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# 0. Preliminaries

## Resources Used

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- **Fundamentals of the Theory of Groups**, translated second Russian Ed., by M.I. Kargapolov and Ju.I. Merzljakov
- **Algebra** by Thomas W. Hungerford
- **Abstract Algebra**, 3rd Ed., by David S. Dummit and Richard M. Foote

## Notation

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- $0 \in \mathbb{N}$  and  $\mathbb{N}^* := \mathbb{N} \setminus \{0\}$ .
- $(m, n)$  denotes the **greatest common divisor** of  $m, n \in \mathbb{N}$ .

# 1. Groups

## Def. Group

---

A **group** is an ordered pair  $(G, \cdot)$  where  $G$  is a set and  $\cdot$  is a binary operation on  $G$  that satisfies:

Simply,  $\cdot$  is a (total) function from  $G$  to  $G$ . Notice that  $G$  is an any set, finite or infinite.

- **Associativity**, that is, for all  $a, b, c \in G$  we have  $(a \cdot b) \cdot c = a \cdot (b \cdot c)$

This alone defines a **semigroup**.

- **Identity**, that is, there exists  $e \in G$  called **identity** (of  $G$ ) such that for all  $a \in G$  we have  $a \cdot e = e \cdot a = a$ .

Until here it defines a **monoid** where identity is two-sided, namely left and right.

- **Inverse**, that is, for each  $a \in G$  there exists an element (called **inverse**)  $b \in G$  such that  $a \cdot b = b \cdot a = e$ .

Noting that the **identity** of a group and the **inverse** of an element in that group is always unique (exercise) we will denote the inverse of an element  $a$  with  $a^{-1}$  unless it is **abelian**.

A group is called **abelian** (or **commutative**) if its elements commute, that is, if for all  $a, b \in G$  we have  $a \cdot b = b \cdot a$ . For abelian groups, we may prefer the additive notation  $+$  instead of  $\cdot$  for the binary operation and denote the inverse with  $-a$  instead.

You might also sometimes want to consider the group as a triplet with identity  $(G, \cdot, e)$  as it is not clear otherwise what is the identity explicitly.

## Remarks

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The definition (or axioms) given above are not minimal. For example, it's enough to just accept **right-identity** and **right-inverse** for it to be group. Using just these two, you can later prove it also holds for the **left-identity** and **left-inverse** with the help of the associative property.

Associative property by far is the most powerful property of the group. It allows you to write your expression (involving only  $\cdot$ ) without any parentheses and much more.

Indeed a structure which only satisfies associative property is called a **semigroup**. A semigroup with identity is called a **monoid** and a monoid with inverses is called a **group**.

## Thm. Basic *Monoid* Properties

---

If  $(M, \cdot)$  is a monoid, then

1. The identity element of  $M$  is unique.

## Thm. Semigroup to Group

---

Let  $(S, \cdot)$  be a semigroup, then it is a group if and only if both of the following hold:

- Left-identity exists, and
- Left-inverse exists for each  $s \in S$ .

By symmetry, the analogous result holds for rights instead of left.

## Thm. Semigroup to Group 2

---

Let  $(S, \cdot)$  be a semigroup, then it is a group if and only if for all  $a, b \in S$  the equations

$$\begin{aligned} ax &= b \\ ya &= b \end{aligned}$$

have solutions in  $G$ .

## Thm. Generalized Associative Law

---

Let  $(S, \cdot)$  be a semigroup and  $a_i \in S$ . Associative property implies that the expression  $a_1 \cdot a_2 \cdot \dots \cdot a_n$  is the same no matter how the expression bracketed.

### ► Proof

Similarly one could also prove **Generalized Commutative Law** for the commutative property.

## Thm. Basic Group Properties

---

Remembering any group is also a monoid and thus a semigroup, let  $(G, \cdot)$  be a group. Then:

1. Identity  $e$  is unique. The uniqueness of the identity element does not require the use of associativity.
2. For each  $a \in G$ , inverse of  $a$  is unique.
3. For each  $a \in G$ , we have  $(a^{-1})^{-1} = a$ .
4. For all  $a, b \in G$ , we have  $(a \cdot b)^{-1} = b^{-1} \cdot a^{-1}$ . Indeed, in general,  $(a_1 \cdot \dots \cdot a_n)^{-1} = a_n^{-1} \cdot \dots \cdot a_1^{-1}$ .

### ► Proof

## Def. Order

---

Let  $(G, \cdot)$  be a group and  $a \in G$ .

The **order of (the group)**  $G$  is denoted by  $|G|$  and is the cardinality of the set  $G$ .

The **order of (the element)**  $a$  is denoted by  $|a|$  and (if exists) it is the least positive integer  $n$  such that  $x^n = e$ . If there is no such  $n$ , we say the order is infinite.

Order of an element  $a$  is sometimes denoted with  $o(a)$ .

If the order of an element  $x$  (or group) is finite, we will denote it with  $|x| < \infty$ . Moreover, if  $x^2 = x$ , then  $x$  is called an **idempotent element** where  $e$  is the **trivial idempotent element**.

We say that a group is **torsion-free** if every nonidentity element has infinite order. If every element of a group has finite order then we say the group is **periodic**.

If orders of a periodic group are bounded, then the least common multiple of their orders is called the **exponent** of the group. If the orders of elements of a periodic group are powers of prime  $p$ , then we call the group a  $p$ -group.

## Notation. The Additive Notation

---

If the binary operation is written additively, which is mostly the case for abelian groups, we may write:

- 0 for the identity instead of 1 (or  $e$  for that matter).
- $na$  instead of  $a^n$  where  $n \in \mathbb{Z}$ . Notice that operation between  $n$  and  $a$  is not the binary operation of our structure but rather " $n$  times  $a$ ".

We define  $a^0$  (or  $0a$ ) as the identity element 1 or 0. Notice that, in additive notation,  $0a$  is not the multiplication by the identity but rather " $0$  times  $n$ " which we define to be *the identity* 0.

## Thm. More Group Properties

---

Let  $G$  be a group, then

1. If  $a^2 = e$  for all  $a \in G$ , then  $G$  is abelian.
2. If  $|G|$  is finite and even, then it has an element of order 2.

