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1 GROUPS

1.1 DEFINITIONS AND BASIC PROPERTIES

Definition 1.1.1 (Group / abelian group). A group is a set $G$ together with a binary operation

$$G \times G \rightarrow G$$

$$(a, b) \mapsto ab$$

such that

(i) $(ab)c = a(bc)$ for all $a, b, c \in G$;

(ii) there exists an identity element $1 \in G$ such that $1 \cdot a = a \cdot 1 = a$ for all $a \in G$;

(iii) for all $a \in G$, there exists an inverse $b \in G$ of $a$ such that $ab = ba = 1$.

If $ab = ba$ for all $a, b \in G$, then $G$ is said to be abelian (or commutative).

Proposition 1.1.2 (†). A group $G$ has exactly one identity.

Proof. If $1$ and $1'$ are identities, then $1' = 1 \cdot 1' = 1$. □

Proposition 1.1.3 (†). If $G$ is a group and $a \in G$, then there exists exactly one inverse of $a$.

Proof. If $b$ and $b'$ are inverses of $a$, then $b' = 1 \cdot b' = bab' = b \cdot 1 = b$. □

Notation. Given $a \in G$, write $a^{-1}$ for the inverse of $a$ in $G$.

Proposition 1.1.4. 1. If $ab = ac$, then $b = c$.

2. If $ac = bc$, then $a = b$.

Notation. Write $a^n$ for the $n$-fold product of $a$ with itself and $a^{-n} = (a^{-1})^n = (a^n)^{-1}$.

Proposition 1.1.5. 1. If $ab = 1$ or $ba = 1$, then $b = a^{-1}$.

2. $(a^{-1})^{-1} = a$.

3. $(a_1 \cdots a_n)^{-1} = a_n^{-1} \cdots a_1^{-1}$.

4. $a^n a^m = a^{n+m}$.

5. $(a^n)^m = a^{nm}$.

Proof. See Homework 2 Problem 1. □

Definition 1.1.6 (Order of a group element). Let $a \in G$. The order of $a$, denoted ord $a$, is the minimum $n > 0$ such that $a^n = 1$. If such an $n$ does not exist, then we write ord $a = \infty$.

Definition 1.1.7 (Order of a group). The order of a group $G$ is the cardinality $|G|$ of $G$ as a set. We say that $G$ is finite if $|G| < \infty$. 

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1.2 Examples of groups

Proposition 1.1.8 (†). Let \( G \) be a finite group and \( a \in G \). Then \( \text{ord} \ a \) is finite.

Proposition 1.1.9 (†). Let \( a \in G \) with \( \text{ord} \ a = n < \infty \). If \( a^m = 1 \) for some integer \( m \), then \( n \mid m \).

Notation. In an abelian group, we may use + for the group operation, i.e. write \( a + b \) instead of \( ab \). In this case, the identity is written as 0 and “powers” are written as \( na \).

1.2 EXAMPLES OF GROUPS

Example 1.2.1. Let \( G = \{g\} \) be any singleton set. We can make \( G \) into an abelian group of order 1 with the operation \( g \cdot g = g \). (This is the only way to define an operation on \( G \).) Such a group is called a trivial group.

A generic trivial group may be written as \( 1 = \{1\} \). If we are only working with abelian groups, then we may write \( 0 = \{0\} \) for a generic trivial group.

Example 1.2.2. The sets \( \mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C} \) with addition are abelian groups with identity 0 (in the ordinary senses of 0). On the other hand, \( \mathbb{N} \) with addition is not a group, since it has no identity element (if 0 is not included) and \( 1 \in \mathbb{N} \) has no inverse (even if 0 is included).

Example 1.2.3. Let \( n \) be a positive integer. For \( a \in \mathbb{Z} \), the congruence class of \( a \) modulo \( n \) is

\[
[a]_n = \{a + nk \mid k \in \mathbb{Z}\} \subset \mathbb{Z}.
\]

The relation \( \sim \) on \( \mathbb{Z} \) given by \( a \sim b \iff [a]_n = [b]_n \) is an equivalence relation whose equivalence classes are precisely the congruence classes modulo \( n \), so these congruence classes partition \( \mathbb{Z} \). The set of congruence classes modulo \( n \) is denoted \( \mathbb{Z}/n\mathbb{Z} \).

To make \( \mathbb{Z}/n\mathbb{Z} \) into a group, we attempt to define \( [a]_n + [b]_n = [a + b]_n \). It needs to be shown that this is well-defined. Suppose that \( [a]_n = [a']_n \) and \( [b]_n = [b']_n \), so there exist \( k, l \in \mathbb{Z} \) with \( a' = a + nk \) and \( b' = b + nl \). From this, we get

\[
[a' + b']_n = [(a + b) + n(k + l)]_n = \{(a + b) + n(k + l) + nm \mid m \in \mathbb{Z}\} = \{(a + b) + nm' \mid m' \in \mathbb{Z}\} = [a + b]_n,
\]

as required. With this addition, \( \mathbb{Z}/n\mathbb{Z} \) is an abelian group of order \( n \).

Example 1.2.4. If \( K \) is a field, then the set \( K^\times = K\setminus\{0\} \) with multiplication is an abelian group. Familiar examples include \( \mathbb{Q}^\times, \mathbb{R}^\times, \) and \( \mathbb{C}^\times \).

Example 1.2.5. Let \( (\mathbb{Z}/n\mathbb{Z})^\times = \{[a]_n \mid \gcd(a, n) = 1\} \). This is well-defined and contains \( \varphi(n) \) elements, where \( \varphi(n) \) is the number of positive integers \( k \leq n \) for which \( \gcd(k, n) = 1 \). The multiplication defined by

\[
[a]_n \cdot [b]_n = [ab]_n.
\]

is well-defined (by a similar argument to the one for addition of congruence classes), and with this operation, \( (\mathbb{Z}/n\mathbb{Z})^\times \) is an abelian group of order \( \varphi(n) \).

Example 1.2.6. Given a set \( G \) with a small number of elements, we can define a group structure on \( G \) by writing down a full multiplication table. This is shown for the Klein four-group \( V_4 \) (also denoted \( V \) or \( K_4 \)) below.
Example 1.2.7. Let $X$ be any set. A permutation of $X$ is a bijection from $X$ to itself. The symmetric group of $X$, denoted $S(X)$, is the group of permutations of $X$ with function composition as the group operation. If $X$ is finite with $|X| = n$ and the exact nature of the elements of $X$ is not important, then we may assume $X = \{1, \ldots, n\}$. In this case, we write $S_n$ for $S(X)$. This is a group of order $n!$, and for $n \geq 3$, $S_n$ is not abelian.

Example 1.2.8. Let $R$ be a ring (with $1 \neq 0$). The set $GL_n(R)$ of invertible $n \times n$ matrices with entries in $R$ is the general linear group of $R$ of $n \times n$ matrices with matrix multiplication as the group operation. This is not commutative for $n \geq 2$, even if $R$ is, as $\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$, $\begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 2 \end{pmatrix}$.

1.3 HOMOMORPHISMS

Definition 1.3.1 (Group homomorphism / isomorphism). Let $G$ and $H$ be groups. A (group) homomorphism from $G$ to $H$ is a function $f : G \to H$ such that $f(ab) = f(a)f(b)$ for all $a, b \in G$. If $f : G \to H$ is a bijective homomorphism, then we say that $f$ is an isomorphism.

Groups $G$ and $H$ are isomorphic, written $G \cong H$, if there exists an isomorphism $f : G \to H$.

Proposition 1.3.2. Let $f : G \to H$ be a homomorphism. Then

1. $f(1) = 1$;
2. $f(a^{-1}) = f(a)^{-1}$ for all $a \in G$;
3. if $f$ is an isomorphism, then so is $f^{-1} : H \to G$.

Proof. 1. We have $1 \cdot f(1) = f(1) = f(1 \cdot 1) = f(1) \cdot f(1)$, so $f(1) = 1$.

2. Since $f$ is a homomorphism, $f(a)f(a^{-1}) = f(aa^{-1}) = f(1) = 1$.

3. The inverse of a bijective function is bijective, hence it is enough to show that $f^{-1} : H \to G$ is a homomorphism. Since $f$ is a homomorphism,

$$f(f^{-1}(ab)) = ab = f(f^{-1}(a))f(f^{-1}(b)) = f(f^{-1}(a)f^{-1}(b)).$$

As $f$ is bijective, it is injective, so $f^{-1}(ab) = f^{-1}(a)f^{-1}(b)$.

Proposition 1.3.3. If $f : G \to H$ and $g : H \to K$ are homomorphisms, then so is $g \circ f : G \to K$. If $f$ and $g$ are isomorphisms, then so is $g \circ f$.
Example 1.3.4. 1. Let $G = \{g\}$ and $H = \{h\}$ be trivial groups. The unique map $f : G \to H$ with $f(g) = h$ is an isomorphism, so there is only one trivial group up to isomorphism.

2. Two groups with the same multiplication tables, up to relabeling of elements, are isomorphic.

3. As additive groups, $\mathbb{C} \cong \mathbb{R}^2$ with $a + bi \leftrightarrow (a, b)$.

4. The map $x \mapsto e^x$ is a homomorphism $\mathbb{R} \to \mathbb{R}^\times$.

Lemma 1.3.5 (†). Let $f : G \to H$ be an isomorphism and $a \in G$. Then $\text{ord}_f(a) = \text{ord} a$.

1.4 CYCLIC GROUPS

Definition 1.4.1 (Generator / cyclic group). Let $G$ be a group and $a \in G$. We say that $a$ is a generator of $G$ if every element of $G$ is of the form $a^n$ for some $n \in \mathbb{Z}$. If $G$ has a generator, we say that $G$ is cyclic.

Example 1.4.2. 1. The additive group $\mathbb{Z}$ is an infinite cyclic group with generators $\pm 1$.

2. The additive group $\mathbb{Z}/n\mathbb{Z}$ is a finite cyclic group. Its generators are $[a]_n$ for $\gcd(a, n) = 1$. There are $\varphi(n)$ such generators.

3. The multiplicative group $(\mathbb{Z}/5\mathbb{Z})^\times$ is cyclic. The elements $[2]_5$ and $[3]_5$ are generators, while $[1]_5$ and $[4]_5$ are not.

Theorem 1.4.3 (Classification of cyclic groups). Every cyclic group is isomorphic to $\mathbb{Z}$ or $\mathbb{Z}/n\mathbb{Z}$ for some $n > 0$.

Proof. Deferred (see Example 1.7.5).

1.5 SUBGROUPS

Definition 1.5.1 (Subgroup). Let $G$ be a group and $H \subseteq G$ be a subset. We say that $H$ is a subgroup of $G$ if it is a group with the operation inherited from $G$.

Notation. We write $H \leq G$ to mean that $H$ is a subgroup of $G$, and $H \triangleleft G$ to mean that $H$ is a normal subgroup of $G$ and $H \neq G$.

Proposition 1.5.2. Let $G$ be a group and $H \subseteq G$. Then $H \leq G$ if and only if

(i) $1 \in H$;

(ii) if $a, b \in H$, then $ab \in H$;

(iii) if $a \in H$, then $a^{-1} \in H$.

Corollary 1.5.3 (†). Let $G$ be a group and $H \subseteq G$. Then $H \leq G$ if and only if

(i) $H$ is nonempty;

(ii) if $a, b \in H$, then $ab^{-1} \in H$. 

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Example 1.5.4.  1. Every group \( G \) has \( 1 \leq G \) and \( G \leq G \).

2. Every subgroup of \( \mathbb{Z} \) is of the form \( n\mathbb{Z} = \{nm \mid m \in \mathbb{Z}\} \) for \( n \geq 0 \).

3. As additive groups, \( \mathbb{Z} \leq \mathbb{Q} \leq \mathbb{R} \leq \mathbb{C} \).

4. As multiplicative groups, \( \mathbb{Q}^\times \leq \mathbb{R}^\times \leq \mathbb{C}^\times \).

5. If \( \{H_i\} \) is a family of subgroups of \( G \), then \( \bigcap_i H_i \) is a subgroup of \( G \).

6. Let \( G \) be a group and \( a \in G \). The cyclic subgroup generated by \( a \) is \( \langle a \rangle = \{a^n \mid n \in \mathbb{Z}\} \). It is the smallest subgroup of \( G \) containing \( a \).

7. Let \( G \) be a group and \( S \subset G \) be any subset. The subgroup generated by \( S \) is the smallest subgroup \( \langle S \rangle \) of \( G \) containing \( S \). It is equivalently the subgroup of all finite products \( s_1 \cdots s_n \) with \( s_i \in S \) or \( s_i^{-1} \in S \) for each \( i \).

Definition 1.5.5 (Kernel / image). Let \( f : G \to H \) be a homomorphism.

1. The kernel of \( f \) is
   \[
   \ker f = f^{-1}(1) = \{a \in G \mid f(a) = 1\} \subset G.
   \]

2. The image of \( f \) is
   \[
   \im f = f(G) = \{f(a) \mid a \in G\} \subset H.
   \]

Proposition 1.5.6. \( \ker f \leq G \) and \( \im f \leq H \).

Proof. For \( \ker f \subset G \), since \( f(1) = 1 \), we have \( 1 \in \ker f \). If \( a, b \in \ker f \), then
   \[
   f(ab^{-1}) = f(a)f(b)^{-1} = 1 \cdot 1^{-1} = 1,
   \]
so \( ab^{-1} \in \ker f \). Thus \( \ker f \leq G \).

For \( \im f \subset H \), it is clear that \( \im f \) is non-empty. If \( x, y \in \im f \) with \( f(a) = x \) and \( f(b) = y \) for some \( a, b \in G \), then
   \[
   xy^{-1} = f(a)f(b)^{-1} = f(ab^{-1}) \in \im f,
   \]
so \( \im f \leq H \). \( \square \)

Theorem 1.5.7. Let \( f : G \to H \) be a homomorphism. Then \( f \) is injective if and only if \( \ker f = 1 \).

Proof. \( (\implies) \) Omitted.

\( (\impliedby) \) Suppose \( \ker f = 1 \) and \( f(a) = f(b) \) for \( a, b \in G \). Then \( f(ab^{-1}) = 1 \), so \( ab^{-1} = 1 \). \( \square \)

Theorem 1.5.8. Let \( f : G \to H \) be an injective homomorphism. Then \( G \cong \im f \leq H \).

Proof. The homomorphism \( f : G \to \im f \) is injective and surjective. \( \square \)

Definition 1.5.9 (Embedding). If \( f : G \to H \) is injective, we say that \( f \) is an embedding of \( G \) into \( H \), written \( f : G \hookrightarrow H \). That \( G \) embeds into \( H \) means that \( G \) is isomorphic to a subgroup of \( H \).
Example 1.5.10 (Cayley’s theorem). Let $G$ be a group. For $a \in G$, define the left multiplication function $f_a : G \to G$ by $f_a(g) = ag$. This is not a homomorphism (unless $a = 1$), but it does satisfy

$$f_a \circ f_b = f_{ab} \quad \text{and} \quad f_1 = \text{id}_G.$$  

In particular, $f_a \circ f_a^{-1} = f_1 = \text{id}_G$, so each $f_a$ is a bijection with $(f_a)^{-1} = f_{a^{-1}}$. Thus $f_a \in S(G)$, and the map $G \to S(G)$ given by $a \mapsto f_a$ is an injective homomorphism.

Cayley’s theorem states that every group $G$ embeds into some symmetric group. Our work here shows that in particular, $G$ embeds into its own symmetric group $S(G)$.

Definition 1.5.11 (Cosets). If $H \leq G$ is a subgroup and $a \in G$, then $aH = \{ah \mid h \in H\}$ is a left coset of $H$ in $G$, while $Ha = \{ha \mid h \in H\}$ is a right coset (of $H$ in $G$).

Given $H \leq G$, say that $a \sim b$ if $b = ah$ for some $h \in H$, or equivalently, if $a^{-1}b \in H$. This is an equivalence relation, and the equivalence class of $a$ is $[a] = aH$. Thus $G$ is partitioned into left cosets of $H$. (These results can be developed similarly for right cosets.)

Notation. The set of left cosets of $H$ in $G$ is denoted $G/H$.

Definition 1.5.12 (Index). The index of $H$ in $G$ is $[G : H] = |G/H|$ (cardinality as a set).

Theorem 1.5.13 (Lagrange). Let $G$ be a group and $H \leq G$. Then $|G| = [G : H] \cdot |H|$.

