

# Mathematics

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Part I

Category Theory





# Chapter 1

## Foundations

This is a placeholder — I am not sure what foundation I want to use for this project yet. I will try to work in a way which is foundation-independent. What I do could be formalized in ZFC, ETCS, or some other system. I will assume the usual set theoretic constructions as needed. Sets will be defined up to bijection only.



# Chapter 2

## Categories

**Definition 2.1** (Category). A *category*  $\mathcal{C}$  consists of:

- A class  $|\mathcal{C}|$  of *objects*. We write  $A \in \mathcal{C}$  for  $A \in |\mathcal{C}|$ .
- For any objects  $A, B$ , a set  $\mathcal{C}[A, B]$  of *morphisms* from  $A$  to  $B$ . We write  $f : A \rightarrow B$  for  $f \in \mathcal{C}[A, B]$ .
- For any object  $A$ , a morphism  $\text{id}_A : A \rightarrow A$ , the *identity* morphism on  $A$ .
- For any morphisms  $f : A \rightarrow B$  and  $g : B \rightarrow C$ , a morphism  $g \circ f : A \rightarrow C$ , the *composite* of  $f$  and  $g$ .

such that:

**Associativity** Given  $f : A \rightarrow B$ ,  $g : B \rightarrow C$  and  $h : C \rightarrow D$ , we have

$$h \circ (g \circ f) = (h \circ g) \circ f$$

**Left Unit Law** For any morphism  $f : A \rightarrow B$ , we have  $\text{id}_B \circ f = f$ .

**Right Unit Law** For any morphism  $f : A \rightarrow B$ , we have  $f \circ \text{id}_A = f$ .

**Proposition 2.2.** *The identity morphism on an object is unique.*

PROOF: If  $i$  and  $j$  are identity morphisms on  $A$  then  $i = i \circ j = j$ .  $\square$

**Example 2.3** (Category of Sets). The *category of sets* **Set** has objects all sets and morphisms all functions.

**Definition 2.4** (Endomorphism). In a category  $\mathcal{C}$ , an *endomorphism* on an object  $A$  is a morphism  $A \rightarrow A$ . We write  $\text{End}_{\mathcal{C}}(A)$  for  $\mathcal{C}[A, A]$ .

**Definition 2.5** (Opposite Category). For any category  $\mathcal{C}$ , the *opposite* category  $\mathcal{C}^{\text{op}}$  is the category with the same objects as  $\mathcal{C}$  and

$$\mathcal{C}^{\text{op}}[A, B] = \mathcal{C}[B, A]$$

## 2.1 Preorders

**Definition 2.6** (Preorder). A *preorder* on a set  $A$  is a relation  $\leq$  on  $A$  that is reflexive and transitive.

A *preordered set* is a pair  $(A, \leq)$  such that  $\leq$  is a preorder on  $A$ . We usually write  $A$  for the preordered set  $(A, \leq)$ .

We identify any preordered set  $A$  with the category whose objects are the elements of  $A$ , with one morphism  $a \rightarrow b$  iff  $a \leq b$ , and no morphism  $a \rightarrow b$  otherwise.

**Example 2.7.** For any ordinal  $\alpha$ , let  $\alpha$  be the preorder  $\{\beta : \beta < \alpha\}$  under  $\leq$ .

**Definition 2.8** (Discrete Preorder). We identify any set  $A$  with the *discrete* preorder  $(A, =)$ .

## 2.2 Monomorphisms and Epimorphisms

**Definition 2.9** (Monomorphism). In a category, let  $f : A \rightarrow B$ . Then  $f$  is a *monomorphism* or *monic* iff, for every object  $X$  and morphism  $x, y : X \rightarrow A$ , if  $fx = fy$  then  $x = y$ .

**Definition 2.10** (Epimorphism). In a category, let  $f : A \rightarrow B$ . Then  $f$  is a *epimorphism* or *epi* iff, for every object  $X$  and morphism  $x, y : B \rightarrow X$ , if  $xf = yf$  then  $x = y$ .

**Proposition 2.11.** *The composite of two monomorphism is monic.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $f : A \rightarrow B$  and  $g : B \rightarrow C$  be monic.