► **Proof**

# 2. Group Examples

All of these groups can be considered their own field of research, so it is suggested you visit their wiki, understand the basics, and follow from there as you see fit.

## Dihedral Groups

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See [Wikipedia: Dihedral group](#).

## Symmetric Groups

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See [Wikipedia: Dihedral group](#).

### Thm. Symmetric Groups Basics

- For  $n > 2$  the symmetric group  $S_n$  is nonabelian. So,  $S_3$  is a good example of nonabelian group of order 3.

## Matrix Groups

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### Exercise 1

Find the order of the (general linear) group  $GL(3, \mathbb{Z}_5)$ .

In General Linear Group, matrix multiplication is the binary operation.

► **Answer**

## The Quaternion Group

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See [Wikipedia: Quaternion group](#).

## The $Q_p$ Group

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Let  $p$  prime. Denote by  $Q_p$  the set:

$$\{m/n^p : m, n \in \mathbb{Z}\}$$



or the group with the usual addition in rationals.

## Def. Homomorphisms

---

Let  $(G, \cdot_G, e_G)$  and  $(H, \cdot_H, e_H)$  be groups.

The (total) function (or map)  $\varphi : G \rightarrow H$  is called a **(group) homomorphism** if, for all  $a, b \in G$ :

$$\varphi(a \cdot_G b) = \varphi(a) \cdot_H \varphi(b)$$

Mostly, we will not be as explicit about the operations and simply write  $\varphi(ab) = \varphi(a)\varphi(b)$ .

The homomorphism  $\varphi : G \rightarrow H$  is called:

- an **monomorphism** if it is injective,
- an **epimorphism** if it is surjective,
- an **isomorphism** if it is bijective.
  
- an **endomorphism** if  $G = H$ , and
- an **automorphism** if it is an endomorphism and bijective.

Notice that if there exists an isomorphism between two groups, then basically, they have the same structure\*.

(Existence of an) isomorphism between two groups  $G$  and  $H$  is denoted with  $G \cong H$ .

## Exercise 2

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Prove  $Q_p$  is *not* isomorphic to  $Q_r$  for distinct primes  $p$  and  $r$ .

► **Proof**

# 3. Homomorphisms

## Def. Homomorphism

---

Let  $(G, \cdot_G)$  and  $(H, \cdot_H)$  be semigroups.

The (total) function (or map)  $\varphi : G \rightarrow H$  is called a **homomorphism** if, for all  $a, b \in G$ :

$$\varphi(a \cdot_G b) = \varphi(a) \cdot_H \varphi(b)$$

Mostly, we will not be as explicit about the operations and simply write  $\varphi(ab) = \varphi(a)\varphi(b)$  instead.

The homomorphism  $\varphi$  is called:

- an **monomorphism** if it is injective,
- an **epimorphism** if it is surjective,
- an **isomorphism** if it is bijective.
  
- an **endomorphism** if  $G = H$ , and
- an **automorphism** if it is an endomorphism and bijective.

Composition of homomorphisms is again a homomorphism. Respectively, this is also the case for monomorphisms, epimorphisms, isomorphisms and automorphisms.

## Example

If  $A$  is abelian, then the map  $a \mapsto a^{-1}$  is an automorphism, and the map  $a \mapsto a^2$  is an endomorphism.

## Def. Kernel

---

If  $\varphi : G \rightarrow H$  is a group homomorphism, then the **kernel** of  $\varphi$  is the set

$$\{ g \in G \mid \varphi(g) = e_H \}$$

denoted by  $\text{Ker } \varphi$ .

This is also sometimes denoted by  $\varphi^{-1}(e_H)$ .

## Notation. Homomorphisms

---

We say semigroups  $G$  and  $H$  are **isomorphic** denoted with  $G \cong H$  if there exists an isomorphism between them.

Let  $\phi : G \rightarrow H$  be a group homomorphism,  $g \in G$  and  $A \subseteq G$ . Then

- $g^\phi$  denotes  $\phi(g)$ , and
- $A^\phi$  denotes  $\phi(A)$  called the **homomorphic (respectively monomorphic, epimorphic, ...) image** of  $A$ .

$\phi(A)$  is sometimes also denoted with  $\text{Im } A$  — we will not prefer this notation.

## Thm. Basic Homomorphism Properties

---

Let  $\varphi : G \rightarrow H$  be a group homomorphism, then

1.  $\varphi(e_G) = e_H$ . This is not necessarily true for monoid homomorphisms!
2.  $\varphi(g^{-1}) = \varphi(g)^{-1}$  for all  $g \in G$ ,
3.  $\varphi(g^n) = \varphi(g)^n$  for all  $g \in G$  and  $n \in \mathbb{Z}$ ,
4.  $\text{Ker } \varphi \leq G$ ,
5.  $\varphi(G) \leq H$

## Def. Basic Kernel Properties

---

Let  $\varphi : G \rightarrow H$  be a group homomorphism, then

1.  $\varphi$  is a monomorphism if and only if  $\text{Ker } \varphi = \{e_G\}$ .
2.  $\varphi$  is an isomorphism if and only if there exists an homomorphism  $\varphi^{-1} : H \rightarrow G$  such that  $\varphi\varphi^{-1} = e_H$ .

## Thm. More Homomorphism Properties

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1.  $A$  is abelian group if and only if the map  $a \mapsto a^{-1}$  is an automorphism.

► **Proof**

## Def. Group Action

---

See **Wikipedia: Group action**.

Let  $G$  be a group and  $X$  any set. A binary operation  $\bullet : G \times X \rightarrow X$  is called a **(left) group action** if, for all  $a, b \in G$  and  $x \in X$ :

- $a \bullet (b \bullet x) = (ab) \bullet x$ , and
- $e \bullet x = x$

For establishing general properties of group actions, it suffices to consider only left actions.

# 4. Subgroups

Until now we have explicitly defined and shown which multiplication is which operator and which identity belongs which group. From now on, these must be understood from the context. We will prefer little brevity over cumbersome notation.

## Def. Subgroup

---

Let  $G$  be a group and non-empty  $H \subseteq G$ . The non-empty subset  $H$  is called a **subgroup** if  $H$  is again a group under the restriction of  $G$ 's binary operation. This implies  $H$  has the same identity as  $G$  under the same binary operation.