Proof. Each coset $X \in G/H$ has cardinality $|H|$ and $G = \bigcup_{X \in G/H} X$. □

Corollary 1.5.14. Let $G$ be a finite group.

1. If $H \leq G$, then $|H|$ divides $|G|$.
2. If $a \in G$, then ord $a$ divides $|G|$.

Proof. 1. Omitted.

2. Apply the first statement to $H = \langle a \rangle$.

□

1.6 NORMAL SUBGROUPS

Definition 1.6.1 (Normal subgroup). A subgroup $H \leq G$ is normal if $aH = Ha$ for every $a \in G$. In this case we write $H \unlhd G$.

Example 1.6.2. 1. In any group $G$, the subgroups 1 and $G$ are normal.

2. In an abelian group $G$, every subgroup of $G$ is normal.

Proposition 1.6.3. $H \leq G$ is normal if and only if $ghg^{-1} \in H$ for all $g \in G$ and $h \in H$.

Proof. ($\implies$) Let $g \in G$ and $h \in H$. Since $gH = Hg$, we have $gHg^{-1} = H$.

($\impliedby$) If $ghg^{-1} \in H$ for all $g \in G$ and $h \in H$, then $gHg^{-1} \subset H$, so $gH \subset Hg$. By the same reasoning applied to $g^{-1}$ and $h$, we have $Hg \subset gH$, so $gH = Hg$. □
Definition 1.6.4 (Conjugate). Given \( g, h \in G \), the conjugate of \( h \) by \( g \) is \( ghg^{-1} \).

Proposition 1.6.5. If \( N \trianglelefteq G \) and \( H \leq G \) with \( N \subset H \), then \( N \trianglelefteq H \).

Proposition 1.6.6. Let \( f : G \to H \) be a homomorphism. Then \( \ker f \trianglelefteq G \).

Proof. Let \( k \in \ker f \) and \( g \in G \). Then

\[
    f(gkg^{-1}) = f(g)f(k)f(g)^{-1} = f(g) \cdot 1 \cdot f(g)^{-1} = 1,
\]

so \( gkg^{-1} \in \ker f \).

Example 1.6.7. Let \( F \) be a field and fix \( n \geq 1 \). Then \( \det : GL_n(F) \to F^\times \) is a homomorphism, so its kernel is a normal subgroup of \( GL_n(F) \). The kernel of \( \det \) is the special linear group

\[
    SL_n(F) = \{ A \in GL_n(F) \mid \det A = 1 \}.
\]

Proposition 1.6.8. If \( H \trianglelefteq G \), then \( G/H \) is a group with operation \( (aH)(bH) = abH \).

Proof. This follows from the calculation

\[
    (aH)(bH) = aHbH = abHH = abH.
\]

Definition 1.6.9 (Quotient group). If \( H \trianglelefteq G \), then the group \( G/H \) is the quotient group or factor group of \( G \) by \( H \). The map \( \pi : G \to G/H \) defined by \( \pi(a) = aH \) is the canonical homomorphism or quotient homomorphism.

Note that \( \ker \pi = H \) and \( \im \pi = G/H \). Thus every normal subgroup of \( G \) is the kernel of some homomorphism from \( G \) to another group.

Example 1.6.10. 1. For any group \( G \), we have \( G/G \cong 1 \) and \( G/1 \cong G \).

2. The subgroup \( n\mathbb{Z} \leq \mathbb{Z} \) is normal since \( \mathbb{Z} \) is abelian, and \( \mathbb{Z}/n\mathbb{Z} \) is the additive group of integers modulo \( n \), in accordance with our earlier use of the notation \( \mathbb{Z}/n\mathbb{Z} \).

3. The elements of \( \mathbb{C}/\mathbb{R} \) are lines \( l_y = \{ x + iy \mid y \in \mathbb{R} \} \). This is isomorphic to \( \mathbb{R} \) via \( l_y \mapsto y \).

Theorem 1.6.11 (Correspondence theorem). Let \( H \trianglelefteq G \). There is a natural bijection

\[
\begin{align*}
\{ \text{subgroups of } G \text{ containing } H \} & \leftrightarrow \{ \text{subgroups of } G/H \} \\
K & \mapsto \pi(K) \\
\pi^{-1}(L) & \mapsto L.
\end{align*}
\]

Furthermore, normal subgroups of \( G \) containing \( H \) are paired with normal subgroups of \( G/H \).

Proof. See Homework 2 Problem 4.

\[9\]
1.7 ISOMORPHISM THEOREMS

**Definition 1.7.1** (Factoring through). Let \( f : G \to H \) be a homomorphism and \( N \trianglelefteq G \) with the canonical homomorphism \( \pi : G \to G/N \). Then \( f \) factors through \( G/N \) if there is a homomorphism \( \overline{f} : G/N \to H \) such that \( f = \overline{f} \circ \pi \).

\[
\begin{array}{ccc}
G & \xrightarrow{f} & H \\
\downarrow & & \downarrow \overline{f} \\
G/N & & \\
\end{array}
\]

**Theorem 1.7.2.** Let \( f : G \to H \) be a homomorphism and \( N \trianglelefteq G \). Then \( f \) factors through \( G/N \) if and only if \( N \subset \ker f \).

*Proof.* \( (\Rightarrow) \) Suppose \( f \) factors through \( G/N \) as \( f = \overline{f} \circ \pi \). Then

\[ f(N) = \overline{f}(NN) = \overline{f}(N) = 1, \]

so \( N \subset \ker f \).

\( (\Leftarrow) \) Suppose \( N \subset \ker f \). For \( f \) to factor as \( \overline{f} \circ \pi \), we must have

\[ \overline{f}(aN) = (\overline{f} \circ \pi)(a) = f(a), \]

so we take this to define \( \overline{f} \) and show that \( \overline{f} \) is well-defined. If \( aN = bN \), then \( a^{-1}b \in N \subset \ker f \), so \( f(a^{-1}b) = 1 \), hence

\[ \overline{f}(aN) = f(a) = f(b) = \overline{f}(bN). \]

The proof that \( \overline{f} \) is a homomorphism is omitted.

**Theorem 1.7.3** (First isomorphism theorem). Let \( f : G \to H \) be a group homomorphism. Then \( G/\ker f \cong \im f \), with isomorphism \( \overline{f} \) given by factoring \( f \) through \( G/\ker f \).

*Proof.* Let \( \pi : G \to G/\ker f \) be the canonical homomorphism, so \( f = \overline{f} \circ \pi \). Then \( \im f = \im \overline{f} \), so \( \overline{f} : G/\ker f \to \im f \) is surjective. To see that it is injective, suppose \( a \ker f \in \ker \overline{f} \). Then

\[ \overline{f}(a \ker f) = (\overline{f} \circ \pi)(a) = f(a) = 1, \]

so \( a \in \ker f \) and \( a \ker f = \ker f \) is the identity in \( G/\ker f \).

**Corollary 1.7.4.** If \( f : G \to H \) is a surjective homomorphism, then \( G/\ker f \cong H \).

**Example 1.7.5.** We prove Theorem 1.4.3 on the classification of cyclic groups.

Let \( G \) be a cyclic group generated by \( a \), and define the homomorphism \( f : \mathbb{Z} \to G \) by \( n \mapsto a^n \). This is surjective since \( G \) is cyclic, so \( \mathbb{Z}/\ker f \cong G \). Since \( \ker f \leq \mathbb{Z} \), it is of the form \( n\mathbb{Z} \) for some \( n \geq 0 \). If \( n = 0 \), then \( G \cong \mathbb{Z} \). Otherwise, \( G \cong \mathbb{Z}/n\mathbb{Z} \).
Theorem 1.7.6 (Second isomorphism theorem). Let $K \leq G$ and $N \trianglelefteq G$. Then

1. $KN \leq G$;
2. $N \trianglelefteq KN$;
3. $K \cap N \trianglelefteq K$;
4. $KN/N \cong K/(K \cap N)$.

Proof. 1. Here $KN$ is non-empty, and

\[(KN)(KN)^{-1} = KNNK = KNK = KKN = KN.\]

2. Omitted.
3. Omitted.
4. Define $f : KN \to K/K \cap N$ by $kn \mapsto k(K \cap N)$. This is well-defined, since if $k'n' = kn$, then $k^{-1}k' = m^{-1} \in K \cap N$, so $k(K \cap N) = k'(K \cap N)$. Then $f$ is a surjective homomorphism with kernel $N$, so $KN/N \cong K/K \cap N$ by the first isomorphism theorem.

\[\square\]

Theorem 1.7.7 (Third isomorphism theorem). Let $K, H \trianglelefteq G$ with $K \subset H$. Then

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

Proof. 1. Given $gK \in G/K$ and $hK \in H/K$,

\[gK(hK)(gK)^{-1} = gK(hK)K^{-1} = ghg^{-1}K \in H/K.\]

2. Define $f : G/K \to G/H$ by $gK \mapsto gH$. This is a well-defined surjective homomorphism with kernel $H/K$, hence $(G/K)/(H/K) \cong G/H$ by the first isomorphism theorem.

\[\square\]

1.8 GROUP ACTIONS

Definition 1.8.1 (Left group action). Let $G$ be a group and $X$ be a set. A left action of $G$ on $X$ is a map

\[\theta : G \times X \longrightarrow X\]

\[(g, x) \mapsto gx\]

such that

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

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A right action can be defined similarly. When we say “action”, we usually mean “left action”.

**Example 1.8.2.** Let $X$ be a set. Then $S(X)$ acts on $X$ by $(f, x) \mapsto f(x)$ for $f \in S(X)$ and $x \in X$.

**Definition 1.8.3** (Pullback of a group action). Let $f : G \to H$ be a homomorphism and suppose $\theta$ is an action of $H$ on $X$. The pullback of $\theta$ by $f$ is the action of $G$ on $X$ given by $gx = f(g)x$.

**Theorem 1.8.4.** There is a bijection
\[
\{\text{actions of } G \text{ on } X\} \leftrightarrow \{\text{homomorphisms } G \to S(X)\}
\]
\[\theta \mapsto (g \mapsto \theta_g = \theta(g, -)) \quad ((g, x) \mapsto [f(g)](x)) \leftrightarrow f.\]

This tells us that every group action is the pullback of the action in Example 1.8.2 for some set $X$. Thus this action may be called the universal action.

\[\begin{array}{c}
G \xrightarrow{f} S(X) \\
\downarrow \quad \quad \quad \quad \downarrow \\
X
\end{array}\]

**Definition 1.8.5** (Kernel / faithful action). Let $\theta$ be an action of $G$ on $X$. The kernel of $\theta$ is the kernel of the induced homomorphism $G \to S(X)$. We say that $\theta$ is faithful if $\ker \theta = 1$.

**Definition 1.8.6** (Orbit / stabilizer). Let $G$ act on $X$ and let $x \in X$.

1. The orbit of $x$, written $\text{orb}_x$ or $Gx$, is
\[\text{orb}_x = \{gx \mid g \in G\} \subset X.\]

2. The stabilizer of $x$, written $\text{stab}_x$ or $G_x$, is
\[\text{stab}_x = \{g \in G \mid gx = x\} \leq G.\]

**Proposition 1.8.7.** $\ker \theta = \bigcap_x \text{stab}_x$.

Define a relation on $X$ by $x \sim y$ if $\text{orb}_x = \text{orb}_y$. Then $\sim$ is an equivalence relation whose equivalence classes are the orbits of $\theta$. In particular, the orbits partition $X$.

**Definition 1.8.8** (Transitive action). An action of $G$ on $X$ is transitive if the only orbit is $X$.

**Example 1.8.9** (Trivial action). The trivial action of $G$ on $X$ is given by $gx = x$ for all $g \in G$ and $x \in X$. This is not faithful (unless $G = 1$) and not transitive (unless $|X| = 1$). We have $\text{orb}_x = \{x\}$ and $\text{stab}_x = G$.

**Example 1.8.10** (Left regular action). The left regular action of $G$ on $X = G$ is the action given by $(g, x) \mapsto gx$. This is faithful and transitive, as $\text{stab}_x = 1$ and $\text{orb}_x = G$ for all $x \in G$. The induced homomorphism $G \to S(G)$ is the embedding from Example 1.5.10.
Example 1.8.11 (Left coset action). If $H \leq G$, then the left coset action of $G$ on $X = G/H$ is the transitive action given by $(g, xH) \mapsto gxH$. Given $gH \in G/H$, we have $\text{orb}(gH) = G/H$ and $\text{stab}(gH) = gHg^{-1}$. The kernel of the left coset action is the normal core of $H$ in $G$, which is the largest normal subgroup of $G$ contained in $H$.

Definition 1.8.12 (Automorphism). An automorphism of $G$ is an isomorphism $G \rightarrow G$. The group of automorphisms of $G$ is denoted Aut$G$.

Example 1.8.13.  
1. $\text{Aut}(\mathbb{Z}) = \{ (n \mapsto n), (n \mapsto -n) \}$.

2. $\text{Aut}(\mathbb{Z}/n\mathbb{Z}) \cong (\mathbb{Z}/n\mathbb{Z})^\times$.

Example 1.8.14. Any automorphism of $G$ is also a permutation of $G$, so Aut$(G)$ $\leq$ S$(G)$. Then Aut$G$ acts on $G$ as the pullback of the universal action by the inclusion Aut$(G)$ $\hookrightarrow$ S$(G)$.

Example 1.8.15 (Conjugation action on group elements). Let $G$ act on $X = G$ by conjugation, i.e. $(g, x) \mapsto gxg^{-1}$. The orbit of $x \in G$ is the conjugacy class of $x$ in $G$, while the stabilizer of $x$ is the centralizer of $x$ in $G$. For each $g \in G$, the map $x \mapsto gxg^{-1}$ is an automorphism of $G$.

Definition 1.8.16 (Center). The center of $G$, denoted $Z$ or Z$(G)$, is the kernel of the conjugation action on the elements of $G$. Equivalently, $Z = \{ g \in G \mid gh = hg \text{ for all } h \in G \}$. In particular, $Z = G$ if and only if $G$ is abelian.

Definition 1.8.17 (Inner automorphism). An inner automorphism of $G$ is an automorphism of the form $x \mapsto gxg^{-1}$ for some $g \in G$. The group of inner automorphisms is denoted Inn$G$, and is a subgroup of Aut$G$.

Proposition 1.8.18. Inn$G \cong G/Z$.

Proof. Apply the first isomorphism theorem to the homomorphism induced by the conjugation action on the elements of $G$. \hfill $\Box$

Example 1.8.19 (Conjugation action on subgroups). Let $G$ act on the set $X$ of all subgroups of $G$ by conjugation, i.e. $(g, H) \mapsto gHg^{-1}$. The stabilizer of $H$ is the normalizer of $H$ in $G$, denoted N$_G(H)$. It is the largest subgroup of $G$ in which $H$ is normal.

Lemma 1.8.20. Let $G$ be a finite group and $H \leq G$ such that $|G : H|$ is the smallest prime divisor of $|G|$. Then $H \leq G$.

Proof. Let $p$ be the smallest prime divisor of $|G|$. Let $G$ act on $G/H$ by left translation and $f : G \rightarrow S(X) \cong S_p$ be the induced homomorphism. Let $N = \ker f \leq G$. Then $N \subset H$ and $|G/N|$ divides $p!$ by the first isomorphism theorem, so in particular $|G/N|$ has no prime factor greater than $p$. On the other hand, $|G/N|$ divides $|G|$, and $|G|$ has no prime factor less than $p$. Thus $|G/N| = p$, i.e. $[G : N] = p$. Since $G$ is finite, this means that $H = N \leq G$. \hfill $\Box$

Theorem 1.8.21 (Orbit-stabilizer). Let $G$ be a group acting on a set $X$ and let $x \in X$. Then $|\text{orb } x| = |G : \text{stab } x|$. In particular, if $G$ is finite, then $|\text{orb } x| = |G|/|\text{stab } x|$.

Proof. Let $y \in \text{orb } x$. Then there exists $g_y$ such that $g_y x = y$. Define a function $\text{orb } x \rightarrow G/\text{stab } x$ by $y \mapsto g_y \text{stab } x$. This is well-defined, as if $g$ satisfies $gx = y$, then $g^{-1}g_yx = x$, so $g^{-1}g_y \in \text{stab } x$ and $g_y \text{stab } x = g \text{stab } x$. The inverse of this function is $g \text{stab } x \mapsto gx$. Thus we have a bijection between $\text{orb } x$ and $G/\text{stab } x$. \hfill $\Box$
Example 1.8.22. If the group $G$ is finite and $H \leq G$, then the number of subgroups conjugate to $H$ is $|G|/|N_G(H)|$.