$\langle 1 \rangle 2$ . LET:  $x, y : X \rightarrow A$

$\langle 1 \rangle 3$ . ASSUME:  $g \circ f \circ x = g \circ f \circ y$

$\langle 1 \rangle 4$ .  $f \circ x = f \circ y$

$\langle 1 \rangle 5$ .  $x = y$

□

**Proposition 2.12.** *The composite of two epimorphisms is epi.*

PROOF: Dual. □

**Proposition 2.13.** *Let  $f : A \rightarrow B$  and  $g : B \rightarrow C$ . If  $g \circ f$  is monic then  $f$  is monic.*

PROOF: If  $f \circ x = f \circ y$  then  $gfx = gfy$  and so  $x = y$ . □

**Proposition 2.14.** *Let  $f : A \rightarrow B$  and  $g : B \rightarrow C$ . If  $g \circ f$  is epi then  $g$  is epi.*

PROOF: Dual. □

**Proposition 2.15.** *A function is a monomorphism in **Set** iff it is injective.*

PROOF:

- ⟨1⟩1. LET:  $f : A \rightarrow B$
- ⟨1⟩2. If  $f$  is monic then  $f$  is injective.
  - ⟨2⟩1. ASSUME:  $f$  is monic.
  - ⟨2⟩2. LET:  $x, y \in A$
  - ⟨2⟩3. ASSUME:  $f(x) = f(y)$
  - ⟨2⟩4. LET:  $\bar{x}, \bar{y} : 1 \rightarrow A$  be the functions such that  $\bar{x}(*) = x$  and  $\bar{y}(*) = y$
  - ⟨2⟩5.  $f \circ \bar{x} = f \circ \bar{y}$
  - ⟨2⟩6.  $\bar{x} = \bar{y}$
  - PROOF: By ⟨2⟩1.
  - ⟨2⟩7.  $x = y$
- ⟨1⟩3. If  $f$  is injective then  $f$  is monic.
  - ⟨2⟩1. ASSUME:  $f$  is injective.
  - ⟨2⟩2. LET:  $X$  be a set and  $x, y : X \rightarrow A$ .
  - ⟨2⟩3. ASSUME:  $f \circ x = f \circ y$
  - PROVE:  $x = y$
  - ⟨2⟩4. LET:  $t \in X$
  - PROVE:  $x(t) = y(t)$
  - ⟨2⟩5.  $f(x(t)) = f(y(t))$
  - ⟨2⟩6.  $x(t) = y(t)$
  - PROOF: By ⟨2⟩1.

□

**Proposition 2.16.** *A function is an epimorphism in **Set** iff it is surjective.*

PROOF:

- ⟨1⟩1. LET:  $f : A \rightarrow B$
- ⟨1⟩2. If  $f$  is an epimorphism then  $f$  is surjective.
  - ⟨2⟩1. ASSUME:  $f$  is an epimorphism.
  - ⟨2⟩2. LET:  $b \in B$
  - ⟨2⟩3. LET:  $x, y : B \rightarrow 2$  be defined by  $x(b) = 1$  and  $x(t) = 0$  for all other  $t \in B$ ,  $y(t) = 0$  for all  $t \in B$ .
  - ⟨2⟩4.  $x \neq y$
  - ⟨2⟩5.  $x \circ f \neq y \circ f$
  - ⟨2⟩6. There exists  $a \in A$  such that  $f(a) = b$ .
- ⟨1⟩3. If  $f$  is surjective then  $f$  is an epimorphism.
  - ⟨2⟩1. ASSUME:  $f$  is surjective.
  - ⟨2⟩2. LET:  $x, y : B \rightarrow X$
  - ⟨2⟩3. ASSUME:  $x \circ f = y \circ f$
  - PROVE:  $x = y$
  - ⟨2⟩4. LET:  $b \in B$
  - PROVE:  $x(b) = y(b)$
  - ⟨2⟩5. PICK  $a \in A$  such that  $f(a) = b$
  - ⟨2⟩6.  $x(f(a)) = y(f(a))$
  - ⟨2⟩7.  $x(b) = y(b)$

□

**Proposition 2.17.** *In a preorder, every morphism is monic and epi.*

PROOF: Immediate from definitions.  $\square$

## 2.3 Sections and Retractions

**Definition 2.18** (Section, Retraction). In a category, let  $r : A \rightarrow B$  and  $s : B \rightarrow A$ . Then  $r$  is a *retraction* of  $s$ , and  $s$  is a *section* of  $r$ , iff  $r \circ s = \text{id}_B$ .

**Proposition 2.19.** *Every identity morphism is a section and retraction of itself.*

PROOF: Immediate from definitions.  $\square$

**Proposition 2.20.** *Let  $r, r' : A \rightarrow B$  and  $s : B \rightarrow A$ . If  $r$  is a retraction of  $s$  and  $r'$  is a section of  $s$  then  $r = r'$ .*

PROOF:

$$\begin{aligned} r &= r \circ \text{id}_A \\ &= r \circ s \circ r' \\ &= \text{id}_B \circ r' \\ &= r' \end{aligned} \quad \square$$

**Proposition 2.21.** *Let  $r_1 : A \rightarrow B$ ,  $r_2 : B \rightarrow C$ ,  $s_1 : B \rightarrow A$  and  $s_2 : C \rightarrow B$ . If  $r_1$  is a retraction of  $s_1$  and  $r_2$  is a retraction of  $s_2$  then  $r_2 \circ r_1$  is a retraction of  $s_1 \circ s_2$ .*

PROOF:

$$\begin{aligned} r_2 \circ r_1 \circ s_1 \circ s_2 &= r_2 \circ \text{id}_B \circ s_2 \\ &= r_2 \circ s_2 \\ &= \text{id}_C \end{aligned} \quad \square$$

**Proposition 2.22.** *Every section is monic.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $s : A \rightarrow B$  be a section of  $r : B \rightarrow A$ .