Equivalently, a subset  $H \subseteq G$  of a group  $G$  is called a **subgroup** if

- $H$  has the same identity as  $G$ ,
- For all  $a, b \in H$ , we have  $ab \in H$ ,
- Every element  $h \in H$  has an inverse.

To be more compact, *non-empty*  $H \subseteq G$  is called a **subgroup** if and only if (exercise):

- For all  $a, b \in H$  we have  $ab^{-1} \in H$ .

From now on, we will denote by  $H \leq G$  that  $H$  is a subgroup of  $G$ , moreover  $H < G$  if  $H \neq G$ . The latter is called a **proper subgroup** of  $G$ .

Any group has two subgroups called the **trivial subgroup** which consists of only the identity and the group itself.

Convention regarding to this **trivial** and **proper** notation differs from author to author — we will stick to this naming.

## Example. Some Subgroups

---

- Under addition,  $\mathbb{Z} < \mathbb{Q}_p, < \mathbb{Q} < \mathbb{R} < \mathbb{C}$ ,
- Under addition,  $\mathbb{Z} = \bigcap \mathbb{Q}_p$ ,
- $\mathbf{GF}(p^m) \leq \mathbf{GF}(p^n)$  if  $m \mid n$  where  $\mathbf{GF}(p^m)$  is the appropriate subset of the algebraic closure of  $\mathbf{GF}(p)$ .
- Under multiplication,  $\mathbb{Z}^* < \mathbb{Q}^*, < \mathbb{R}^* < \mathbb{C}^*$ ,
- Under multiplication,  $\mathbb{C}_p^* < \mathbb{C}_{p^2}^* < \dots < \mathbb{C}_{p^\infty}^*$ ,
- $\mathbb{C}_{p^\infty} = \bigcup \mathbb{C}_{p^n}$ ,
- $\mathbf{GF}(p^m)^* \leq \mathbf{GF}(p^n)^*$  if  $m \mid n$ .

- The subset  $A_n$  of all *even* permutations forms a subgroup called the **alternating group of degree  $n$** , and  $|A_n| = n!/2$ .

## Thm. Finite and Closed Subset

---

Let  $G$  be a group and  $S$  a non-empty subset of  $G$ . If  $S$  is finite and closed under the group product, then  $S$  is a subgroup of  $G$ .

So, we don't even need the inverse condition if  $S$  non-empty and finite.

► **Proof**

## Thm. Intersection of Subgroups

---

Let  $\{H_i\}$  be any non-empty family of subgroups of  $G$ , then  $\bigcup H_i$  is also a subgroup of  $G$ .

► **Proof**

## Thm. Subgroups Under Multiplication

---

Let  $G$  be a group and  $H, K \leq G$ , then

- $HH = H$  and  $H^{-1} = H$ , thus obviously
- $HH^{-1} = H$ ,
- $HK$  is a group if and only if  $HK = KH$ , and
- If  $A, B$  are finite subgroups of a group  $G$ , then

$$|AB| = \frac{|A| \cdot |B|}{|A \cap B|}$$

# 5. Generators

## Def. Generators

---

From now on, for a group  $G$  and a subset  $A \subseteq G$ , we will denote by  $L(G, A)$  the set of all subgroups of  $G$  that contain  $A$ . In particular,  $L(G)$  denotes the **set of all subgroups of  $G$** .

Noting that intersection of any collection of subgroups are again a subgroup, we define for any set  $M \subseteq G$ , the **subgroup generated by  $M$** , denoted  $\langle M \rangle$ , as the intersection of all subgroups which contain  $M$ . That is

$$\langle M \rangle := \bigcap_{H_i \in L(G, M)} H_i$$

Elements of  $M$ , or even  $M$  itself, are called the **generators** of the subgroup  $\langle M \rangle$ . If  $M$  is finite, then we say  $\langle M \rangle$  is **finitely generated**.

From now on, when we use set builder notation, instead of  $\langle \{ x_1, x_2, \dots \in X \mid \dots \} \rangle$  we will omit the parentheses and simply write  $\langle x_1, x_2, \dots \mid \dots \rangle$ .

An element is called a **non-generator** of a group  $G$  if it can be omitted from every generating set for  $G$ .

Generally, this definition of a generated subgroup is not really easy to work with. So equivalently...

### Thm. Equivalent Generation Definition

If  $M$  is a subset of a group  $G$ , then

$$\langle M \rangle = \{ a_1^{\epsilon_1} \cdots a_k^{\epsilon_k} \mid a_i \in M, \epsilon_i = \pm 1, k = 1, 2, \dots \}.$$

### Thm. Equivalent Generation Definition 2

Let  $G$  be a group and  $M \subseteq G$ , then

$$\langle M \rangle = \{ a_1^{n_1} \cdots a_k^{n_k} \mid a_i \in M \text{ and } k, n_i \in \mathbb{Z} \}.$$

That is,  $\langle M \rangle$  consists of all finite products of  $a_1^{n_1} \cdots a_k^{n_k}$ .

Therefore, in particular  $\langle x \rangle = \{ x^n \mid n \in \mathbb{Z} \}$ . We will inspect these structures in detail in the next chapter.

#### ► Proof

## Def. Join of Subgroups

---

Let  $H_i$  be subgroups of  $G$ , then their **join** is defined as  $\langle \bigcup H_i \rangle$  or, if finitely many, as  $\langle H_1, \dots, H_n \rangle$ . The join of two subgroups  $H, K$  will simply be denoted as  $H \vee K$ .

This notation will make sense later on when we define lattices over groups.

## Example. Generator Examples

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- $\mathbb{Z} = \langle 1 \rangle,$
- $\mathbb{Z}_n = \langle \bar{1} \rangle,$
- $\mathbb{Q} = \left\langle \frac{1}{n} \mid n = 1, 2, \dots \right\rangle,$
- $\mathbb{Z}^* = \langle -1 \rangle,$
- $\mathbb{Q}^* = \langle -1, 2, 3, 5, 11, \dots \rangle,$



# 6. Cyclic Groups

This section contains important counting theorems (not just for cyclic or abelian groups); hence, it is important to be familiar with every proof in this exercise.