Definition 1.8.23 (Fixed point). Given an action of $G$ on $X$ and $S \subseteq G$, a fixed point of $g$ is an element $x \in X$ with $gx = x$ for all $g \in S$. The set of fixed points of $S$ is denoted $X^S$. When $S = \{g\}$, we write $X^g$ for $X^S$.

Proposition 1.8.24. If $H = \langle S \rangle \leq G$, then $X^S = X^H$.

Lemma 1.8.25 (Burnside, †). Let $G$ be a finite group acting on a finite set $X$. Then the number of orbits of the action is

$$\frac{1}{|G|} \sum_{g \in G} |X^g|.$$

Proof. The number of orbits can be counted as a weighted sum over all $x \in X$ by $1/|\text{orb } x|$, so we get by orbit-stabilizer

$$\sum_{x \in X} \frac{1}{|\text{orb } x|} = \sum_{x \in X} \frac{|\text{stab } x|}{|G|} = \frac{1}{|G|} \sum_{x \in X} |\text{stab } x| = \frac{1}{|G|} \sum_{x \in X} \sum_{g \in G} |\{(g,x) \in G \times X \mid gx = x\}|$$

$$= \frac{1}{|G|} \sum_{x \in X} |\{x \in X \mid gx = x\}| = \frac{1}{|G|} \sum_{g \in G} |X^g|.$$

\square

1.9 SYLOW THEOREMS

Throughout, let $G$ be a finite group and $p$ be a prime.

Definition 1.9.1 ($p$-group). 1. $G$ is a $p$-group if $|G| = p^n$ for some $n \geq 0$.

2. If $H \leq G$, then $H$ is a $p$-subgroup of $G$ if $H$ is a $p$-group. (Here $G$ need not be a $p$-group.)

Lemma 1.9.2. Let a $p$-group $H$ act on a finite set $X$. Then $|X^H| \equiv |X| \pmod{p}$.

Proof. If $X^H = \{x_1, \ldots, x_k\}$, then $\text{orb}(x_i) = \{x_i\}$ for each $i$. All other orbits have size divisible by $p$ by orbit-stabilizer, hence the result. \square

Theorem 1.9.3 (Cauchy). If $p$ divides $|G|$, then $G$ has an element of order $p$.

Proof. Let $X = \{(x_1, \ldots, x_p) \in G^p \mid x_1 \cdots x_p = 1\}$. Then $|X| = |G|^{p-1}$, which is divisible by $p$. Consider the action of $H = \langle \sigma \rangle$ on $X$ with $\sigma(x_1, \ldots, x_p) = (x_p, x_1, \ldots, x_{p-1})$. Since $|H| = p$, it is a $p$-group, so by Lemma 1.9.2, $|X^H| \equiv |X| \equiv 0 \pmod{p}$. Any fixed point (element of $X^H$) is of the form $(x, \ldots, x)$ with $x^p = 1$. Note that $(1, \ldots, 1) \in X^H$, so $|X^H| \geq 1$ and is divisible by $p \geq 2$. Thus there exists $(x_1, \ldots, x) \in X^H$ with $x \neq 1$, so $x$ is an element of order $p$. \square

Theorem 1.9.4. Let $G$ be a non-trivial $p$-group. Then $Z \neq 1$.

Proof. Let $G$ act on $X = G$ by conjugation, so $X^G = Z$. By Lemma 1.9.2, $|Z| \equiv |G| \equiv 0 \pmod{p}$, so $Z$ is non-trivial. \square
Lemma 1.9.5. Let $H$ be a $p$-subgroup of a finite group $G$. Then $[N_G(H) : H] \equiv [G : H] \pmod{p}$.

Proof. Let $H$ act on $X = G/H$ by left multiplication. If $gH \in X^H$, i.e. $h(gH) = gH$ for all $h \in H$, then $g \in N_G(H)$. Hence $|X^H| = [N_G(H) : H]$. The result follows by Lemma 1.9.2. \qed

Definition 1.9.6 (Sylow $p$-subgroup). Write $|G| = p^nm$ with $n \geq 0$ and $p \nmid m$. A Sylow $p$-subgroup $H \leq G$ is a subgroup of $G$ with $|H| = p^n$.

Theorem 1.9.7 (First Sylow theorem). Let $p$ be a prime and $G$ be a finite group with $p$ dividing $|G|$. If $H \leq G$ is a $p$-subgroup, then

1. if $H$ is not a Sylow $p$-subgroup, then $H$ lies in a subgroup $N$ of order $p \cdot |H|$ with $H \leq N$;
2. $H$ is contained in a Sylow $p$-subgroup of $G$.

Proof. 1. Let $|H| = p^i$ for some $i < n$. Then $[N_G(H) : H] \equiv [G : H] = p^{n-i}m \equiv 0 \pmod{p}$ by Lemma 1.9.5, so $N_G(H)/H$ has order divisible by $p$. By Cauchy’s theorem, it has an element of order $p$, hence a subgroup $F$ of order $p$. By the correspondence theorem, if $\pi : N_G(H) \to N_G(H)/H$ is the canonical homomorphism, then $N = \pi^{-1}(F)$ is a subgroup of $N_G(H)$ containing $H$ and $[N : H] = p$. Since $H \leq N_G(H)$, we also have $H \leq N$.

2. Apply the first statement repeatedly. \qed

Theorem 1.9.8 (Second Sylow theorem). Suppose $p \mid |G|$.

1. If $H \leq G$ is a $p$-subgroup and $P \leq G$ is a Sylow $p$-subgroup, then $gHg^{-1} \leq P$ for some $g \in G$.
2. Any two Sylow $p$-subgroups of $G$ are conjugate.

Proof. 1. Let $H$ act on $X = G/P$ by left multiplication. Then $|X^H| \equiv |X| = m \not\equiv 0 \pmod{p}$, so $|X^H| \geq 1$. Let $gP \in X^H$. Then $hgP = gP$ for all $h \in H$, so $g^{-1}Hg \leq P$.

2. Immediate from the first statement. \qed

Corollary 1.9.9. Let $P \leq G$ be a Sylow $p$-subgroup. Then $P \leq G$ if and only if $P$ is the unique Sylow $p$-subgroup of $G$.

Notation. Given a finite group $G$ and prime $p$, write $\text{Syl}_p(G)$ for the set of all Sylow $p$-subgroups of $G$ and $n_p = |\text{Syl}_p(G)|$.

Theorem 1.9.10 (Third Sylow theorem). Suppose $p \mid |G|$. Then $n_p \mid m$ and $n_p \equiv 1 \pmod{p}$.

Proof. By the second Sylow theorem, $G$ acts transitively on $X = \text{Syl}_p(G)$ by conjugation. Let $P \in X$ be some Sylow $p$-subgroup. Then $|X^P| = |X| = n_p$ (mod $p$) by Lemma 1.9.2. If $Q \in X^P$, then $gQg^{-1} = Q$ for all $g \in P$. Thus $P, Q \leq N_G(Q)$ are Sylow $p$-subgroups. Since $Q \leq N_G(Q)$, this means that $Q = P$. Thus $X^P = \{P\}$ and $n_p \equiv 1 \pmod{p}$. \qed
1.10 DIRECT PRODUCTS

**Definition 1.10.1** (Direct product). Let \( G_1, \ldots, G_n \) be groups. Then \( G = G_1 \times \cdots \times G_n \) forms a group with componentwise group operations, called the (external) direct product of \( G_1, \ldots, G_n \).

**Proposition 1.10.2** (†). If \( G_1 \cong G_2 \) and \( H_1 \cong H_2 \), then \( G_1 \times H_1 \cong G_2 \times H_2 \).

**Example 1.10.3.** 1. \( (\mathbb{Z}/2\mathbb{Z}) \times (\mathbb{Z}/2\mathbb{Z}) \) has order 4 and is non-cyclic, so it is isomorphic to \( V_4 \).

2. The direct product of abelian groups is abelian.

**Definition 1.10.4** (Internal direct product). Let \( H_1, \ldots, H_n \leq G \). We say that \( G \) is the internal direct product of \( H_1, \ldots, H_n \) if the multiplication map

\[
f : H_1 \times \cdots \times H_n \rightarrow G
\]

is a group isomorphism.

**Proposition 1.10.5.** If \( G \) is the internal direct product of \( H_1, \ldots, H_n \), then \( G \cong H_1 \times \cdots \times H_n \).

**Theorem 1.10.6** (Direct product theorem). Let \( G \) be a group and \( H_1, \ldots, H_n \leq G \) be subgroups. Then \( G \) is the internal direct product of \( H_1, \ldots, H_n \) if and only if

1. \( H_i \trianglelefteq G \);
2. \( G = H_1 \cdots H_n \);
3. if \( 1 = h_1 \cdots h_n \) for \( h_i \in H_i \), then \( h_i = 1 \) for all \( i \).

**Proof.** ( \( \Rightarrow \) ) Let \( f \) be the multiplication isomorphism above. The first condition follows from the fact that \( f^{-1}(H_i) \) is the copy of \( H_i \) embedded in \( H_1 \times \cdots \times H_n \) in the natural way, which is normal. The last two conditions are surjectivity and injectivity of \( f \), respectively.

( \( \Leftarrow \) ) By the third condition, \( H_i \cap H_j = 1 \) for \( i \neq j \). Then if \( h_i \in H_i \) and \( h_j \in H_j \), we have \( h_i h_j h_i^{-1} h_j^{-1} \in H_i \cap H_j = 1 \) by normality of \( H_i \) and \( H_j \) in \( G \), so \( H_i \) and \( H_j \) commute. This is enough to ensure that the multiplication map \( f \) above is a group homomorphism. That \( f \) is surjective and injective follows from the second and third conditions, respectively.

**Corollary 1.10.7.** 1. If \( n = 2 \), then condition 3 may be replaced by \( H_1 \cap H_2 = 1 \).

2. If \( G \) is finite, then one of conditions 2 or 3 may be replaced by \( |G| = |H_1| \cdots |H_n| \).

**Example 1.10.8** (Chinese remainder theorem). Let \( m \) and \( n \) be relatively prime positive integers, and consider \( \mathbb{Z}/mn\mathbb{Z} \). The subgroups \( m\mathbb{Z}/mn\mathbb{Z} \) and \( n\mathbb{Z}/mn\mathbb{Z} \) satisfy the conditions of the direct product theorem, so (Homework 1 Problem 9(b))

\[ \mathbb{Z}/mn\mathbb{Z} \cong (m\mathbb{Z}/mn\mathbb{Z}) \times (n\mathbb{Z}/mn\mathbb{Z}) \cong (\mathbb{Z}/m\mathbb{Z}) \times (\mathbb{Z}/n\mathbb{Z}) \]
Theorem 1.10.9. Let $G$ be a finite group with $|G| = p_1^{k_1} \cdots p_n^{k_n}$, where the $p_i$ are distinct primes. For each $i$, let $H_i \leq G$ be a Sylow $p_i$-subgroup. If $H_i \trianglelefteq G$ for all $i$, then $G$ is the internal direct product of $H_1, \ldots, H_n$.

Proof. We apply the direct product theorem.

1. This is given.

2. We replace $G = H_1 \cdots H_n$ with $|G| = |H_1| \cdots |H_n|$, and this holds since $|H_i| = p_i^{k_i}$ for each $i$.

3. Suppose $1 = h_1 \cdots h_n = 1$ with $h_i \in H_i$ for each $i$. Since each $H_i$ is normal in $G$, the product $H_1 \cdots H_{n-1}$ is a subgroup of $G$ of order not divisible by $p_n$, so $h_1 \cdots h_{n-1} = h_n^{-1}$ has order not divisible by $p_n$. On the other hand, $h_n \in H_n$, so $h_n$ has order 1 or order divisible by $p_n$. Thus we must have $h_n = 1$. By the same reasoning, $h_i = 1$ for all $i$, as required.

Proposition 1.10.10. Let $G$ be a group of order $pq$, where $p < q$ are primes. If $q \not\equiv 1 \pmod{p}$, then $G$ is cyclic.

Proof. If $H_p$ and $H_q$ are Sylow subgroups, then $|H_p| = p$ and $|H_q| = q$. By Sylow’s third theorem, $H_p$ and $H_q$ are normal (here we use $q \not\equiv 1 \pmod{p}$). Thus

$$G \cong H_p \times H_q \cong (\mathbb{Z}/p\mathbb{Z}) \times (\mathbb{Z}/q\mathbb{Z}) \cong \mathbb{Z}/pq\mathbb{Z}$$

by the Chinese remainder theorem.

1.11 NILPOTENT AND SOLVABLE GROUPS

Definition 1.11.1 (Commutator / commutator subgroup). Given $g, h \in G$, the commutator of $g$ and $h$ is $[g, h] = ghg^{-1}h^{-1}$.

If $H, K \leq G$, then the commutator subgroup $[H, K]$ of $G$ is the subgroup generated by commutators $[h, k]$ with $h \in H$ and $k \in K$.

Proposition 1.11.2. 1. $[g, h]^{-1} = [h, g]$;

2. $[g, [h, k]] = [[g, h], [g, k]]$;

3. $[x, y] = 1$ if and only if $xy = yx$.

Corollary 1.11.3. $[G, G] = 1$ if and only if $G$ is abelian.

Proposition 1.11.4. 1. If $H, K \leq G$, then $[H, K] \leq G$.

2. If $H \leq G$, then $[G, H] \leq G$.

3. If $H, K \leq G$ and $[H, K] \leq H$, then $K \leq N_G(H)$.

Proof. See Homework 3 Problem 7.
Definition 1.11.5 (Central series / lower central series). A central series is a series of subgroups

\[ G = G_0 \triangleright G_1 \triangleright \cdots \triangleright G_n = 1 \]

such that \( G_i \leq G \) and \([G, G_i] \leq G_{i+1} \) for each \( i \), or equivalently, \( G_i/G_{i+1} \subset Z(G/G_{i+1}) \) for each \( i \). The lower central series is the series

\[ G = G_0 \triangleright G_1 \triangleright \cdots \]

with \( G_{i+1} = [G, G_i] \) for each \( i \).

Definition 1.11.6 (Nilpotent group). A group is nilpotent if it has a (terminating) central series. Equivalently, the lower central series terminates in the trivial group.

Example 1.11.7. 1. Abelian groups are nilpotent.

2. Products of finitely many nilpotent groups are nilpotent.

Lemma 1.11.8. If \( G/Z \) is nilpotent, then \( G \) is nilpotent.

Proof. See Homework 3 Problem 8.

Corollary 1.11.9. Every \( p \)-group is nilpotent.

Lemma 1.11.10. Let \( G \) be a nilpotent group and \( H < G \) be a proper subgroup. Then \( H \neq N_G(H) \).

Proof. Take a central series \( G = G_0 \triangleright G_1 \triangleright \cdots \triangleright G_n = 1 \). There exists \( j \) such that \( G_j \not\leq H \) but \( G_{j+1} \leq H \). Then \([H, G_j] \leq [G, G_j] \leq G_{j+1} \leq H \), so \( G_j \leq N_G(H) \), which means \( N_G(H) \neq H \).

Lemma 1.11.11. Let \( P \) be a Sylow \( p \)-subgroup of \( G \) and \( H = N_G(P) \). Then \( N_G(H) = H \).

Proof. Let \( g \in N_G(H) \). Then \( P \) and \( gPg^{-1} \) are Sylow \( p \)-subgroups of \( H \). Since \( P \) is normal in \( H \), we have \( gPg^{-1} = P \), so \( g \in H \).

Theorem 1.11.12. A finite group \( G \) is nilpotent if and only if \( G \) is a product of \( p \)-groups.

Proof. \(( \Leftarrow \Rightarrow ) \) Products of nilpotent groups, in particular \( p \)-groups, are nilpotent.

\(( \Rightarrow \Leftarrow ) \) By Theorem 1.10.9, it suffices to show that every Sylow \( p \)-subgroup \( P \leq G \) is normal. Let \( H = N_G(P) \). Then \( N_G(H) = H \) by Lemma 1.11.11, so by Lemma 1.11.10, \( H \) cannot be a proper subgroup of \( G \), i.e. \( H \leq G \). Thus \( P \triangleleft G \).

Proposition 1.11.13. Let \( N \leq G \). Then \( G/N \) is abelian if and only if \([G, G] \leq N \).

