R})$ on \mathbb{R}^n .

A very natural group action is D_n acting on the regular polygon with n sides, as D_n is the symmetries of the regular n -gon. Furthermore S_n (which is often thought of as the bijections $f: [n] \rightarrow [n]$) can act on said $[n]$.

Another group action which we have also seen many times is conjugation where G acts on itself.

Definition 11.2. Let G be a group and X a set.

We say that a group action $G \times X \rightarrow X$ is faithful if for any $g \in G$, $g \neq e$ implies there is some $x \in X$ such that $gx \neq x$.

Alternatively it can be defined to be a group action for which any $g_1, g_2 \in G$ with $g_1 \neq g_2$ implies that there exists $x \in X$ such that $g_1x \neq g_2x$.

Proposition 11.1. Consider a group action $G \times X \rightarrow X$. It defines a group homomorphism $\phi: G \rightarrow \text{Sym}(X)$ for which $\ker \phi = \{e\}$ if and only if the group action is faithful.

Problem 11.1 (Problem 11 Fraleigh's p.160). *Let X be a G -set. Show that G acts faithfully on X if and only if no two distinct elements of G have the same action on each element X . (I.e. prove the equivalent definition posed in definition 11.2)*

Proof. Let G be a group, X a G -set.

Assume first that the action of G on X is faithful. Then $e \neq g \in G$ implies the existence of some $x \in X$ for which

$$gx \neq x$$

Suppose, for a contradiction, that there exist some distinct $g_1, g_2 \in G$ which coincide on every $x \in X$. Then

$$\begin{aligned} g_1x &= g_2x \\ g_2^{-1}g_1x &= x \end{aligned}$$

In other words there exists $g = g_2^{-1}g_1 \in G$ for which every $x \in X$ is a fixed-point, contradicting the assumption that G acts faithfully on X . Thus G acting faithfully on X must imply that any distinct pair of elements of G have some $x \in X$ for which they do not coincide.

Assume now that G acts on X such that for every distinct $g_1, g_2 \in G$ for which there exists $x \in X$ such that $g_1x \neq g_2x$. Let $g_2 = e \neq g_1$. They are clearly distinct and furthermore

$$g_1x \neq g_2x = x$$

This holds for any $g_1 \in G$ so G acts faithfully on X . □

Definition 11.3 (Orbit). *Let G be a group acting on a G -set X . Let $x \in X$. The orbit of x , often denoted $\text{Orb}(x)$ or Gx is the set*

$$\text{Orb}(x) := \{gx \mid g \in G\}$$

Definition 11.4 (Stabilizer). *Let G be a group acting on a G -set X . Let $x \in X$. The stabilizer of x , often denoted $\text{Stab}_G(x)$ or G_x is the set*

$$\{g \in G \mid gx = x\}$$

Theorem 11.1 (Orbit-Stabilizer). *For a finite group G acting on a set X , the following holds (conditions are equivalent).*

$$|\text{Orb}(x)| = [G : \text{Stab}_G(x)]$$

$$|G| = |\text{Orb}(x)| \cdot |\text{Stab}_G(x)|$$

Problem 11.2. *Let $\{X_i \mid i \in I\}$ be a disjoint collection of sets. Let each X_i be a G -set for the same group G .*

- a) *Show that $\bigcup_{i \in I} X_i$ can be viewed in a natural way as a G -set, the **union** of the G -sets X_i .*
b) *Show that every G -set X is the union of its orbits.*

Proof of (a). Let $X = \bigcup_{i \in I} X_i$. Since the union is disjoint, each $x \in X$ lies in a unique X_i . Define

$$g \cdot x := g \cdot_{X_i} x$$

where the right-hand side denotes the given G -action on X_i .

This is well-defined because the union is disjoint. For $x \in X_i$ we have

$$e \cdot x = x$$

since X_i is a G -set, and

$$(gh) \cdot x = (gh) \cdot_{X_i} x = g \cdot_{X_i} (h \cdot_{X_i} x) = g \cdot (h \cdot x).$$

Thus the action axioms hold, and X becomes a G -set. □

Proof of (b). For $x \in X$, define the orbit

$$G \cdot x = \{g \cdot x \mid g \in G\}.$$

Since $x = e \cdot x$, every element lies in its orbit, so

$$X = \bigcup_{x \in X} G \cdot x.$$

If $G \cdot x \cap G \cdot y \neq \emptyset$, then $g \cdot x = h \cdot y$ for some $g, h \in G$. Then

$$x = g^{-1}h \cdot y,$$

so $x \in G \cdot y$, which implies $G \cdot x = G \cdot y$. Thus distinct orbits are disjoint, and X is the disjoint union of its orbits. □

Theorem 11.2 (Burnside's Formula). Let G be a finite group and X a finite G -set. If r is the number of orbits in X under G , then

$$r \cdot |G| = \sum_{g \in G} |X_g|$$

where X_g are the fixed points of g , namely all $x \in X$ satisfying $gx = x$.

Problem 11.3 (Problem 1 Fraileigh's p.164). Find the number of orbits in $\{1, \dots, 8\}$ under the cyclic subgroup $\langle (1\ 3\ 5\ 6) \rangle \leq S_8$.

Solution. Both $[8]$ and the given subgroup of S_8 are finite so we use Burnside's formula. Denote $\langle \sigma \rangle := \langle (1\ 3\ 5\ 6) \rangle$. We know that $|\sigma| = 4$ so we must simply calculate the sum of sizes of fixed points of each permutation in $\langle \sigma \rangle$. Obviously $|X_e| = |X| = 8$. Next up σ has 2, 4, 7, 8 as fixed points so $|X_\sigma| = 4$. Next up $\sigma^2 = (1\ 5)(3\ 6)$ and has the same fixed points. $\sigma^3 = (1\ 6\ 5\ 3)$ with the same fixed points once again. Thus

$$r = 8 + 4 + 4 + 4/|\sigma| = 5$$

□