## Def. Cyclic Group

---

A group  $H$  is called **cyclic group**, or simply **cyclic**, if  $H$  can be generated by a single element. That is, there exists an element  $x \in H$  such that  $H = \langle x \rangle = \{ x^n \mid n \in \mathbb{Z} \}$ . Such  $x$  is called the **generator** of  $H$  or  $H$  is **generated by  $x$** .

Since cyclic groups are abelian (exercise), additive notation may also be used. In that case,  $x^n$  becomes  $nx$ .

Notice that the order of the element  $x$  and the group  $\langle x \rangle$  are the same.

## Thm. Basic Cyclic Properties

---

Let  $H$  be a cyclic group, then

- $H$  is also abelian. So, cyclic implies abelian!
- If  $x$  is a generator of  $H$ , then so is  $x^{-1}$ .
- If  $x$  is a generator of  $H$ , then  $|H| = |x|$ .

## Thm. Fundamental Order Property

---

Let  $G$  be a group,  $g \in G$ , and  $m, n \in \mathbb{Z}$ . If  $x^m = e$  and  $x^n = e$ , then  $x^d = e$  where  $d = (m, n)$ .

In particular, for any  $m$  such that  $x^m = e$ , we have  $|x|$  divides  $m$ .

► **Proof**

## Thm. Every Subgroup of $\mathbb{Z}$ is Also Cyclic

---

Noting subgroup of a cyclic is cyclic, let  $(H, +) \leq (\mathbb{Z}, +)$ . Then, either

- $H = \langle 0 \rangle$  which is the trivial subgroup  $\{0\}$ , or
- $H = \langle m \rangle$  where  $m$  is the least positive integer in  $H$ . In this case,  $H$  is infinite.

► **Proof**

## Thm. Same Order Cyclics are Isomorphic

---

For any two cyclic groups  $\langle x \rangle$  and  $\langle y \rangle$ , if their orders are the same, there exists an isomorphism  $\varphi : \langle x \rangle \rightarrow \langle y \rangle$ .

1. Indeed, if they are finite, then the map

$$\varphi : \langle x \rangle \rightarrow \langle y \rangle$$

$$x^k \mapsto y^k$$

is well-defined and an isomorphism. Therefore, any finite cyclic group of order  $n$  is isomorphic to the cyclic group  $(\mathbb{Z}_n, +_{\mathbb{Z}})$ .

2. If they are infinite, then the map

$$\varphi : \mathbb{Z} \rightarrow \langle x \rangle$$

$$k \mapsto x^k$$

is well-defined and an isomorphism. Therefore, any infinite cyclic group is isomorphic to  $(\mathbb{Z}, +_{\mathbb{Z}})$ .

► **Proof**

## Thm. Fundamentals of Element Orders

---

Let  $G$  be any group,  $x \in G$  and  $a \in \mathbb{Z}^*$ , then

1. If  $|x| = \infty$ , then  $|x^a| = \infty$ .
2. If  $|x| = n$ , then  $|x^a| = \frac{n}{(n, a)}$ .

## Thm. Orders of Commutative Elements

---

Let  $G$  be a group and  $a$  and  $b$  elements of  $G$  whose orders are respectively  $m$  and  $n$ . If  $a$  and  $b$  commute, then

1.  $(m, n) = 1 \implies |ab| = |a| |b|$ ,
2. There exists  $g \in G$  such that  $|g| = \text{lcm}(m, n)$ .

► **Proof**

## Thm. Commutative Elements

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## Thm. On Generators of Cyclics

---

Let  $H = \langle x \rangle$ , then

1. If  $H$  is infinite, then  $x$  and  $x^{-1}$  are the only generators of  $H$ .
2. If  $H$  is finite of order  $n$ , then  $x^k$  is a generator of  $H$ , if and only if  $(k, n) = 1$ .

Therefore, the number of generators of  $H$  equals to  $\varphi(n)$  where  $\varphi$  is Euler's  $\phi$ -function.

## Thm. Basic Cyclic Properties

---

Let  $H = \langle x \rangle$  be cyclic, then

1. Every subgroup of  $H$  is also cyclic.
2. If  $H$  is infinite, then for any distinct non-negative integers  $a$  and  $b$ ,  $\langle x^a \rangle \neq \langle x^b \rangle$ .
3. For every integer  $m$  we have  $\langle x^m \rangle = \langle x^{-m} \rangle$ . Therefore, every non-trivial subgroup of  $H$ ...

## Def. Locally Cyclic

---

A group  $G$  is said to be **locally cyclic** if every finitely generated subgroup is cyclic.

## Thm. Locally Cyclic Properties

---

1. Every cyclic group is locally cyclic.
2. Every finitely-generated locally cyclic group is cyclic.
3. Every subgroup (and quotient group) of a locally cyclic group is locally cyclic.
4. Every homomorphic image of a locally cyclic group is locally cyclic.
5. A group is locally cyclic if and only if every pair of elements in the group generates a cyclic group.
6. A group is locally cyclic if and only if its lattice of subgroups is distributive.

Let  $\varphi : G \rightarrow H$  be a group homomorphism,  $G$  cyclic, and  $a \in G$ . Then,  $\langle \varphi(a) \rangle$  is also cyclic. In particular,  $\varphi(G)$  is cyclic.

### ► Proof

→

## Thm. Finite Subgroups Imply Finite Group

---

Any group which has only finitely many subgroups must also be finite.

### ► Proof

# 7. Cosets and Index

## Def. Coset

---

Let  $G$  be a group and  $H \leq G$ . Then, for all  $a \in G$  the set  $Ha$  is called a **right coset** and the set  $aH$  is called a **left coset**.

## Def. Coset Congruence

---

Let  $G$  be a group,  $H \leq G$ , and  $a, b \in G$ . We say,

- $a$  is **right-congruent to  $b$  modulo  $H$** , denoted by  $a \equiv_R b \pmod{H}$  when  $ab^{-1} \in H$ ,
- $a$  is **left-congruent to  $b$  modulo  $H$** , denoted by  $a \equiv_L b \pmod{H}$  when  $a^{-1}b \in H$ .