Proof. \(( \Rightarrow ) \) Let \( g, h \in G \). Then since \( G/N \) is abelian, \([gN, hN] = [g, h]N = N \), so \([g, h] \in N \). Since \( N \) contains all commutators, it contains \([G, G] \).

\(( \Leftarrow ) \) If \([G, G] \leq N \), then \( G/N \cong (G/[G, G])/(N/[G, G]) \), so it suffices to show that \( G/[G, G] \) is abelian. This is immediate from \([G, G] \) containing all commutators.

Definition 1.11.15 (Derived series). The derived series of $G$ is

$$G = G^{(0)} \triangleright G^{(1)} \triangleright \cdots$$

with $G^{(i+1)} = [G^{(i)}, G^{(i)}]$ for each $i$.

Definition 1.11.16 (Solvable group). We say that $G$ is solvable if its derived series terminates in the trivial group. Equivalently, there is a sequence of subgroups

$$G = G_0 \triangleright G_1 \triangleright \cdots \triangleright G_n = 1$$

with $G_i/G_{i+1}$ abelian for each $i$.

Example 1.11.17. 1. Every nilpotent group, in particular every abelian group, is solvable.
2. A subgroup of a solvable group is solvable.
3. A quotient of a solvable group is solvable.

Lemma 1.11.18. If $N \triangleleft G$ and $G/N$ are solvable, then so is $G$.

Example 1.11.19. Let $|G| = pq$ for $p < q$ primes. If $H$ is the Sylow $q$-group, then $G$ is solvable since $H$ and $G/H$ are cyclic, hence solvable.

For a group of this form, $G$ is nilpotent if and only if $G$ is abelian (in which case it is cyclic). Thus for example, $S_3$ is solvable but not nilpotent.

1.12 SYMMETRIC AND ALTERNATING GROUPS

Recall that $S_n$ is the symmetric group on the indices $\{1, 2, \ldots, n\}$.

Definition 1.12.1 (Cycle / transposition). An element $\sigma \in S_n$ is a $k$-cycle if there exist $k$ distinct indices $a_1, \ldots, a_k$ with $\sigma(a_j) = a_{j+1}$ and every other element fixed by $\sigma$. (Here $a_{k+1} = a_1$.)

A transposition is a 2-cycle.

Notation. A cycle is written $\sigma = (a_1, a_2, \ldots, a_k)$. This is the same as $(a_2, \ldots, a_k, a_1)$, etc.

Example 1.12.2. The elements of $S_3$ are

$\text{id}, \ (1, 2), \ (1, 3), \ (2, 3), \ (1, 2, 3), \ (1, 3, 2)$.

Proposition 1.12.3. Every $\sigma \in S_n$ can be written as a product of disjoint cycles. Moreover, this is unique up to rearrangement and internal cycling of indices.

Definition 1.12.4 (Cycle type). Let $\sigma \in S_n$ and write

$$\sigma = (a_{1,1}, \ldots, a_{1,k_1})(a_{2,1}, \ldots, a_{2,k_2})\cdots(a_{r,1}, \ldots, a_{r,k_r})$$

with $k_1 \geq k_2 \geq \cdots \geq k_r$ and $k_1 + \cdots + k_r = n$. The cycle type of $\sigma$ is the $r$-tuple $(k_1, \ldots, k_r)$. 

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Notation. It is convenient to drop 1’s from the cycle type if the degree \( n \) of the symmetric group \( S_n \) is understood. For example, \((12)(34)(5) \in S_5\) has cycle type \((2, 2, 1)\) or simply \((2, 2)\).

Proposition 1.12.5. Two permutations \( \sigma, \tau \in S_n \) are conjugate if and only if they have the same cycle type.

Proof. See Homework 5 Problem 1. \( \square \)

Definition 1.12.6 (Permutation representation). The (complex) permutation representation of \( S_n \) is the homomorphism \( \pi : S_n \to GL_n(\mathbb{C}) \) given by

\[ \pi(\sigma) = (\delta_{\sigma(i), j}) . \]

Definition 1.12.7 (Sign homomorphism / alternating group). The sign homomorphism of \( S_n \) is \( \text{sgn} = \det \circ \pi : S_n \to \{\pm 1\} \). The alternating group is \( A_n = \ker \text{sgn} \leq S_n \).

Proposition 1.12.8. Every element in \( S_n \) is a product of transpositions.

Example 1.12.9. The \( k \)-cycle \((a_1, \ldots, a_k)\) is a product of \( k - 1 \) transpositions

\[ (a_1, a_k)(a_1, a_{k-1}) \cdots (a_1, a_2). \]

Proposition 1.12.10. If \( \sigma \) can be written as a product of \( k \) transpositions, then \( \text{sgn} \sigma = (-1)^k \).

Lemma 1.12.11. \( A_n \) is generated by 3-cycles.

Proof. It suffices to write any product of two transpositions in terms of 3-cycles, as elements of \( A_n \leq S_n \) can be written as products of transpositions, and being in \( A_n \) requires these products to have an even number of factors. For this, we have

\[
\begin{align*}
(a, b)(a, b) &= \text{id}, \\
(a, b)(b, c) &= (a, b, c), \\
(a, b)(c, d) &= (a, b, c)(b, c, d).
\end{align*}
\]

Lemma 1.12.12. If \( n \geq 5 \), then any two 3-cycles in \( A_n \) are conjugate.

Proof. Let \( \sigma, \tau \in A_n \) be 3-cycles. Then there exists \( \rho \in S_n \) with \( \tau = \rho \sigma \rho^{-1} \). If \( \rho \in A_n \), we are done. Otherwise, suppose \( \sigma = (a, b, c) \). Since \( n \geq 5 \), there are indices \( d, e \) disjoint from \( \sigma \). Then \( \rho' = \rho(d, e) \in A_n \), and

\[
\rho' \sigma \rho'^{-1} = \rho(d, e)(a, b, c)(d, e)\rho^{-1} = \rho(a, b, c)\rho^{-1} = \tau.
\]

Definition 1.12.13 (Simple group). A group \( G \neq 1 \) is simple if its only normal subgroups are 1 and \( G \).

Example 1.12.14. If \( G \) is abelian or solvable, then \( G \) is simple if and only if \( G \cong C_p \).
Theorem 1.12.15. If \( n \geq 5 \), then \( A_n \) is simple.

Proof. Let \( N \trianglelefteq A_n \) be non-trivial. It suffices to show that \( N \) contains a 3-cycle. Pick some \( \sigma \in N \). If \( \sigma \) is not a 3-cycle, then since (single) transpositions are not in \( A_n \), \( \sigma \) moves at least four indices. Suppose \( \sigma \) contains a \( k \)-cycle for some \( k \geq 4 \), say \( \sigma = (12\cdots k)\tau \) by relabeling (conjugation). Then
\[
\sigma(123)\sigma^{-1}(123)^{-1} = (234)(132) = (142) \in N.
\]
Suppose \( \sigma = (123)(456)\tau \) for some \( \tau \) which is a product of 3-cycles and transpositions. Then
\[
\sigma(124)\sigma^{-1}(124)^{-1} = (234)(142) = (14352) \in N,
\]
so we are done by the previous case.

Suppose \( \sigma = (123)\tau \) for some \( \tau \) which is a product of transpositions. Then \( \sigma\tau = (132) \in N \).

Finally, suppose \( \sigma = (12)(34)\tau \) for some \( \tau \) which is a product of transpositions. Then
\[
\pi = \sigma(123)\sigma^{-1}(123)^{-1} = (241)(132) = (24) \in N
\]
and \( \pi(135)\pi^{-1}(135)^{-1} = (315)(153) = (135) \in N \).

\( \square \)

Corollary 1.12.16. \( S_n \) is not solvable for \( n \geq 5 \).

Remark 1.12.17. The group \( A_3 \cong C_3 \) is also simple, while groups \( A_1 \) and \( A_2 \) are trivial.

By order, \( A_5 \) is the smallest non-abelian simple group.

Proposition 1.12.18. \( S_n \) is solvable for \( n \leq 4 \).

1.13 SEMIDIRECT PRODUCTS

Definition 1.13.1 (Semidirect product). Let \( N \) and \( K \) be groups and \( f : K \to \text{Aut} N \) be a homomorphism. The (external) semidirect product \( N \rtimes_f K \) is the group on \( N \times K \) with operation
\[
(h_1, k_1)(h_2, k_2) = (h_1f(k_1)(h_2), k_1k_2).
\]

Example 1.13.2. 1. If \( f \) is the trivial homomorphism, then \( N \rtimes_f K = N \times K \).

2. Let \( N = C_n \) and \( K = C_2 \). There is a non-trivial homomorphism \( f : C_2 \to C_n \) which sends the non-identity element of \( C_2 \) to the map \( g \mapsto g^{-1} \). This gives us the group \( C_n \rtimes_f C_2 \) with
\[
(r_1, s_1)(r_2, s_2) = (r_1r_2^{-1}, s_1s_2).
\]
This is the dihedral group of degree \( n \), denoted \( D_n \). It has order \( 2n \).

3. If \( p < q \) are primes and \( q \equiv 1 \pmod{p} \), then there is a non-trivial \( f : C_p \to \text{Aut} C_q \). Then \( C_q \rtimes_f C_p \) is a non-abelian group of order \( pq \).

Proposition 1.13.3. \( N \trianglelefteq N \rtimes_f K \).

Definition 1.13.4 (Internal semidirect product). Let \( N \trianglelefteq G \) and \( K \trianglelefteq G \). If \( N \cap K = 1 \) and \( G = NK \), then we say that \( G \) is the internal semidirect product of \( N \) and \( K \).

Proposition 1.13.5. If \( G \) is the internal semidirect product of \( N \) and \( K \), then \( G \cong N \rtimes_f K \) for some homomorphism \( f : K \to \text{Aut} N \).

Proposition 1.13.6 (f). If \( H \) is a group, then \( \text{Aut} H \leq \text{Inn} G \) for some group \( G \) containing \( H \).

Proof. We can take \( G = H \rtimes_f \text{Aut} H \) with \( f : \text{Aut} H \to \text{Aut} H \) the identity. \( \square \)
1.14 GROUPS OF SMALL ORDER

In this section we classify groups of order \( n = |G| \leq 15 \) up to isomorphism.
Throughout, write \( C_n = \mathbb{Z}/n\mathbb{Z} \) and assume \( p < q \) are primes.

**Proposition 1.14.1.** The only group of order 1 is 1.

**Proposition 1.14.2.** If \( n = p \), then \( G \cong C_p \).

*Proof.* See Homework 2 Problem 5b.

**Proposition 1.14.3.** If \( n = p^2 \) for \( p \) prime, then \( G \cong C_{p^2} \) or \( G \cong C_p \times C_p \).

*Proof.* If \( G \) contains an element of order \( p^2 \), then \( G \cong C_{p^2} \).
Otherwise, every non-identity element of \( G \) has order \( p \). Let \( h \in G \) be such an element and consider the subgroup \( H = \langle h \rangle \) of order \( p \). We can then pick \( k \in G \setminus H \) and take \( K = \langle k \rangle \), also of order \( p \). Then \( H \) and \( K \) satisfy the conditions of the direct product theorem, so \( G \cong H \times K \cong C_p \times C_p \). □

**Proposition 1.14.4.** If \( n = pq \) and \( q \not\equiv 1 \pmod{p} \), then \( G \cong C_{pq} \).

*Proof.* This is Proposition 1.10.10.

**Proposition 1.14.5.** If \( q \equiv 1 \pmod{p} \) instead, then \( G \cong C_{pq} \) or \( G \cong C_q \rtimes_f C_p \) for \( f \) non-trivial.

*Proof.* The Sylow \( q \)-subgroup \( Q \cong C_q \) is normal in \( G \), while the number of Sylow \( p \)-subgroups is either 1 or \( q \). If \( n_p = 1 \), then \( G \cong C_q \times C_p \cong C_{pq} \) by Proposition 1.10.10.
If \( n_p = q \), then fix some Sylow \( p \)-subgroup \( P \). The subgroups \( Q \) and \( P \) meet the conditions for \( G \) to be an internal semidirect product, i.e. \( G = Q \rtimes_f P \) for some non-trivial \( f : P \to \text{Aut } Q \). □

**Corollary 1.14.6.** If \( p \) is an odd prime and \( |G| = 2p \), then \( G \cong C_{2p} \) or \( G \cong D_p \).

*Proof.* By Proposition 1.14.5, either \( G \cong C_{2p} \) or \( G \cong C_p \rtimes_f C_2 \) for some non-trivial \( f : C_2 \to \text{Aut } C_p \).
The only such \( f \) is the one which sends the generator of \( C_2 \) to the inversion automorphism of \( C_p \), which gives the dihedral group \( D_p \). □

Using these results, we can classify groups of order up to \( n = 15 \) except for \( n = 8 \) and \( n = 12 \).

1. 1
2. \( C_2 \)
3. \( C_3 \)
4. \( C_4, C_2 \times C_2 \)
5. \( C_5 \)
6. \( C_6, D_3 \cong S_3 \)
7. \( C_7 \)
8. \( C_8 \)
9. \( C_9, C_3 \times C_3 \)
10. \( C_{10}, D_5 \)
11. \( C_{11} \)
12. \( C_{12}, D_6 \)
13. \( C_{13} \)
14. \( C_{14}, D_7 \)
15. \( C_{15} \)
16. \( C_{16} \)
17. \( C_{17} \)
18. \( C_{18} \)
19. \( C_{19} \)
20. \( C_{20} \)
21. \( C_{21} \)
22. \( C_{22} \)
Proposition 1.14.7. The groups of order 8 are \( C_8, C_4 \times C_2, C_2 \times C_2 \times C_2, D_4, \) and
\[
Q_8 = \left\{ \pm \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \pm \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}, \pm \begin{pmatrix} 0 & 1 \\ -i & 0 \end{pmatrix}, \pm \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix} \right\}.
\]

Proof. If \( G \) has an element of order 8, then \( G \cong C_8 \).

If \( G \) has no elements of order 4 or 8, so every non-identity element has order 2, then repeated use of the direct product theorem shows that \( G \cong C_2 \times C_2 \times C_2 \).

If \( h \in G \) has order 4 and no element of \( G \) has order 8, then let \( H = \langle h \rangle \leq G \) and pick \( k \in G \backslash H \).

If \( k \) has order 2, then \( K = \langle k \rangle \) intersects \( H \) trivially and \( |G| = |H||K| \), so \( G = H \rtimes f K \) for some \( f : K \to \text{Aut} H \). There are two possibilities for \( f \), which correspond to \( C_2 \times C_2 \) if \( f \) is trivial and \( D_4 \) if \( f \) sends \( k \) to the inversion automorphism.

If no \( k \in G \backslash H \) has order 2, so then every \( k \in G \backslash H \) has order 4, we have \( k^2 = h^2 \) for all \( k \in G \backslash H \) since \( (kH)(kH) = H \) in \( G/H \) and \( k^2 \) has order 2. From this we can deduce that \( h^2 = Z \) and \( hk = kh^3 \), which is enough to deduce the multiplication table of \( G \). One can check that \( Q_8 \) has the same multiplication table.

Proposition 1.14.8. The groups of order 12 are \( C_{12}, C_6 \times C_2, D_6, A_4, \) and \( C_3 \times f C_4 \) for
\[
C_3 = \{1, a, a^2\}; \quad C_4 = \{1, b, b^2, b^3\}; \quad f(b)(a) = a^{-1}.
\]

Proof. Let \( P \leq G \) be a Sylow 3-subgroup.

If \( P \) is not normal, then there are 4 Sylow 3-subgroups, each of which contains 2 elements of order 3. Then there are only four elements of \( G \) not of order 3, so the unique Sylow 2-subgroup \( Q \) of 4 elements must contain all of them, and thus \( Q \) is normal. Hence \( G \cong Q \rtimes f P \) for some \( f : P \to \text{Aut} \).

If \( Q \cong C_4 \), then we seek homomorphisms \( f : C_3 \to \text{Aut} C_4 \). There are two elements of \( \text{Aut} C_4 \), and only the identity satisfies \( \sigma^3 = 1 \), so the only possible choice of \( f \) is the trivial map. This gives \( G \cong C_4 \times C_3 \cong C_{12} \).

If \( Q \cong C_2 \times C_2 \), then \( \text{Aut} Q \cong S_3 \), which has three elements \( \sigma \) satisfying \( \sigma^3 = 1 \). Thus we have three possible choices of \( f : P \to \text{Aut} \). If \( f \) is trivial, then \( G \cong C_2 \times C_2 \times C_3 \cong C_6 \times C_2 \).

Otherwise, if \( P = \{1, a, a^2\} \) and \( Q = \{1, b, bc\} \), then without loss of generality \( f(a)(b) = c \) and \( f(a)(c) = bc \) (otherwise, relabel elements). The multiplication table is then completely determined, and it matches that of \( A_4 \).

Now suppose \( P \) is normal and let \( Q \) be a Sylow 2-subgroup of order 4. In this case \( G \cong P \rtimes_g Q \) for some \( g : Q \to \text{Aut} \).

If \( Q \cong C_4 \), then \( \text{Aut} P \) has two elements, both satisfying \( \sigma^4 = 1 \), so there are two choices for \( g \). If \( g \) is trivial, then we get \( G \cong C_3 \times C_4 \cong C_{12} \) again. Otherwise, if \( P = \{1, a, a^2\} \) and \( Q = \{1, b, b^2, b^3\} \), then elements of \( G \) have the form \( a^ib^j \), and multiplication is determined by \( ba = a^{-1}b \). This is the last group of the list.

If \( Q \cong C_2 \times C_2 \), then there are four homomorphisms \( g : Q \to \text{Aut} P \), but three of them are the same up to an isomorphism of \( Q \) (i.e. by relabeling generators). The trivial \( g \) produces \( G \cong C_6 \times C_2 \), while the non-trivial choices of \( g \) turn out to produce \( D_6 \).

Remark 1.14.9. There are 14 isomorphism classes of groups of order 16.
1.15 EXACT SEQUENCES

Definition 1.15.1 (Exact sequence). A sequence of group homomorphisms

\[ G_0 \xrightarrow{f_1} G_1 \xrightarrow{f_2} \cdots \xrightarrow{f_n} G_n \]

is exact if \( \text{im} f_i = \text{ker} f_{i+1} \) for all \( i = 1, \ldots, n - 1 \).

Proposition 1.15.2. 1. \( f: G \to H \) is injective if and only if \( 1 \to G \xrightarrow{f} H \) is exact.

2. \( f: G \to H \) is surjective if and only if \( G \xrightarrow{f} H \to 1 \) is exact.

Definition 1.15.3 (Short exact sequence). A short exact sequence is an exact sequence

\[ 1 \to H \xrightarrow{\alpha} G \xrightarrow{\beta} F \to 1, \]

i.e. \( \alpha \) is injective, \( \beta \) is surjective, and \( \text{im} \alpha = \ker \beta \). Then \( H \) identifies with \( \text{im} \alpha \leq G \) and \( F \cong G/H \).

Proposition 1.15.4. If \( H \trianglelefteq G \), then the sequence

\[ 1 \to H \xrightarrow{i} G \xrightarrow{\pi} G/H \to 1 \]

is exact.

Definition 1.15.5 (Split exact sequence). A short exact sequence

\[ 1 \to H \xrightarrow{\alpha} G \xrightarrow{\beta} F \to 1 \]

is split (or right split) if there exists \( \gamma: F \to G \) such that \( \beta \circ \gamma = \text{id}_F \).

Theorem 1.15.6. The short exact sequence

\[ 1 \to H \xrightarrow{\alpha} G \xrightarrow{\beta} F \to 1 \]

is split if and only if there is a subgroup \( K \leq G \) such that \( \beta|_K: K \to F \) is an isomorphism. In this case, \( G \cong H \rtimes \varphi F \) with \( \varphi: F \to \text{Aut} H \) given by \( \varphi(f)(h) = ghg^{-1} \), where \( g = \gamma(f) \).

Proof. (\( \Longrightarrow \)) Let \( K = \text{im} \gamma \). If \( f \in F \) and \( k = \gamma(f) \in K \), then \( \beta|_K(k) = \beta(\gamma(f)) = f \), so \( \beta|_K: K \to F \) is surjective. If \( k \in \ker \beta|_K \), then \( k = \gamma(f) \) for some \( f \in F \) since \( K = \text{im} \gamma \), and then \( f = \beta(\gamma(f)) = \beta(k) = 1 \). This means \( k = \gamma(1) = 1 \), so \( \ker \beta|_K \) must be trivial.

(\( \Longleftarrow \)) Suppose such a \( K \) exists, so \( \beta|_K: K \to F \) is an isomorphism. Take \( \gamma = \beta|_K^{-1} \circ i \).

If these conditions are met, then regard \( K \cong \gamma(K) \) as a subgroup of \( G \). We have that \( H = \ker \beta \leq G \), and \( H \cap K = 1 \) since \( \beta(H) = 1 \) and \( \beta|_K: K \to F \) is an isomorphism. Finally, if \( g \in G \) and \( f = \beta(g) \in F \), then \( k = \gamma(f) \in K \) and \( h = gk^{-1} \in H \) satisfy \( hk = g \), so \( G = HK \). Hence \( G \) is the internal semidirect product of \( H \) and \( K \), so \( G \cong H \rtimes \varphi F \) for some \( \varphi: F \to \text{Aut} H \). To determine \( \varphi \), let \( g = \gamma(f) \in K \) and \( h \in H \). Then \( gh = \varphi(g)(h) \cdot g \), so \( \varphi(g)(h) = ghg^{-1} \), as required. \( \square \)
Example 1.15.7. Let $G$ be a non-abelian group of order 8, and let $h \in G$ be an element of order 4. Then $H = \langle h \rangle \trianglelefteq G$, so we have a short exact sequence

$$1 \rightarrow H \rightarrow G \rightarrow G/H \rightarrow 1.$$  

If there is an element of order 2 in $G \setminus H$, then the sequence splits and we obtain $G \cong D_4$ via the theorem. Otherwise, there is no splitting, and we obtain $Q_8$ as before.

1.16 FREE GROUPS

Definition 1.16.1 (Words). Let $X$ be a set, called the alphabet. The elements of $X$ are referred to as letters. Form an inverse alphabet $\overline{X}$ of formal symbols $\{ \overline{x} \mid x \in X \}$.

For $n \geq 0$, a word of length $n$ on $X$ is a sequence of $n$ letters (not necessarily distinct) from $X \cup \overline{X}$.

Concatenation of words $w$ and $v$ to get a new word $wv$ defines an associative non-commutative binary operation on the set of words on a given alphabet. The empty word is the identity for this operation, but no element (other than $\underline{\text{w}}$) has an inverse.

Definition 1.16.2 (Truncation / irreducible word). Let $w$ be a word on $X$ of the form $u a a v$ or $u a a a v$, where $u, v$ are words on $X$ and $a \in X$ is a letter. The word $w' = uv$ is a truncation of $w$. If $w$ is a word on $X$, then $w$ is irreducible if there is no word $u$ on $X$ which is a truncation of $w$.

For two words $u, v$ on $X$, write $u \sim w$ is there is a sequence of words $u = w_0, w_1, \ldots, w_n = v$ such that for each $i$, one of the words $w_i, w_{i+1}$ is a truncation of the other. Then $\sim$ is an equivalence relation on the set of words on $X$.

Proposition 1.16.3. If $u_1 \sim v_1$ and $u_2 \sim v_2$, then $u_1 u_2 \sim v_1 v_2$.

Theorem 1.16.4. Each equivalence class of words on $X$ contains exactly one irreducible word.

Proof. For existence, let $w$ be a word of minimum length in a given equivalence class. Since truncation reduces the length of a word by 2, $w$ must be irreducible.

For uniqueness, let $u$ and $v$ be irreducible words in the same equivalence class, and write down a sequence $u = w_0, w_1, \ldots, w_n = v$ as above. To show that $u = v$, we induct on $n$ and then the total length of the words $w_0, \ldots, w_n$. When $n = 0$, we have $u = w_0 = v$. Now consider $n \geq 1$ and look at a longest word $w_k$ in the sequence. Then $w_{k-1}$ and $w_{k+1}$ are necessarily truncations of $w_k$.

If the truncations are $stb\overline{u} \leftarrow saa\overline{b}b\overline{u} \rightarrow saa\overline{tu}$, then we replace $w_k$ with $stu$ and have truncations $w_{k-1} \rightarrow w_k$ and $w_{k+1} \rightarrow w_k$ instead. This does not change the number of words $n$ in the sequence, but it does reduce the total length of all words in the sequence, so we can apply the inductive hypothesis.

If the truncations are $sat \leftarrow saat \rightarrow sat$ or $st \leftarrow aat \rightarrow st$, then we can reduce the number of words $n$ in the sequence by omitting $w_k$ and $w_{k+1}$.

We can obtain every other case by swapping the roles of letters and inverse letters. □
1.16 Free groups

Definition 1.16.5 (Free group). Let $X$ be an alphabet. The free group on $X$, denoted $F(X)$ (or Free $X$), is the set of all equivalence classes of words on $X$ with the concatenation operation.

Example 1.16.6. 1. If $X = \emptyset$, then $F(X) = 1$.

2. If $X = \{a\}$, then $F(X) \cong \mathbb{Z}$ is the cyclic group generated by $[a]$.

3. If $|X| \geq 2$ with $a, b \in X$ distinct, then $ab$ and $ba$ are distinct irreducible words. Hence $[ab] \neq [ba]$, so $F(X)$ is non-abelian.

Notation. In $F(X)$, we write $a^{-1}$ for $a$ when $a \in X$.

For convenience, we will write $w$ for $[w]$ and work on words themselves whenever possible.

Theorem 1.16.7 (Universal property of free groups). Let $X$ be a set, $G$ be a group, and $f : X \rightarrow G$ be a set function. Then there is a unique group homomorphism $\overline{f} : F(X) \rightarrow G$ such that $\overline{f}(x) = f(x)$ for all $x \in X$.

Proof. Let $w \in F(X)$ and write $w = b_1 \cdots b_n$ where $b_i = x_i^{\epsilon_i}$ for some $x_i \in X$ and $\epsilon_i \in \{\pm 1\}$. Then

$$\overline{f}(w) = \overline{f}(b_1) \cdots \overline{f}(b_n) = f(x_1)^{\epsilon_1} \cdots f(x_n)^{\epsilon_n},$$

which shows that if $\overline{f}$ exists, then it is unique and must be given by this formula.

To show existence, we can define $\overline{f}$ using this formula, provided it is well-defined on $F(X)$. For this, note that $\overline{f}$ is unchanged by truncations, hence whenever two words are equivalent. \qed

Corollary 1.16.8. Let $X \subset G$ generate $G$. Then $G \cong F(X)/N$ for some $N \trianglelefteq F(X)$.

Proof. The inclusion function $i : X \hookrightarrow G$ extends to a homomorphism $f : F(X) \rightarrow G$. That $X$ generates $G$ means that $f$ is surjective, so $F(X)/\ker f \cong G$. \qed

Notation. If $G$ is a group and $S \subset G$ is a subset, then

$$\langle \langle S \rangle \rangle = \left( \bigcup_{g \in G} gSg^{-1} \right)$$

is the smallest normal subgroup of $G$ containing $S$.

Definition 1.16.9 (Presentation / finite presentation). Let $G$ be a group and $X \subset G$ generate $G$. Choose a subset $R \subset F(X)$ such that $G \cong F(X)/\langle \langle R \rangle \rangle$. Then we write

$$G \cong \langle X \mid R \rangle = F(X)/\langle \langle R \rangle \rangle.$$

This is a presentation for $G$. We say that the presentation is finite if $X$ and $R$ are finite.

Example 1.16.10. 1. $\langle \sigma \mid \sigma^n \rangle \cong \mathbb{Z}/n\mathbb{Z}$

2. $\langle \sigma, \tau \mid \sigma^n, \tau^2, \tau \sigma \tau \sigma \rangle \cong D_n$

Proposition 1.16.11 (†). Every group $G$ has a presentation.

Proof. An explicit presentation is $G \cong \langle G \mid \{g_1g_2g_3 \mid g_1, g_2, g_3 \in G \text{ with } g_1g_2g_3 = 1\} \rangle$. \qed
Definition 1.16.12 (Free product). Let $G$ and $H$ be groups. The *free product* of $G$ and $H$, denoted $G * H$, is the group $F(G \cup H) / \langle \langle R \rangle \rangle$, where
\[
R = \{1_G, 1_H\} \cup \{g_1g_2g_3 \mid g_1, g_2, g_3 \in G \text{ with } g_1g_2g_3 = 1_G \text{ in } G\} \\
\cup \{h_1h_2h_3 \mid h_1, h_2, h_3 \in H \text{ with } h_1h_2h_3 = 1_H \text{ in } H\}.
\]

Proposition 1.16.13. Let $G$ and $H$ be groups with presentations $\langle X \mid R \rangle$ and $\langle Y \mid S \rangle$. Then

\[G * H \cong \langle X \cup Y \mid R \cup S \rangle.\]

Proof. See Homework 7 Problem 2. \qed

Example 1.16.14. 1. $G * 1 \cong G$ and $1 * H \cong H$.

2. If $G, H \neq 1$, then $G * H$ is infinite with trivial center (see Homework 6 Problem 7).

Theorem 1.16.15 (Universal property of free products). Let $i, j : G, H \rightarrow G * H$ be the natural maps and let $g, h : G, H \rightarrow K$ be homomorphisms to some group $K$. Then there is a unique homomorphism $k : G * H \rightarrow K$ such that the following diagram commutes.

\[\begin{array}{ccc}
G & \xrightarrow{i} & G * H \\
\downarrow{j} & & \downarrow{k} \\
H & \xrightarrow{h} & K
\end{array}\]

This is closely related to the following result for direct products.

Theorem 1.16.16 (Universal property of direct products). Let $\pi_G, \pi_H : G \times H \rightarrow G, H$ be the projections and let $g, h : K \rightarrow G, H$ be homomorphisms from some group $K$. Then there is a unique homomorphism $k : K \rightarrow G \times H$ such that the following diagram commutes.

\[\begin{array}{ccc}
G & \xrightarrow{\pi_G} & G \times H \\
\downarrow{g} & & \downarrow{k} \\
H & \xleftarrow{\pi_H} & K
\end{array}\]
2 CATEGORIES AND FUNCTORS

2.1 DEFINITIONS AND BASIC PROPERTIES

Definition 2.1.1 (Category). A category \( \mathcal{C} \) consists of a collection (more formally a class) \( \text{Ob}\mathcal{C} \) of objects, a collection \( \text{Hom}\mathcal{C} \) (or \( \text{Mor}\mathcal{C} \)) of morphisms (arrows) between objects, and a composition operation, which forms from morphisms \( X \xrightarrow{f} Y \xrightarrow{g} Z \) a morphism \( g \circ f : X \to Z \), such that

(i) if \( W \xrightarrow{f} X \xrightarrow{g} Y \xrightarrow{h} Z \) are morphisms, then \( h \circ (g \circ f) = (h \circ g) \circ f \);

(ii) for any object \( X \in \text{Ob}\mathcal{C} \), there is a unique identity morphism \( \text{id}_X : X \to X \) such that for any morphisms \( f : X \to Y \) and \( g : W \to X \), we have

\[
\text{id}_X \circ f = f = f \circ \text{id}_X, \quad g \circ \text{id}_X = g.
\]

The collection of morphisms \( X \to Y \) is denoted \( \text{Hom}_{\mathcal{C}}(X,Y) \) (or \( \text{Mor}_{\mathcal{C}}(X,Y) \)).

Notation. We write \( X \in \mathcal{C} \) to mean \( X \in \text{Ob}\mathcal{C} \).

Example 2.1.2. 1. In \( \text{Set} \), the category of sets, the morphisms are functions.

2. In \( \text{Grp} \), the category of groups, the morphisms are group homomorphisms.

3. Given a group \( G \), we can form a category \( \mathcal{C} \) with \( \text{Ob}\mathcal{C} = \{\ast\} \) and \( \text{Hom}(\ast, \ast) = G \).

4. Given a poset \( X \), we can form a category \( \mathcal{C} \) with \( \text{Ob}\mathcal{C} = X \) and

\[
\text{Hom}(x, x') = \begin{cases} 
\{(x, x')\} & x \geq x', \\
\emptyset & \text{otherwise}.
\end{cases}
\]

5. Given categories \( \mathcal{C} \) and \( \mathcal{D} \), the product category \( \mathcal{C} \times \mathcal{D} \) has \( \text{Ob} \mathcal{C} \times \mathcal{D} = \text{Ob}\mathcal{C} \times \text{Ob}\mathcal{D} \) and \( \text{Hom}_{\mathcal{C} \times \mathcal{D}}((A, X); (B, Y)) = \text{Hom}_{\mathcal{C}}(A, B) \times \text{Hom}_{\mathcal{D}}(X, Y) \) in the natural way.