## Thm. Coset Congruence

---

1. The relations  $\equiv_R$  and  $\equiv_L$  are equivalence relations.
2. The right (respectively left) equivalence class of  $a \in G$  is the set  $Ha$  (respectively  $aH$ ).
3. If  $G$  is abelian, then left and right congruence coincide. (This is also possible if  $G$  is not abelian.)
4. For all  $a \in G$ , the orders (cardinalities) of the sets  $Ha$ ,  $H$  and  $aH$  are the same.

## Corollary. Coset Congruence

Let  $G$  be a group and  $H \leq G$ . Then

1.  $G$  is the union of right (respectively left) cosets of  $H$ ,
2. Two right (respectively left) cosets are either *disjoint* or *equal*,
3. Number of distinct left cosets are equal to number of distinct right cosets.

## Def. Index

---

### Wiki: Index of a subgroup

Let  $G$  be group and  $H \leq G$  then the **index of  $H$  in  $G$** , denoted  $|G : H|$  is the *cardinal number* of the set of distinct right (or left) cosets of  $H$  in  $G$ .

## Thm. Index Theorem

---

Let  $G$  be a group and  $K \leq H \leq G$ , then

$$|G : K| = |G : H||H : K|$$

### Corollary: Lagrange's Theorem

Let  $G$  be a group and  $H \leq G$ , then the order of  $H$  divides the order of  $G$ . In general, even if  $G$  is infinite

$$|G| = |G : H| \cdot |H|$$

### Corollary: Element Order Divides Group Order

Let  $G$  be a group and  $g \in G$ , then  $|x|$  divides  $|G|$ .

### Corollary: Every Group of Prime Order is Cyclic

Let  $G$  be a group of prime order  $p$ . Then  $G$  is cyclic, therefore  $G \cong \mathbb{Z}_p$ .

## Thm. Cauchy's Theorem

---

Let  $G$  be a finite group of order  $n$  and  $p$  is any prime that divides  $n$ . Then  $G$  contains an element of order  $p$ .

We will prove this useful theorem later on, after Sylow Theorems.

## Thm. Order of Subgroup Multiplication

---

Let  $G$  be group such that  $H$  and  $K$  are finite subgroups of  $G$ . Then

$$|HK| = \frac{|H| \cdot |K|}{|H \cap K|}$$

## Thm. 1

---

Let  $G$  be a group and  $H, K \leq G$ . Then we have  $|H : (H \cap K)| \leq |G : K|$ .

If  $|G : K|$  is finite, then  $|H : (H \cap K)| = |G : K|$  if and only if  $G = KH$ .

## Thm. 2

---

Let  $H$  and  $K$  be subgroups of finite index of a group  $G$ . Then

1.  $|G : H \cap K|$  is finite,
2.  $|G : H \cap K| \leq |G : H||G : K|$ , and
3.  $|G : H \cap K| = |G : H||G : K|$  if and only if  $G = HK$ .

# 8. Conjugates and Normals

## Def. Conjugate

---

Let  $G$  be a group,  $H \leq G$ , and  $a, b \in G$ , then

1. the element  $aba^{-1}$  is called **the conjugate of  $a$  by  $b$** ,
2. the set  $aHa^{-1}$  is called **the conjugate of  $H$  by  $a$** ,
3. the element  $a$  is said to **normalize  $H$**  if  $aHa^{-1} = H$ .

Note that more general definitions would use only commutativity (that is  $gh = hg$ ) instead of inverses for semigroups.

We also say  $a$  is **conjugate to an element  $b$  by an element  $x$**  if  $a = xbx^{-1}$  denoted with  $a = b^x$ . We further define for sets  $A, B \subseteq G$ , and  $g \in G$

$$\begin{aligned} A^B &:= \{ a^b \mid a \in A, b \in B \} \neq BAB^{-1} \\ A^g &:= gAg^{-1} \end{aligned}$$

Notice that  $A^B$  is defined as the set of elements  $bab^{-1}$ , not  $ba(b')^{-1}$  for some  $b'$ .

## Thm. Basic Conjugate Properties

Let  $G$  a group and  $a, b, x \in G$ , then

- $(ab)^x = a^x b^x$ ,
- $(a^x)^y = a^{xy}$ ,
- $a = b^x \implies |a| = |b|$ .

## Def. Normal

---

Let  $G$  be a group and  $N$  its subgroup. If for all  $a \in G$  we have  $aN = Na$ , then  $N$  is called a **normal subgroup** (or simply a **normal**) of  $G$  denoted by  $N \trianglelefteq G$ .

If  $N \neq G$ , then  $N \triangleleft G$  will also be used to denote  $N$  is a **proper normal subgroup** of  $G$ .

From now on, it should be understood from  $A \trianglelefteq B$  alone that  $B$  is a group and  $A$  is its normal subgroup.

## Thm. Equivalent Normal Definitions

Let  $G$  be a group and  $N \leq G$ . Then the following are equivalent

1.  $\equiv_L$  and  $\equiv_R$  modulo  $N$  coincide,
2.  $gN = Ng$ ,
3.  $N^g = gNg^{-1} \subseteq N$  for all  $g \in G$ , that is  $N^G \subseteq N$ ,
4.  $N^g = gNg^{-1} = N$  for all  $g \in G$ , that is  $N^G = N$ .

## Thm. Basic Normal Properties

---

Recall that the "join" of two subgroup  $H, K$  denoted  $H \vee K$  is the subgroup  $\langle H \cup K \rangle$ .

Let  $N \trianglelefteq G$  and  $K \leq G$ , then

1.  $(N \cap K) \trianglelefteq G$ , so intersection of any subgroup with a normal is a normal,
2.  $N \vee K = NK = KN$ , so join of any subgroup with a normal is their product,
3.  $N \trianglelefteq (N \vee K)$ .

## Thm. More Normal Properties

---

1. Let  $M, N \trianglelefteq G$ . If  $M \cap N = \{e\}$ , then  $mn = nm$  for all  $m \in M$  and  $n \in N$ .
2. Kernel of any group homomorphism is a normal subgroup.
3. If  $|G : H| = 2$ , then  $H \trianglelefteq G$ .
4.  $A, B \trianglelefteq G$  implies  $AB \trianglelefteq G$ .
5. Find normal subgroups  $A, B, C$  such that  $A \trianglelefteq B \trianglelefteq C$ , but  $A \not\trianglelefteq C$ .