6. Given a category \( \mathcal{C} \), the dual category (opposite category), denoted \( \mathcal{C}^{\text{op}} \) (or \( \mathcal{C}^0 \)) is the category with \( \text{Ob}\mathcal{C}^{\text{op}} = \text{Ob}\mathcal{C} \) and \( \text{Hom}_{\mathcal{C}^{\text{op}}}(X, Y) = \text{Hom}_{\mathcal{C}}(Y, X) \). For disambiguation, we may write \( X^{\text{op}} \) or \( X^0 \) to denote the copy of \( X \) in \( \mathcal{C}^{\text{op}} \).

7. Given a category \( \mathcal{C} \), the arrow category \( \text{Arr}\mathcal{C} \) has \( \text{Ob}\mathcal{C} = \text{Hom}\mathcal{C} \). A morphism between \( f : X \to Y \) and \( f' : X' \to Y' \) is given by morphisms \( g : X \to X' \) and \( h : Y \to Y' \) such that the following diagram commutes.

\[
\begin{array}{ccc}
X & \xrightarrow{f} & Y \\
\downarrow{g} & & \downarrow{h} \\
X' & \xrightarrow{f'} & Y'
\end{array}
\]

Definition 2.1.3 (Isomorphism). A morphism \( f : X \to Y \) is an isomorphism if there exists a morphism \( g : Y \to X \) such that \( f \circ g = \text{id}_Y \) and \( g \circ f = \text{id}_X \).
Proposition 2.1.4. If \( f : X \to Y \) is an isomorphism with \( g : Y \to X \) as above, then \( g \) is unique and \( g \) is an isomorphism.

Notation. If \( f \) is an isomorphism, then write \( f^{-1} \) for the morphism \( g \) above.

Definition 2.1.5 (Subcategory / full subcategory). Let \( C \) be a category. A category \( C' \) is a subcategory of \( C \) if \( \text{Ob} C' \subset \text{Ob} C \), \( \text{Hom}_{C'}(X,Y) \subset \text{Hom}_C(X,Y) \), and the composition law in \( C' \) is inherited from \( C \).

We say that \( C' \) is a full subcategory of \( C \) if \( \text{Hom}_{C'}(X,Y) = \text{Hom}_C(X,Y) \) for all \( X,Y \in C' \).

Example 2.1.6. 1. In \( \text{Grp} \), the subcategory \( \text{Ab} \) of abelian groups is a full subcategory.

2. For any subclass \( A \subset \text{Ob} C \), there is a unique full subcategory \( C' \) of \( C \) such that \( \text{Ob} C' = A \).

Definition 2.1.7 (Initial and terminal objects). Let \( X \in C \) be an object.

1. \( X \) is initial if for every \( Y \in C \), there is a unique morphism \( X \to Y \).

2. \( X \) is terminal (final) if for every \( W \in C \), there is a unique morphism \( W \to X \).

Proposition 2.1.8. If \( X \in C \) is an object, then \( X \) is initial (terminal) in \( C \) if and only if \( X \) is terminal (initial) in \( C^{\text{op}} \).

Example 2.1.9. 1. In \( \text{Set} \), the initial object is \( \emptyset \) and the terminal objects are singleton sets.

2. In \( \text{Grp} \), the trivial group is initial and terminal.

3. Let \( G \) be a group and form \( C \) on one object as before. Then \( C \) has no initial or terminal objects (unless \( G \) is trivial).

4. Let \( X \) be a poset and form \( C \) on \( X \) as before. The initial object of \( C \) is the maximum of \( X \) (if it exists), while the terminal object is the minimum of \( X \) (if it exists).

Theorem 2.1.10. If \( X \) and \( X' \) are initial (terminal), then there is a unique isomorphism \( X \to X' \), i.e. \( X \) and \( X' \) are canonically isomorphic.

Proof. Let \( X \) and \( X' \) be initial, and let \( f : X \to X' \) and \( g : X' \to X \) be the unique morphisms. Then \( g \circ f : X \to X \) is a morphism \( X \to X \), but since \( X \) is initial and \( \text{id}_X : X \to X \) is a morphism, \( g \circ f = \text{id}_X \). Similarly, \( f \circ g = \text{id}_{X'} \), so \( f \) and \( g \) are inverses and \( f \) is an isomorphism. \( \square \)

2.2 PRODUCTS AND COPRODUCTS

Universal properties are applications of Theorem 2.1.10. As an example, we consider products.

Definition 2.2.1 (Product of two objects). Let \( X,Y \in C \). An object \( X \times Y \) together with morphisms \( p,q : X \times Y \to X,Y \) is a product of \( X \) and \( Y \) if for any morphisms \( f : Z \to X \) and \( g : Z \to Y \), there is a unique morphism \( h : Z \to X \times Y \) such that the following diagram commutes.
Theorem 2.2.2. Let \( X \times Y \) and \( \tilde{X} \times \tilde{Y} \) be two products of \( X \) and \( Y \), with projections \( p, q \) and \( \tilde{p}, \tilde{q} \), respectively. Then there is a unique isomorphism \( h : X \times Y \to \tilde{X} \times \tilde{Y} \) such that the following diagram commutes.

\[
\begin{array}{ccc}
X \times Y & \xrightarrow{p} & X \\
\downarrow{q} & & \downarrow{\tilde{p}} \\
Y & \xleftarrow{\tilde{q}} & \tilde{X} \times \tilde{Y}
\end{array}
\]

Proof. Fix \( X \) and \( Y \), and consider a new category \( D \) whose objects are diagrams of the form

\[
\begin{array}{ccc}
Z & \to & X \\
\downarrow & & \downarrow \\
Y & & \\
& & \\
\end{array}
\]

A morphism between diagrams for \( Z \) and \( Z' \) is given by a morphism \( Z \to Z' \) in \( C \) such that the following diagram commutes.

\[
\begin{array}{ccc}
Z & \to & X \\
\downarrow & & \downarrow \\
Y & \leftarrow & Z'
\end{array}
\]

The diagram for \( Z = X \times Y \) is a terminal object in \( D \), which is unique up to unique isomorphism. \( \square \)

Proposition 2.2.3. Let \( p, q : X \times Y \to X, Y \) be the projections. The function

\[
\text{Hom}(Z, X \times Y) \to \text{Hom}(Z, X) \times \text{Hom}(Z, Y) \\
h \mapsto (p \circ h, q \circ h)
\]

is a bijection.

Definition 2.2.4 (Arbitrary product). Let \( \{X_i\}_{i \in I} \) be a family of objects. The product is the object \( \prod_i X_i \) along with morphisms \( p_j : \prod_i X_i \to X_j \) for which \( \text{Hom}(Z, \prod_i X_i) \cong \prod_i \text{Hom}(Z, X_i) \) with bijection \( h \mapsto \prod_i \{p_i \circ h\} \).

Definition 2.2.5 (Product morphism). Let \( f : X \to X' \) and \( g : Y \to Y' \) be morphisms. The product morphism \( f \times g : X \times Y \to X' \times Y' \) is given by the following commuting diagram.

\[
\begin{array}{ccc}
X \times Y & \xrightarrow{q} & Y \\
\downarrow{p} & & \downarrow{g} \\
X & \xrightarrow{f} & Y' \\
& & \downarrow{q'} \\
& & X' \times Y'
\end{array}
\]
Example 2.2.6. 1. In \( \text{Set} \), the product is the ordinary Cartesian product.

2. In \( \text{Grp} \), the product is the (external) direct product.

3. In \( \text{Ab} \), the product is the (external) direct product. Within the context of abelian groups, it is also known as the \text{direct sum}, written \( G \oplus H \).

4. In the category \( n \to n-1 \to \cdots \to 2 \to 1 \), we have \( i \times j = \max(i, j) \).

Definition 2.2.7 (Coproduct). The \text{coproduct} of \( X, Y \in \mathcal{C} \) is \( (X \times \_ \_ \_Y)^{\text{op}} \), i.e. the product in \( \mathcal{C}^{\text{op}} \). More explicitly, the coproduct is an object \( X \mathbin{\star} Y \) together with morphisms \( i, j : X, Y \to X \mathbin{\star} Y \) such that given morphisms \( f : X \to Z \) and \( g : Y \to Z \), there is a unique morphism \( h : X \mathbin{\star} Y \to Z \) such that \( h \circ i = f \) and \( h \circ g = j \).

\[
\begin{array}{ccc}
X & \xrightarrow{f} & Z \\
\downarrow{\scriptstyle i} & & \downarrow{\scriptstyle h} \\
Y & \xleftarrow{j} & X \mathbin{\star} Y \\
\end{array}
\]

Proposition 2.2.8. The function
\[
\text{Hom}(X \mathbin{\star} Y, Z) \longrightarrow \text{Hom}(X, Z) \times \text{Hom}(Y, Z) \\
h \longmapsto (h \circ i, h \circ j)
\]
is a bijection.

Definition 2.2.9 (Arbitrary coproduct). Let \( \{X_J\}_{J \in J} \) be a family of objects. The \text{coproduct} is the object \( \bigsqcup_J X_J \) along with morphisms \( i_k : \bigsqcup_J X_J \to X_k \) for which \( \text{Hom}(\bigsqcup_J X_J, Z) \cong \prod_J \text{Hom}(X_J, Z) \) with bijection \( h \mapsto \prod_J \{h \circ i_J\} \).

Example 2.2.10. 1. In \( \text{Set} \), the coproduct is the disjoint union \( X \sqcup Y \).

2. In \( \text{Grp} \), the coproduct is the free product \( G * H \).

3. In \( \text{Ab} \), the coproduct is the direct sum \( G \oplus H \).

4. In \( n \to n-1 \to \cdots \to 2 \to 1 \), we have \( i \ast j = \min(i, j) \).

Definition 2.2.11 (Group object). Let \( \mathcal{C} \) be a category. A \text{group object} in \( \mathcal{C} \) is a quadruple \((G, m, e, i)\) such that

(i) \( G \) is an object;

(ii) \( m : G \times G \to G \) is a morphism (corresponding to multiplication);

(iii) \( e : F \to G \) is a morphism (corresponding to the identity element), where \( F \) is terminal;

(iv) \( i : G \to G \) is a morphism (corresponding to inverses);
(v) (associativity) the following diagram commutes;
\[
\begin{array}{c}
G \times G \times G \xrightarrow{\text{id}_G \times m} G \times G \\
\downarrow m \times \text{id}_G \quad \quad \downarrow m \\
G \times G \xrightarrow{m} G
\end{array}
\]

(vi) (identity) the following diagrams commute, where \( \pi_G \) is projection onto \( G \);
\[
\begin{array}{cc}
G \times F \xrightarrow{\text{id}_G \times e} G \times G & F \times G \xrightarrow{e \times \text{id}_G} G \times G \\
\downarrow \pi_G & \downarrow \pi_G \\
G & G
\end{array}
\]

(vii) (inverse) the following diagrams commute.
\[
\begin{array}{cc}
G \xrightarrow{(\text{id}_G, i)} G \times G & G \xrightarrow{(i, \text{id}_G)} G \times G \\
\downarrow m & \downarrow m \\
F \xrightarrow{e} G & G \xrightarrow{e} G
\end{array}
\]

Example 2.2.12. 1. The group objects in \( \text{Set} \) are the usual groups.

2. Group objects in \( \text{Top} \), the category of topological spaces, are topological groups.

3. Group objects in \( \text{Grp} \) are abelian groups.

2.3 FUNCTORS

Definition 2.3.1 (Functor). Let \( \mathcal{C} \) and \( \mathcal{D} \) be categories. A (covariant) functor \( F : \mathcal{C} \to \mathcal{D} \) is a collection of functions \( \text{Ob}\mathcal{C} \to \text{Ob}\mathcal{D} \) and \( \text{Hom}_\mathcal{C}(X,Y) \to \text{Hom}_\mathcal{D}(F(X),F(Y)) \) such that

(i) \( F(\text{id}_X) = \text{id}_{F(X)} \) for \( X \in \mathcal{C} \);

(ii) for morphisms \( X \xrightarrow{f} Y \xrightarrow{g} Z \) in \( \mathcal{C} \), we have \( F(g \circ f) = F(g) \circ F(f) \).

If instead \( F \) maps \( \text{Hom}_\mathcal{C}(X,Y) \) to \( \text{Hom}_\mathcal{D}(F(Y),F(X)) \) and \( F(g \circ f) = F(f) \circ F(g) \) for all \( f, g \), we say that \( F \) is a contravariant functor.

Remark 2.3.2. Contravariant functors are covariant functors \( \mathcal{C}^{\text{op}} \to \mathcal{D} \) or \( \mathcal{C} \to \mathcal{D}^{\text{op}} \), so it is only necessary to consider covariant functors.

Lemma 2.3.3. If \( f : X \to Y \) is an isomorphism in \( \mathcal{C} \), then \( F(f) : F(X) \to F(Y) \) is an isomorphism in \( \mathcal{D} \) and \( F(f)^{-1} = F(f^{-1}) \).

Corollary 2.3.4. If \( X \cong Y \) in \( \mathcal{C} \), then \( F(X) \cong F(Y) \) in \( \mathcal{D} \).
Example 2.3.5. 1. The identity functor $\text{id} : \mathcal{C} \to \mathcal{C}$ is defined by $\text{id}(X) = X$ and $\text{id}(f) = f$.

2. Let $Y \in \mathcal{D}$. The constant functor $c_Y : \mathcal{C} \to \mathcal{D}$ is given by $c_Y(X) = Y$ and $c_Y(f) = \text{id}_Y$.

3. The forgetful functor $\text{Forget} : \text{Grp} \to \text{Set}$ has $\text{Forget}(G) = G$ and $\text{Forget}(f) = f$.

4. If $\mathcal{C}' \subset \mathcal{C}$ is a subcategory, there is an inclusion functor $I : \mathcal{C}' \hookrightarrow \mathcal{C}$.

5. Let $F : \text{Grp} \to \text{Ab}$ send a group $G$ to its abelianization $G/G'$. Given $f : G \to H$, composing with the projection $H \to H/H'$ gives a homomorphism $\tilde{f} : G \to H/H'$. Then $G/\ker \tilde{f}$ is abelian, so $\tilde{f}$ descends to a homomorphism $G/G' \to H/H'$, which we call $F(f)$. One can check that with this definition of $F$ on morphisms, $F$ is a functor.

Definition 2.3.6 (Small / locally small category). A small category is a category $\mathcal{C}$ for which $\text{Ob} \mathcal{C}$ and $\text{Hom} \mathcal{C}$ are sets. A locally small category is one for which we can only say that $\text{Hom} \mathcal{C}(X,Y)$ is a set for each pair of objects $X,Y \in \mathcal{C}$.

Example 2.3.7. 1. Let $I$ be a small category. A functor $I \to \mathcal{C}$ is a commutative diagram in $\mathcal{C}$ of shape $I$.

2. Let $\mathcal{C}$ be a locally small category and fix $X \in \mathcal{C}$. The hom-functor given by $X$ is $h_X(Y) = \text{Hom}_\mathcal{C}(X,Y)$, $h_X(f)(g) = f \circ g$, $f : Y \to Z$ and $g \in \text{Hom}_\mathcal{C}(X,Y)$.

If we fix $Y$ instead, then we obtain a contravariant functor $h_Y$, i.e. a functor $\mathcal{C}^{\text{op}} \to \text{Set}$.

Definition 2.3.8 (Category of small categories). In the category of small categories, denoted $\text{Cat}$, the objects are small categories and the morphisms are functors.

Remark 2.3.9. For reasons related to Russell’s paradox, it is not possible to form the category of all categories.

Definition 2.3.10 (Faithful / full functor). Let $F : \mathcal{C} \to \mathcal{D}$ be a functor. For each pair of objects $X,Y \in \mathcal{C}$, there is a set map $\varphi_{X,Y} : \text{Hom}_\mathcal{C}(X,Y) \to \text{Hom}_\mathcal{D}(F(X),F(Y))$ given by $\varphi_{X,Y}(f) = F(f)$.

1. $F$ is faithful if $\varphi_{X,Y}$ is injective for all $X,Y$.

2. $F$ is full if $\varphi_{X,Y}$ is surjective for all $X,Y$.

Example 2.3.11. If $\mathcal{C}' \subset \mathcal{C}$ is a subcategory, the inclusion $\mathcal{C}' \hookrightarrow \mathcal{C}$ is faithful. It is full if and only if $\mathcal{C}'$ is a full subcategory.