# 10. Normalizer And Centralizer

## Def. Centralizer

---

Let  $G$  be a (sub)group and  $A$  a non-empty subset of  $G$ . Then the **centralizer of  $A$**  is defined as

$$C_G(A) := \{ g \in G \mid a^g = a \quad \forall a \in A \}$$

Beware that if we were to write  $A^g = A$  to right-hand side it wouldn't be the same definition.

Note that a more general definition would use  $ga = ag$  for semigroups.

## Def. Center

---

The **center** of a (sub)group  $G$  denoted with  $Z(G)$  is defined as  $Z(G) := C_G(G)$ .

It is basically the set of all elements that commute with all other elements.

## Def. Normalizer

---

Let  $G$  be a group and  $A$  a non-empty subset of  $G$ . Similar to centralizer (but not equivalent), the **normalizer of  $A$**  in  $G$  is defined as

$$N_G(A) = \{ g \in G \mid A^g = A \}$$

and it is also a subgroup of  $G$ .

The definitions of centralizer and normalizer are similar but not identical. If  $g \in C_G(A)$  and  $a \in A$ , then it must be the case that  $a^g = s$ , but if  $g \in N_G(S)$ , then  $a^g = a'$  for some  $a' \in A$ , with  $a'$  possibly different from  $s$ .

Obviously a subgroup is a normal subgroup in a group if and only if its normalizer is the whole group.

This is one reason why the notation  $gag^{-1}$  (or  $a^g$ ) is preferred over  $ga = ag$  — unless we working with semigroups of course.



## Thm. '

---

Let  $G$  be a group and  $a \in G$ , then

$$|a^G| = [G : N_G(a)]$$

You may check out Kargapolov p. 16 for a more general version of theorem and the proof.

## Thm. Building Normal from a Subgroup

---

Let  $A \leq G$ , then the set

$$N = \bigcap_{x \in G} A^x$$

is a normal subgroup of  $G$ .

► **Proof**

## Thm. Centralizer, Normalizer and Normals

---

TODO

# 10. Commutators

## Def. Commutator

---

Let  $G$  be a group and  $a, b \in G$ . Obviously, two elements  $a$  and  $b$  commute if and only if  $a^{-1}b^{-1}ab = e$ . The left-hand side of this equation will be denoted with  $[a, b]$  called the **commutator** of  $a$  and  $b$ , that is

$$[a, b] := a^{-1}b^{-1}ab$$

For  $A, B \subseteq G$ , we define **mutual commutator subgroup** as

$$[A, B] := \langle [a, b] \mid a \in A, b \in B \rangle$$

More generally,

$$[a_1, a_2, \dots, a_{n+1}] = [[a_1, \dots, a_n], a_{n+1}]$$

and

$$[A_1, A_2, \dots, A_{n+1}] = [[A_1, \dots, A_n], A_{n+1}]$$

## Thm. Basic Commutator Properties

Let  $G$  be a group and  $a, b, c, x \in G$ . Then

- $[a, b] = e$  if and only if  $ab = ba$ , indeed
- $e$  is the only commutator if and only if  $G$  is abelian,
- $[a, b]^{-1} = [b, a]$ ,
- $[a, b]^x = [a^x, b^x]$ ,
- $[ab, c] = [ac]^b[b, c]$ ,
- $[a^{-1}, b] = [b, a]^{a^{-1}}$ ,
- For any group homomorphism  $\phi : G \rightarrow H$ , we have  $\phi([a, b]) = [\phi(a), \phi(b)]$ .

The product of two or more commutators need not be a commutator. Indeed, it is known that the least order of a finite group for which there exists two commutators whose product is not a commutator is 96; in fact there are two nonisomorphic groups of order 96 with this property — See **Stack Exchange**: Mariano Suárez-Álvarez.

## Def. Commutator Subgroup and Derived Series

---

Let  $G$  be a group. Then the **commutator subgroup** (or **derived subgroup**) of  $G$  denoted with  $G'$  or  $G^{(1)}$  is the normal subgroup  $[G, G]$ .

Applied recursively, we get the **derived series** of the group  $G$

$$G^{(0)} := G \supseteq G' \supseteq G'' \supseteq G^{(3)} \supseteq \dots$$

For a finite group this series terminates, to what is called a **perfect group** which may be trivial or not.

## Thm. Three Commutator Lemma

---

Let  $G$  be a group,  $A, B, C \leq G$ , and  $N \trianglelefteq G$ . If any two commutator subgroups

$$[A, B, C], [B, C, A], [C, A, B]$$

lie in  $N$ , then so is the other one.

► **Proof**

## Exercise

---

Let  $A, B, C \trianglelefteq G$ , then  $[AB, C] = [A, C][B, C]$ .

# 11. Quotients and Isomorphisms

## Def. (Group) Congruence Relation

---

An equivalence relation  $\equiv$  on a group  $G$  is called a (group) **congruence relation** if for all  $x_1, x_2, y_1, y_2 \in G$

$$x_1 \equiv x_2 \wedge y_1 \equiv y_2 \implies x_1 y_1 \equiv x_2 y_2$$

The product of two congruence classes is again a congruence class. Indeed, the set of all congruence classes  $G/\equiv$  is a group under the multiplication of classes called the **quotient group with respect to  $\equiv$** .

## Thm. Group Congruences and Normals

---

The congruence relations on a group  $G$  are in one-to-one correspondence with the normal subgroups of  $G$ .

Usually quotient groups in group theory are defined via normal groups but this paints a much wider picture. Following this motivation, here is the classical definition of quotient groups.

## Def. Quotient Group

---

Let  $G$  be a group and  $N \trianglelefteq G$ . The set of all cosets of  $N$  in  $G$  denoted by  $G/N$  (read as  $G$  modulo  $N$ ) forms a group under the binary operation

$$(aN)(bN) = (ab)N$$

and is of order  $[G : N]$ . This group is called the **quotient group** (or **factor group**) of  $G$  by  $N$ .

Notice how we are not multiplying cosets directly, but rather the elements in front of them.

## Thm. Basic Quotient Properties

---

Let  $G$  be a group and  $N \trianglelefteq G$ .