Definition 2.3.12 (Equivalence of categories). A functor $F : \mathcal{C} \to \mathcal{D}$ is an equivalence if

(i) $F$ is full and faithful;

(ii) for any object $Y \in \mathcal{D}$, there exists $X \in \mathcal{C}$ such that $F(X) \cong Y$.

Proposition 2.3.13. Let $F : \mathcal{C} \to \mathcal{D}$ be a functor.

1. If $X \cong Y$ in $\mathcal{C}$, then $F(X) \cong F(Y)$ in $\mathcal{D}$. 

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2. If \( F \) is full and faithful and \( F(X) \cong F(Y) \) in \( D \), then \( X \cong Y \) in \( C \).

3. If \( F \) is an equivalence, then \( F \) induces a bijection between isomorphism classes in \( C \) and \( D \).

Example 2.3.14. 1. Let \( C' \subset C \) be a full subcategory. Then \( C' \hookrightarrow C \) is an equivalence if and only if for every \( Y \in C \), there exists \( X \in C' \) such that \( X \cong Y \).

2. Consider \( \text{Vect}_K \), the category of vector spaces over \( K \). The full subcategory of \( K \)-vector spaces of the form \( K^n \), where \( n \) is any cardinal number, is equivalent to \( \text{Vect}_K \).

In particular, if we look at the full subcategory \( \text{FdVect}_K \) of finite-dimensional vector spaces over \( K \), it has as an equivalent full subcategory the vector spaces \( K^n \) for \( n \in \mathbb{N} \), which is a small category.

Proposition 2.3.15. If \( F : C \rightarrow D \) is an equivalence, then there exists \( G : D \rightarrow C \) such that \( F \circ G : D \rightarrow D \) and \( G \circ F : C \rightarrow C \) are equivalences.

2.4 NATURAL TRANSFORMATIONS

Definition 2.4.1 (Natural transformation). Let \( F \) and \( G \) be two functors \( C \rightarrow D \). A natural transformation \( \alpha : F \rightarrow G \) is a collection of morphisms \( \alpha_X : F(X) \rightarrow G(X) \) in \( D \) such that for every morphism \( f : X \rightarrow Y \) in \( C \), the following diagram commutes.

\[
\begin{array}{ccc}
F(X) & \xrightarrow{\alpha_X} & G(X) \\
\downarrow^{F(f)} & & \downarrow^{G(f)} \\
F(Y) & \xrightarrow{\alpha_Y} & G(Y)
\end{array}
\]

Definition 2.4.2 (Category of functors). Let \( C \) and \( D \) be two categories with \( C \) small. The category of functors from \( C \) to \( D \), denoted \( \text{Fun}(C, D) \), has objects the functors \( C \rightarrow D \) and morphisms the natural transformations.

Proposition 2.4.3. If \( F, G : C \rightarrow D \) and \( \alpha : F \rightarrow G \) is a natural isomorphism, i.e. an isomorphism in \( \text{Fun}(C, D) \), then \( \alpha_X : F(X) \rightarrow G(X) \) is an isomorphism in \( D \) for all \( X \in C \).

Example 2.4.4. 1. Let \( F : \text{Grp} \rightarrow \text{Grp} \) be the abelianization functor (with target \( \text{Grp} \)). For each \( G \in \text{Grp} \), set \( \alpha_G = \pi : G \rightarrow G/G' \). Then \( \alpha \) is a natural transformation \( \text{id}_{\text{Grp}} \rightarrow F \).

2. Let \( C \) be a small category. Given \( f : X \rightarrow X' \), we have a morphism \( h^{X'}(Y) \rightarrow h^X(Y) \) for each \( Y \) given by \( g \mapsto g \circ f \), and one can check that this produces a natural transformation \( h^f : h^{X'} \rightarrow h^X \). Hence there is a functor \( C^{\text{op}} \rightarrow \text{Fun}(C, \text{Set}) \) with \( X^{\text{op}} \mapsto h^X \) and \( f^{\text{op}} \mapsto h^f \).

Equivalently, we have a functor \( C^{\text{op}} \times C \rightarrow \text{Set} \) with \( (X^{\text{op}}, Y) \mapsto \text{Hom}_C(X, Y) \), or a functor \( C \rightarrow \text{Fun}(C^{\text{op}}, \text{Set}) \) with \( Y \mapsto h_Y \), where \( h_Y(X^{\text{op}}) = \text{Hom}_C(X, Y) \).

Notation. Let \( C, D \) be categories and \( F, G : C \rightarrow D \) be functors. Write \( \text{Nat}(F, G) \) for the collection of natural transformations \( F \rightarrow G \).
Lemma 2.4.5 (Yoneda). Let $\mathcal{C}$ be a locally small category and fix $X \in \mathcal{C}$. Let $F : \mathcal{C} \to \text{Set}$ be a functor. Then there is a bijection $\varphi : \text{Nat}(h^X, F) \to F(X)$ given by

$$\varphi(\alpha) = \alpha_X(id_X).$$

Proof. We construct an inverse map $\psi : F(X) \to \text{Nat}(h^X, F)$. Let $u \in F(X)$. To determine what $\alpha = \psi(u)$ should be, let $Y \in \mathcal{C}$. Given $f \in \text{Hom}_\mathcal{C}(X, Y)$, there is a function $F(f) : F(X) \to F(Y)$, so let

$$\alpha_Y(f) = F(f)(u).$$

This is a natural transformation $h^X \to F$, as if $g : Y \to Z$ is a morphism, we have

$$(F(g) \circ \alpha_Y)(f) = F(g)(\alpha_Y(f)) = F(g)(F(f)(u)) = F(g \circ f)(u),$$

$$(\alpha_Z \circ h^X(g))(f) = \alpha_Z(h^X(g)(f)) = \alpha_Z(g \circ f) = F(g \circ f)(u).$$

To see that $\varphi \circ \psi = \text{id}_{F(X)}$, we have

$$(\varphi \circ \psi)(u) = \varphi(\psi(u)) = \varphi(\alpha) = \alpha_X(id_X) = F(id_X)(u) = \text{id}_{F(X)}(u) = u.$$  

To see that $\psi \circ \varphi = \text{id}_{\text{Nat}(h^X, F)}$, we must show that given $\beta : R^X \to F$ with $\varphi(\beta) = \beta_X(id_X) = u$, we have $\alpha = \psi(u) = \beta$. For any $Y \in \mathcal{C}$ and $f : X \to Y$, we compute

$$\beta_Y(f) = \beta_Y(h^X(f)(id_X)) = F(f)(\beta_X(id_X)) = F(f)(u) = \alpha_Y(f).$$

\hfill $\square$

Corollary 2.4.6. $\text{Nat}(h^X, h^Y) \cong \text{Hom}_\mathcal{C}(Y, X)$.

Corollary 2.4.7. Every natural transformation $h^X \to h^Y$ is of the form $h^f$ for a unique $f : Y \to X$.

Definition 2.4.8 (Presheaf of sets). A functor $C^{\text{op}} \to \text{Set}$ is a presheaf of sets.

Definition 2.4.9 (Representable functor). A functor $F : \mathcal{C} \to \text{Set}$ is represented by $X$ if $F$ is naturally isomorphic to $h^X$.

Proposition 2.4.10. Let $F$ be representable and suppose $F$ is represented by $X$ and $Y$. Then there is a unique isomorphism $f : X \to Y$ such that the following diagram commutes.

$$
\begin{array}{ccc}
F & \cong & h^Y \\
\downarrow^{h^f} & & \downarrow_{\text{iso}} \\
h^X & \cong & h^X
\end{array}
$$

Example 2.4.11. 1. $c_{\{\ast\}} : \mathcal{C} \to \text{Set}$ is represented by any initial object of $\mathcal{C}$.

2. Let $X$ be a set and define $F : \text{Grp}^{\text{op}} \to \text{Set}$ by $G^{\text{op}} \to \{\text{left } G\text{-actions on } X\}$. Then the symmetric group $S(X)$ represents $F$.

3. Let $\mathcal{C}$ be a locally small category with products and fix $X, Y \in \mathcal{C}$. Let $F : C^{\text{op}} \to \text{Set}$ be given by $F(Z) = \text{Hom}(Z, X) \times \text{Hom}(Z, Y)$. This is represented by $X \times Y$, i.e. $R_{X \times Y} \cong R_X \times R_Y$. Similarly, $R^X \times R^Y \cong R^{X \times Y}$ if $\mathcal{C}$ has coproducts.
4. Let $\mathcal{C}$ be a small category and consider the functor $\text{Fun}(\mathcal{C}, \text{Set}) \to \text{Set}$ given by $F \mapsto F(X)$. This functor is represented by $h^X$.

5. The forgetful functor $\text{Grp} \to \text{Set}$ is represented by $Z$.

**Definition 2.4.12** (Adjunction). Let $F : \mathcal{C} \to \mathcal{D}$ and $G : \mathcal{D} \to \mathcal{C}$ be two functors. There are two functors $\mathcal{C}^{\text{op}} \times \mathcal{D} \to \text{Set}$, given by

\[
(X^{\text{op}}, Y) \mapsto \text{Hom}_{\mathcal{C}}(X, G(Y))
\]

\[
(X^{\text{op}}, Y) \mapsto \text{Hom}_{\mathcal{D}}(F(X), Y).
\]

We say that $F, G$ form an adjunction pair, with $F$ a left adjoint to $G$ and $G$ a right adjoint to $F$, if these two functors are naturally isomorphic.

**Proposition 2.4.13.** Let $F, G$ and $F', G$ be adjunction pairs. Then $F$ and $F'$ are naturally isomorphic.

**Proof.** For any $X \in \mathcal{C}$, the functor $\mathcal{D} \to \text{Set}$ given by

\[
Y \mapsto \text{Hom}_{\mathcal{C}}(X, G(Y)) \cong \text{Hom}_{\mathcal{D}}(F(X), Y) = h^{F(X)}(Y)
\]

is represented by $F(X)$. Thus $F(X) \cong F'(X)$ for all $X \in \mathcal{C}$, so $F$ and $F'$ are isomorphic. □

**Example 2.4.14.**
1. The forgetful functor $\text{Grp} \to \text{Set}$ has a left adjoint $X \mapsto \text{Free} X$, but no right adjoint.
2. The inclusion functor $\text{Ab} \hookrightarrow \text{Grp}$ has as a left adjoint the abelianization functor.

**Definition 2.4.15** (Commuting with products). Let $F : \mathcal{C} \to \mathcal{D}$ be a functor between two categories with products. We say that $F$ commutes with products if the unique morphism

\[
\alpha_{X,Y} : F(X \times Y) \to F(X) \times F(Y)
\]

is an isomorphism for all $X, Y \in \mathcal{C}$.

**Proposition 2.4.16.** If $F : \mathcal{C} \to \mathcal{D}$ has a left adjoint, then $F$ commutes with products.

**Proof.** Let $X, Y \in \mathcal{C}$ and $Z \in \mathcal{D}$. Then

\[
\text{Hom}_{\mathcal{D}}(Z, F(X \times Y)) \cong \text{Hom}_{\mathcal{C}}(G(Z), X \times Y) \cong \text{Hom}_{\mathcal{C}}(G(Z), X) \times \text{Hom}_{\mathcal{C}}(G(Z), Y)
\]

\[
\cong \text{Hom}_{\mathcal{D}}(Z, F(X)) \times \text{Hom}_{\mathcal{D}}(Z, F(Y)) \cong \text{Hom}_{\mathcal{D}}(Z, F(X) \times F(Y)).
\]

□

**Example 2.4.17.** The forgetful functor $\text{Grp} \to \text{Set}$ commutes with products.

**Definition 2.4.18** (Limits / colimits). Let $\mathcal{I}$ be a small category and $X \in \mathcal{C}$. Let $c_X : \mathcal{I} \to \mathcal{C}$ be the constant functor and $F : \mathcal{I} \to \mathcal{C}$ be a functor. A morphism $X \to Y$ induces a natural transformation $c_X \to c_Y$, so we have a functor $\mathcal{C}^{\text{op}} \to \text{Set}$ given by $X^{\text{op}} \mapsto \text{Nat}(c_X, F)$. The limit of $F$ is an object $\text{lim} F$ in $\mathcal{C}$ representing this functor, if it exists.

The colimit of $F$ is an object $\text{colim} F$ representing the functor $\mathcal{C} \to \text{Set}$ given by $X \mapsto \text{Nat}(F, c_X)$. 37
Example 2.4.19.  
1. Let $\mathcal{I}$ have no non-identity morphisms. Then $\text{lim } F = \prod_i F(i)$.

2. Let $\mathcal{I}$ be the following diagram and let $\mathcal{C} = \textbf{Set}$.

```
\begin{array}{ccc}
\cdot & \to & \cdot \\
\downarrow & & \downarrow \\
\cdot & \to & \cdot 
\end{array}
```

The limit of a diagram of this shape is a pullback (or fiber product), while the colimit is just the target of the two morphisms.
3 RINGS

3.1 DEFINITIONS AND BASIC PROPERTIES

Definition 3.1.1 (Ring / commutative ring). A ring (with identity) \( R \) is a set together with two binary operations + and \( \cdot \) such that

(i) \((R, +)\) is an abelian group with identity \( 0 \in R \);
(ii) \((xy)z = x(yz)\) for all \( x, y, z \in R \);
(iii) there exists \( 1 \in R \) such that \( 1 \cdot x = x \cdot 1 = x \) for all \( x \in R \);
(iv) \( x(y + z) = xy + xz \) and \( (x + y)z = xz + yz \) for all \( x, y, z \in R \).

A ring \( R \) is commutative if \( xy = yx \) for all \( x, y \in R \).

Proposition 3.1.2. 1. The identities 0 and 1 are unique.
2. \( 0 \cdot x = x \cdot 0 = 0 \) for all \( x \in R \).
3. \((−x)y = x(−y) = (−xy)\) for all \( x, y \in R \).

Definition 3.1.3 (Unit / inverse). An element \( x \in R \) is a unit (is invertible) if there exists \( y \in R \) such that \( xy = yx = 1 \). Such a \( y \) is an inverse of \( x \).

Proposition 3.1.4. 1. If \( x \in R \) is invertible, then its inverse is unique.
2. If \( x, y \in R \) are invertible, then \( xy \) is invertible with \((xy)^{-1} = y^{-1}x^{-1}\).
3. The set \( R^\times = \{ x \in R \mid x \text{ is a unit} \} \) forms a group under multiplication.

Definition 3.1.5 (Unit group). \( R^\times \) is the unit group of \( R \).

Definition 3.1.6 (Field). A commutative ring \( R \) is a field if \( R \neq 0 \) and \( R^\times = R \setminus \{0\} \).

Definition 3.1.7 (Zero divisor / domain). Let \( x \in R \) be non-zero. We say that \( x \) is a (left) zero divisor if there exists a non-zero \( y \in R \) such that \( xy = 0 \).

A commutative ring \( R \) is a domain (integral domain) if \( R \neq 0 \) and \( R \) has no zero divisors.

Example 3.1.8. 1. The zero ring is \( 0 = \{0\} \) with \( 0 = 1 \). Conversely, if \( 0 = 1 \) in a ring \( R \), then \( R = 0 \).
2. \( \mathbb{Z} \) is a domain, but not a field. Its unit group is \( \mathbb{Z}^\times = \{\pm 1\} \).
3. \( \mathbb{Q} \subset \mathbb{R} \subset \mathbb{C} \) are fields, hence domains.
4. If \( R \) is a ring, then \( \text{Mat}_n(R) = \{ n \times n \text{ matrices over } R \} \) is a non-commutative ring for \( n \geq 2 \).
   Its unit group is \( (\text{Mat}_n(R))^\times = GL_n(R) \), the general linear group of degree \( n \) over \( R \). If \( R \) is commutative, then \( A \in GL_n(R) \) if and only if \( \det A \neq 0 \).
5. \( \mathbb{Z}/n\mathbb{Z} \) is a commutative ring. It is a domain if and only if \( n \) is prime, in which case \( \mathbb{Z}/n\mathbb{Z} \) is a field. Its unit group is \( (\mathbb{Z}/n\mathbb{Z})^\times = \{[a] \mid \gcd(a, n) = 1\} \), which has order \( \varphi(n) \).
6. An endomorphism of a group $A$ is a homomorphism $A \to A$. If $A$ is an abelian group, then the set of endomorphisms of $A$, denoted $\text{End } A$, is a ring with pointwise addition and composition. It is generally not commutative. Its unit group is $(\text{End } A)^\times = \text{Aut } A$.