1. If  $G$  is cyclic, then so is  $G/N$ .
2.  $G/N$  is abelian if and only if  $[G, G] \subseteq N$ .

► **Proof**

## Def. Projection

---

Let  $N \trianglelefteq G$ . Then

$$\begin{aligned}\pi : G &\rightarrow G/N \\ a &\mapsto aN\end{aligned}$$

is an epimorphism and  $\text{Ker } \pi = N$ . Such  $\pi$  is called the **canonical epimorphism** or **(natural) projection**.

Therefore, unless otherwise stated,  $G \rightarrow G/N$  always denotes the canonical epimorphism.

► **Proof**

### Thm. Commutativity of Projection

Let  $\pi : G \rightarrow G/H$  be the natural projection of  $G$  and  $N (\trianglelefteq G)$ . Then  $G/H$  is abelian if and only if  $[G, G] \subseteq H$ .

► **Proof**

## Thm. Fundamental Theorem on Homomorphisms

---

Let  $\varphi : G \rightarrow H$  be a group homomorphism and  $N \trianglelefteq \text{Ker } \varphi \trianglelefteq G$ . Then there exists a unique homomorphism  $\bar{\varphi}$  where

$$\begin{aligned}\bar{\varphi} : G/N &\rightarrow H \\ aN &\mapsto \varphi(a)\end{aligned}$$

and

- $\varphi(G) = \bar{\varphi}(G/N)$ ,
- $\text{Ker } \bar{\varphi} = (\text{Ker } \varphi)/N$

► **Proof**

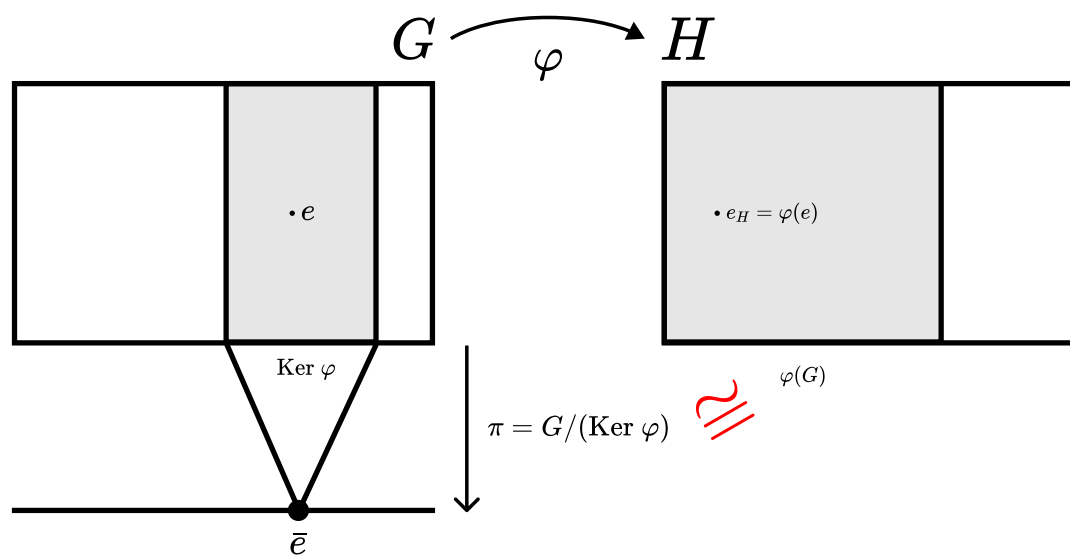
## Thm. First Isomorphism Theorem

---

Let  $\varphi : G \rightarrow H$  be a group homomorphism. Then

1.  $\text{Ker } \varphi \trianglelefteq G$ , so kernel of any group homomorphism is normal,
2.  $\varphi(G) \leq H$ , so image of any group homomorphism is a subgroup,
3.  $\varphi(G) \cong G/(\text{Ker } \varphi)$ , so if  $\varphi$  is an epimorphism, then  $H \cong G/(\text{Ker } \varphi)$ .

► **Proof**



(Figure 1) First Isomorphism Theorem

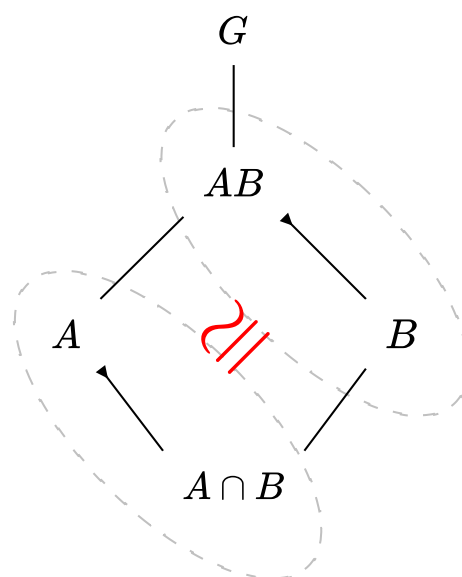
## Thm. Second Isomorphism Theorem

This theorem is also called the **Diamond Isomorphism Theorem** or **Parallelogram Theorem** due to lattice it draws.

Let  $B \leq G$  and  $A \leq N_G(B)$ , so that  $A$  is a subgroup of the *normalized*  $B$ . Then, noting  $A$  is normal

1.  $AB \leq G$ ,
2.  $B \trianglelefteq AB$ ,
3.  $A \cap B \trianglelefteq A$ , and
4.  $AB/B \cong A/A \cap B$ .

► **Proof**



(Figure 2) Second Isomorphism Theorem

## Thm. Third Isomorphism Theorem

---

Let  $K \trianglelefteq H \trianglelefteq G$ , then

1.  $K/H \trianglelefteq G/H$ , and
2.  $(G/K)/(H/K) \cong G/H$ .

► **Proof**

# 12. Symmetric Groups

## Def. Permutation

---

A **permutation**  $\sigma$  on a set  $X$  is a bijective function from  $X$  to  $X$ . The permutation  $x \mapsto x$  will be called the **identity permutation**.

We say an element  $x \in X$  is **fixed under**  $\sigma$  if  $\sigma(x) = x$ . Similarly, we say  $x$  is **moved by**  $\sigma$  if  $\sigma(x) \neq x$ .

For simplicity, we will use the set  $\mathbf{I}_n = \{ 1, 2, \dots, n \}$  instead of any  $X$  of any cardinality.

More formally, we could make use of Well-Ordering Principle, initial segments, and ordinals. For now, this definition should suffice.

## Def. Support

---

The **support** of a permutation  $\sigma$  denoted by  $\text{supp } \sigma$  is defined as the set of elements that are moved by  $\sigma$ , that is

$$\text{supp } \sigma := \{ i \in \mathbf{I}_n \mid \sigma(i) \neq i \}.$$

Similarly, the set of fixed elements denoted with  $\text{fix } \sigma$  is the set

$$\text{fix } \sigma := \{ i \in \mathbf{I}_n \mid \sigma(i) = i \}.$$

## Def. Disjoint Permutations

---

The permutations  $\sigma_1, \sigma_2, \dots, \sigma_n$  are said to be **disjoint** if their support is disjoint.

## Def. Symmetric Group

---

Set of all permutations (bijections) on  $\mathbf{I}_n$  will be denoted with  $\mathbf{S}_n$  and it forms a group under function composition (exercise) called the **symmetric group** (of  $n$  letters).

Notice that  $\mathbf{S}_n$  is of order  $n!$ .



## Def. Cycle

---

Let  $\tau$  be a permutation on  $\mathbf{I}_n$  with the support  $\{k_1, k_2, \dots, k_r\}$ . Then  $\tau$  is said to be a **cycle** (or **cyclic**) of **length**  $r$  if

$$\begin{array}{ccc} k_1 & \mapsto & k_2 \\ k_2 & \mapsto & k_3 \\ & \vdots & \\ k_r & \mapsto & k_1 \end{array}$$

A cycle of length  $k$  will be called a  **$k$ -cycle**. A 2-cycle is called a **transposition**.

There is no widespread consensus on how to define a cycle, but the intuition should be clear.

## Thm. Permutations are (Unique) Product of Disjoint Cycles

---

Every non-identity permutation in  $\mathbf{S}_n$  is uniquely (up to the order of the factors) a product of disjoint cycles, each of which has length at least 2.

### Corollary. Order of Permutation

The order of a permutation is the least common multiple of the orders of its disjoint cycles.

### Corollary. Permutations are a Product of Transpositions

Every permutation can be written as a product of (not necessarily unique) transpositions.

## Def. Odd and Even

---

A permutation is said to be **even** (resp. **odd**) if it can be written as a product of even (resp. **odd**) number of transpositions.

## Thm. Exclusively Odd or Even

---

A permutation  $\sigma \in \mathbf{S}_n$  where  $n \geq 2$  is either even or odd, but not both.

Therefore, the **sign** of a permutation  $\sigma$  denoted  $\text{sgn } \sigma$  is defined to be 1 if even and  $-1$  if odd.

## Thm. Alternating Group

---

Let  $\mathbf{A}_n$  denote the set of all permutations of  $\mathbf{S}_n$ . Then  $\mathbf{A}_n$  is a normal subgroup of  $\mathbf{S}_n$  of index 2.

Moreover,  $\mathbf{A}_n$  is the only subgroup of  $\mathbf{S}_n$  of index 2.

$A_n$  is called the **alternating group** (of **degree**  $n$ ).

## Thm. $A_n$ is (Generally) Simple

---

The alternating group  $A_n$  is simple if and only if  $n \neq 4$ .

### Lemma. 1

Let  $r, s \in \mathbf{I}_n$  where  $n \geq 3$ . Then  $A_n$  is generated by 3-cycles such that

$$\{ (rsk) \mid 1 \leq k \leq n, k \neq r, s \}$$

### Lemma. 2

For  $n \geq 3$ , if  $N \trianglelefteq A_n$  and  $N$  contains a 3-cycle, then  $N = A_n$ .

Proofs are skipped for this theorem, curious reader may checkout Hungerford (pp. 49-50).

## Thm. Dihedral Group Generators

---

Let  $n \geq 3$ , then the dihedral group  $D_n$  (whose order is  $2n$ ) is generated by  $a$  and  $b$  such that, for  $(1)$  as the identity

1.  $a^n = b^2 = (1)$  and  $a^k \neq (1)$  if  $0 < k < n$ ,
2.  $aba = b$ .

### ► Proof

## Exercise. Generator of $D_n$

---

Let  $\langle a \rangle \leq D_n$  for  $a \in D_n$ , and  $|a| = n$ . Then

1.  $\langle a \rangle \trianglelefteq D_n$ , and
2.  $D_n / \langle a \rangle = \mathbb{Z}_2$ .

## Thm. Center of $D_n$

---

Let  $Z$  be the center of the group  $D_n$ , then

- $Z = \langle e \rangle$  if  $n$  is odd,
- $Z \cong \mathbb{Z}_2$  if  $n$  is even.

### ► Proof

# A1. Appendix 1

This is not really an appendix, but rather parking space for stuff I wasn't able to locate yet.

## Def. Maximal Subgroup

---

Let  $G$  be a group and let  $H$  be a proper subgroup of  $G$ . We say  $H$  is a **maximal subgroup** if  $H \subseteq K$  implies  $K = H$  for all  $K < G$ .

Simply,  $H$  is maximal if there is no greater proper subgroup which contains it.

## Def. Frattini Subgroup

---

Let  $G$  be a group. We define **frattini subgroup**  $\Phi(G)$  as the intersection of all maximal subgroups of  $G$ . In the case  $G$  has no maximal subgroups, we define  $\Phi(G) = G$ .

This is analogous to the Jacobson radical in the ring theory.

## Thm. Frattini Subgroup and Non-Generators

---

The frattini subgroup  $\Phi(G)$  of a group  $G$  is equal to the set of all non-generators of  $G$ . Therefore, non-generators of a group form a subgroup — namely the frattini subgroup.

---

## Def. Simple Group

---

A group is said to be **simple** if it has no proper normal subgroups.

## Thm. On Simple Groups

---

1.  $\mathbb{Z}_p$  is simple if  $p$  is prime. Does the converse hold?
-

**Def. Perfect Group**

---

---