7. If $R$ is a ring, then $R[x] = \{a_0 + a_1 x + \cdots + a_n x^n \mid a_i \in R\}$ is the polynomial ring over $R$. By induction, we define polynomial rings in several variables by $R[x_1, \ldots, x_n] = (R[x_1, \ldots, x_{n-1}])[x_n]$. More generally, we may construct polynomial rings $R[\{x_i\}_{i \in I}]$ in infinitely many variables as sums of (finite) monomials. If $R$ is commutative, then $R[x]$ is commutative.

8. Taking variables to be non-commuting, i.e. $x_ix_j \neq x_jx_i$ for $i \neq j$, we obtain non-commutative polynomial rings, which are denoted $R[\{x_i\}_{i \in I}]$.

**Definition 3.1.9** (Ring homomorphism). Let $R$ and $S$ be rings. A map $f : R \to S$ is a (ring) homomorphism such that

(i) $f(1) = 1$;
(ii) $f(x + y) = f(x) + f(y)$;
(iii) $f(xy) = f(x)f(y)$.

**Notation.** Write $f^\times$ for the group homomorphism $R^\times \to S^\times$ induced by $f$.

**Example 3.1.10.** There is no ring homomorphism $\mathbb{Q} \to \mathbb{Z}$.

**Notation.** The category of rings is denoted $\text{Ring}$, while the category of commutative rings is denoted $\text{CRing}$.

**Proposition 3.1.11.**
1. In $\text{Ring}$, $\mathbb{Z}$ is an initial object.
2. $\text{CRing}$ is a full subcategory of $\text{Ring}$.
3. $\text{Forget} : \text{CRing} \to \text{Set}$ has left adjoint $I \mapsto \mathbb{Z}[\{X_i\}_{i \in I}]$.
4. $\text{Forget} : \text{Ring} \to \text{Set}$ has left adjoint $I \mapsto \mathbb{Z}[\{X_i\}_{i \in I}]$.

**Definition 3.1.12** (Subring). Let $R$ be a ring. A subring of $R$ is a subset $S \subseteq R$ such that $0, 1 \in S$ and $S$ forms a ring with the inherited operations from $R$.

**Proposition 3.1.13.** If $S \subseteq R$ is a subring, then the inclusion $i : S \hookrightarrow R$ is a ring homomorphism.

**Example 3.1.14.**
1. $\mathbb{Z} \subseteq \mathbb{Q} \subseteq \mathbb{R} \subseteq \mathbb{C}$
2. The set $S = \left\{ \begin{pmatrix} * & 0 \\ 0 & 0 \end{pmatrix} \right\} \subseteq \text{Mat}_2(R)$ is not a subring of $\text{Mat}_2(R)$, even though it forms a ring with the inherited operation, since $I \notin S$. 

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3.2 IDEALS

**Definition 3.2.1** (Ideal). Let \( R \) be a ring. A subset \( I \subset R \) is a left ideal of \( R \) if

(i) \((I, +)\) is a subgroup of \((R, +)\);

(ii) if \( x \in R \), then \( xI \subset I \).

A right ideal is defined analogously.

We say that \( I \) is an ideal (two-sided ideal) if \( I \) is a left ideal and a right ideal.

**Example 3.2.2.**

1. Every ring \( R \) has the zero ideal \( 0 = \{0\} \) and the unit ideal \( R \).

2. In Mat\(_n\)(\( R \)), the set of matrices for which all columns but the first are zero is an ideal.

3. For any \( x \in R \), \( Rx = \{ax | a \in R\} \) is a left ideal, the principal left ideal generated by \( x \). In particular, \( 0 = R \cdot 0 \) and \( R = R \cdot 1 \).

4. The intersection of left ideals is a left ideal.

5. If \( I \) is a left ideal and \( I \cap R^\times \) is non-empty, then \( I = R \).

6. Given two ideals \( I, J \subset R \), the product ideal \( IJ \) is the smallest ideal containing all products \( ab \) with \( a \in I \) and \( b \in J \).

**Notation.** If \( R \) is a commutative ring and \( x \in R \), then write \((x) = Rx \) for the principal ideal generated by \( x \). More generally, if \( S \subset R \), then write \((S) \) for the ideal generated by \( S \), i.e. the smallest ideal of \( R \) containing \( S \).

**Proposition 3.2.3.**

1. \( u \in R^\times \) if and only if \((u) = R \).

2. \( a \in R \) is non-zero if and only if \((a) \neq 0 \).

**Definition 3.2.4** (Quotient ring). Let \( R \) be a ring and \( I \subset R \) be an ideal. The quotient ring \( R/I \) is the quotient group \( R/I \) together with the multiplication \((x + I)(y + I) = xy + I \).

**Proposition 3.2.5.**

1. The multiplication is well-defined and makes \( R/I \) into a ring.

2. The canonical map \( \pi : R \to R/I \) is a ring homomorphism.

**Definition 3.2.6** (Kernel / image). Let \( f : R \to S \) be a homomorphism.

1. The kernel of \( f \) is \( f^{-1}(0) \subset R \).

2. The image of \( f \) is \( f(R) \subset S \).

**Proposition 3.2.7.** Let \( f : R \to S \) be a homomorphism.

1. \( \ker f \) is an ideal of \( R \).

2. \( \im f \) is a subring of \( S \).

**Theorem 3.2.8** (First isomorphism theorem). Let \( f : R \to S \) be a ring homomorphism. Then the map \( \overline{f} : R/\ker f \to \im f \) given by \( \overline{f}(x + \ker f) = f(x) \) is an isomorphism.
Proof. By the first isomorphism theorem for groups, \( \overline{f} \) is a group isomorphism of \((R/\ker f)\) and \((\text{im } f, +)\). For products,

\[
\overline{f}(x + I)(y + I) = \overline{f}(xy + I) = f(xy) = f(x)f(y) = \overline{f}(x + I)\overline{f}(y + I).
\]

\[\blacksquare\]

**Theorem 3.2.9** (Correspondence theorem). Let \( I \subseteq R \) be an ideal. Then there is a bijection between ideals of \( R/I \) and ideals of \( R \) containing \( I \) given by \( J \mapsto \overline{J} = J/I \) and \( \overline{J} \mapsto J = \pi^{-1}(\overline{J}) \).

**Example 3.2.10.**
1. \( \mathbb{Z}/n\mathbb{Z} \) is the quotient of \( \mathbb{Z} \) by the ideal \( n\mathbb{Z} \).

2. Let \( f : \mathbb{R}[x] \to \mathbb{C} \) be given by \( f(g) = g(i) \). Then \( \ker f = (x^2 + 1) \), so \( \mathbb{C} \cong \mathbb{R}[x]/(x^2 + 1) \).

**Notation.** Let \( I \subseteq R \) be an ideal and \( x, y \in R \). We write \( x \equiv y \pmod{I} \) if \( x - y \in I \).

**Definition 3.2.11** (Product ring). Let \( R \) and \( S \) be rings. The **product ring** \( R \times S \) is the Cartesian product of \( R \) and \( S \) with component-wise operations.

**Theorem 3.2.12** (Chinese remainder theorem). Let \( R \) be a ring and \( I_1, \ldots, I_n \subseteq R \) be ideals such that \( I_i + I_j = R \) for all \( i \neq j \). Let \( a_1, \ldots, a_n \in R \). Then there exists \( x \in R \) such that \( x \equiv a_i \pmod{I_i} \) for all \( i \).

Proof. We induct on \( n \). The case \( n = 1 \) is trivial. When \( n = 2 \), we have \( I_1 + I_2 = R \), so in particular \( a_1 - a_2 = b_1 + b_2 \) for some \( b_1 \in I_1 \) and \( b_2 \in I_2 \). Take \( x = a_1 - b_1 \).

Now consider \( n \geq 3 \). We claim that \((I_1 \cap \cdots \cap I_{n-1}) + I_n = R \). Indeed, we have that \( I_i + I_n = R \) for each \( i < n \), so we can pick \( y_i \in I_i \) and \( z_i \in I_n \) such that \( y_i + z_i = 1 \). Then

\[
1 = (y_1 + z_1) \cdots (y_{n-1} + z_{n-1}) = y_1 \cdots y_{n-1} + \text{monomials including } z_i \text{'s in } I_1 \cap \cdots \cap I_{n-1} + I_n,
\]
as required. By induction, there exists \( x' \in R \) such that \( x' \equiv a_i \pmod{I_i} \) for \( i < n \). By the claim and the case \( n = 2 \), there exists \( x \in R \) with \( x \equiv x' \pmod{I_1 \cap \cdots \cap I_{n-1}} \) and \( x \equiv a_n \pmod{I_n} \). For \( i < n \), we have \( x \equiv x' \pmod{I_1 \cap \cdots \cap I_{n-1}} \) and \( I_1 \cap \cdots \cap I_{n-1} \subseteq I_i \), so \( x \equiv x' \equiv a_i \pmod{I_i} \).

\[\blacksquare\]

**Corollary 3.2.13.** Let \( I_1, \ldots, I_n \) be ideals of \( R \) with \( I_i + I_j = R \) for \( i \neq j \). Then

\[
R/(I_1 \cap \cdots \cap I_n) \cong (R/I_1) \times \cdots \times (R/I_n).
\]

Proof. Define the ring homomorphism \( f : R \to (R/I_1) \times \cdots \times (R/I_n) \) by

\[
f(x) = (x + I_1, x + I_2, \ldots, x + I_n).
\]

Then \( \ker f = I_1 \cap \cdots \cap I_n \), and by the Chinese remainder theorem, \( f \) is surjective, so

\[
\overline{f} : R/(I_1 \cap \cdots \cap I_n) \to (R/I_1) \times \cdots \times (R/I_n)
\]
is an isomorphism by the first isomorphism theorem.

\[\blacksquare\]

**Example 3.2.14.** Let \( m_1, \ldots, m_n \in \mathbb{Z} \) with \( \gcd(m_i, m_j) = 1 \) for \( i \neq j \). Let \( I_i = m_i \mathbb{Z} \), so then \( I_1 \cap \cdots \cap I_n = m_1 \cdots m_n \mathbb{Z} \). We have

\[
\mathbb{Z}/(m_1 \cdots m_n \mathbb{Z}) \cong \mathbb{Z}/m_1 \mathbb{Z} \times \cdots \times \mathbb{Z}/m_n \mathbb{Z}.
\]

Comparing sizes, \( \varphi(m_1 \cdots m_n) = \varphi(m_1) \cdots \varphi(m_n) \) for \( m_1, \ldots, m_n \) pairwise coprime.
Definition 3.2.15 (Prime ideal). Let \( R \) be a commutative ring. An ideal \( p \subset R \) is prime if \( p \neq R \) and whenever \( xy \in p \), we have \( x \in p \) or \( y \in p \).

Theorem 3.2.16. An ideal \( p \subset R \) is prime if and only if \( R/p \) is a domain.

Proof. \((\Rightarrow)\) Since \( p \neq R \), \( R/p \neq 0 \). Suppose \((x + p)(y + p) = p\). Then \( xy \in p \), so \( x \in p \) or \( y \in p \), i.e. \( x + p = p \) or \( y + p = p \). Hence there are no zero divisors in \( R/p \), so \( R/p \) is a domain.

\((\Leftarrow)\) If \( R/p \neq 0 \), then \( p \neq R \). If \( xy \in p \), then \( p = xy + p = (x + p)(y + p) \). Since \( R/p \) is a domain, \( x + p = p \) or \( y + p = p \), in which case \( x \in p \), or \( y \in p \).

Definition 3.2.17 (Maximal ideal). Let \( R \) be a commutative ring. An ideal \( m \subset R \) is maximal if \( m \neq R \) and if \( m \subset I \) for an ideal \( I \), then \( I = m \) or \( I = R \).

Lemma 3.2.18. A commutative ring \( R \) has exactly two ideals if and only if \( R \) is a field.

Theorem 3.2.19. An ideal \( m \subset R \) is maximal if and only if \( R/m \) is a field.

Proof. By the correspondence theorem, \( m \) is maximal if and only if \( R/m \) has exactly two ideals, which happens if and only if \( R/m \) is a field.

Example 3.2.20. 1. The zero ring has no prime or maximal ideals.

2. Let \( R = \mathbb{Z} \) and \( n \geq 0 \). Then \( n\mathbb{Z} \) is prime if and only if \( n = 0 \) or \( n = p \) is prime. It is maximal if and only if \( n = p \) is prime.

Theorem 3.2.21. Every non-zero commutative ring has a maximal ideal.

Proof. Let \( A \) be the set of all proper ideals of a non-zero commutative ring \( R \). Then \( 0 \in A \), so \( A \) is non-empty. Order \( A \) by inclusion and let \( \{I_k\} \) be a chain of ideals in \( A \). Then \( I = \bigcup_k I_k \) is a proper ideal of \( R \), since \( 1 \notin I_k \) for each \( k \), and \( I \) is an upper bound for \( \{I_k\} \). By Zorn’s lemma, \( A \) has a maximal element, i.e. a maximal ideal.

Corollary 3.2.22. Every non-zero commutative ring has a prime ideal.

Proof. Every maximal ideal is prime.

3.3 EUCLIDEAN RINGS

Definition 3.3.1 (Euclidean ring). A Euclidean ring is a commutative ring \( R \) such that there is a function \( \varphi : R \setminus \{0\} \to \mathbb{N}_0 \) such that for every \( a \in R \) and \( 0 \neq b \in R \), there exist \( q, r \in R \) with \( a = bq + r \), where either \( r = 0 \) or \( \varphi(r) < \varphi(b) \).

Example 3.3.2. 1. For \( \mathbb{Z} \), we may take \( \varphi(x) = |x| \).

2. For \( F \) a field and \( R = F[x] \), we may take \( \varphi(f) = \deg f \).

3. Consider the ring of Gaussian integers \( \mathbb{Z}[i] \). Letting \( \varphi(a + bi) = a^2 + b^2 = |a + bi|^2 \) makes \( \mathbb{Z}[i] \) a Euclidean ring.
Definition 3.3.3 (Principal ideal ring). A principal ideal ring is a commutative ring $R$ for which every ideal of $R$ is principal.

Theorem 3.3.4. Every Euclidean ring is a principal ideal ring.

Proof. Let $I \subset R$ be an ideal. If $I = 0$, then we are done. Otherwise, choose $b \in I$ non-zero to have minimal $\varphi(b)$. We claim that $I = (b)$. Indeed, it is clear that $(b) \subset I$, and conversely, let $a \in I$. Since $R$ is Euclidean, we can write $a = bq + r$. If $r = 0$, then $a = bq \in (b)$. Otherwise, $\varphi(r) < \varphi(b)$, contradicting the choice of $b$. Thus $a \in (b)$, so $I \subset (b)$.

Remark 3.3.5. The converse does not hold. For example, $\mathbb{Z}[(1 + \sqrt{-19})/2]$ is a principal ideal ring which is not a Euclidean ring.

3.4 FACTORIZATION IN DOMAINS

Definition 3.4.1 (Divisibility). Let $R$ be a domain and $a, b \in R$ with $b \neq 0$. We say that $b$ divides $a$ ($a$ is divisible by $b$), written $b \mid a$, if there exists $q \in R$ with $a = bq$.

Proposition 3.4.2. 1. $b \mid a$ if and only if $(b) \supset (a)$.

2. If $a \mid b$, then $a \mid bc$ for all $c \in R$.

3. If $a \mid b$ and $b \mid c$, then $a \mid c$.

4. $(a) = (b)$ if and only if $b = au$ for some $u \in R^\times$.

Definition 3.4.3 ( Associates). Two elements $a, b$ in a domain $R$ are associates if $(a) = (b)$.

Definition 3.4.4 (Irreducible element). Let $R$ be a domain and $c \in R$ be a non-zero non-unit element of $R$. Then $c$ is irreducible if whenever $c = xy$ for $x, y \in R$, either $x \in R^\times$ or $y \in R^\times$.

Definition 3.4.5 (Prime element). A non-zero element $p \in R$ is prime if $(p)$ is a prime ideal, or equivalently, if whenever $p \mid xy$, either $p \mid x$ or $p \mid y$.

Example 3.4.6. In $\mathbb{Z}[(1 + \sqrt{-5})/2]$, 2 is irreducible but not prime, since $2 \mid (1 + \sqrt{-5})(1 - \sqrt{-5}) = 6$ but 2 does not divide either factor.