$\langle 1 \rangle 2$ . LET:  $x, y : X \rightarrow A$  satisfy  $sx = sy$ .

$\langle 1 \rangle 3$ .  $rsx = rsy$

$\langle 1 \rangle 4$ .  $x = y$

$\square$

**Proposition 2.23.** *Every retraction is epi.*

PROOF: Dual.  $\square$

**Proposition 2.24.** *In Set, every epimorphism has a retraction.*

PROOF: By the Axiom of Choice.  $\square$

**Example 2.25.** It is not true in general that every monomorphism in any category has a section. nor that every epimorphism in any category has a retraction.

In the category **2**, the morphism  $0 \leq 1$  is monic and epi but has no retraction or section.

## 2.4 Isomorphisms

**Definition 2.26** (Isomorphism). In a category  $\mathcal{C}$ , a morphism  $f : A \rightarrow B$  is an *isomorphism*, denoted  $f : A \cong B$ , iff there exists a morphism  $f^{-1} : B \rightarrow A$ , the *inverse* of  $f$ , such that  $f^{-1} \circ f = \text{id}_A$  and  $f \circ f^{-1} = \text{id}_B$ .

An *automorphism* on an object  $A$  is an isomorphism between  $A$  and itself. We write  $\text{Aut}_{\mathcal{C}}(A)$  for the set of all automorphisms on  $A$ .

Objects  $A$  and  $B$  are *isomorphic*,  $A \cong B$ , iff there exists an isomorphism between them.

**Proposition 2.27.** *The inverse of an isomorphism is unique.*

PROOF: Proposition 2.20.  $\square$

**Proposition 2.28.** *For any object  $A$  we have  $\text{id}_A : A \cong A$  and  $\text{id}_A^{-1} = \text{id}_A$ .*

PROOF: Since  $\text{id}_A \circ \text{id}_A = \text{id}_A$  by the Unit Laws.  $\square$

**Proposition 2.29.** *If  $f : A \cong B$  then  $f^{-1} : B \cong A$  and  $(f^{-1})^{-1} = f$ .*

PROOF: Immediate from definitions.  $\square$

**Proposition 2.30.** *If  $f : A \cong B$  and  $g : B \cong C$  then  $g \circ f : A \cong C$  and  $(g \circ f)^{-1} = f^{-1} \circ g^{-1}$ .*

PROOF: From Proposition 2.21.  $\square$

**Definition 2.31** (Groupoid). A *groupoid* is a category in which every morphism is an isomorphism.

## 2.5 Initial and Terminal Objects

**Definition 2.32** (Initial Object). An object  $I$  in a category is *initial* iff, for any object  $X$ , there is exactly one morphism  $I \rightarrow X$ .

**Example 2.33.** The empty set is the initial object in **Set**.

**Definition 2.34** (Terminal Object). An object  $T$  in a category is *terminal* iff, for any object  $X$ , there is exactly one morphism  $X \rightarrow T$ .

**Example 2.35.** Every singleton is terminal in **Set**.

**Proposition 2.36.** *If  $I$  and  $J$  are initial in a category, then there exists a unique isomorphism  $I \cong J$ .*

PROOF:

- $\langle 1 \rangle 1$ . LET:  $i$  be the unique morphism  $I \rightarrow J$ .
- $\langle 1 \rangle 2$ . LET:  $i^{-1}$  be the unique morphism  $J \rightarrow I$ .
- $\langle 1 \rangle 3$ .  $i \circ i^{-1} = \text{id}_J$

PROOF: Since there is only one morphism  $J \rightarrow J$ .

- $\langle 1 \rangle 4$ .  $i^{-1} \circ i = \text{id}_I$

PROOF: Since there is only one morphism  $I \rightarrow I$ .  
 $\square$

**Proposition 2.37.** *If  $S$  and  $T$  are terminal in a category, then there exists a unique isomorphism  $S \cong T$ .*

PROOF: Dual.  $\square$



## Chapter 3

# Functors

**Definition 3.1** (Functor). Let  $\mathcal{C}$  and  $\mathcal{D}$  be categories. A *functor*  $F : \mathcal{C} \rightarrow \mathcal{D}$  consists of:

- for every object  $A \in \mathcal{C}$ , an object  $FA \in \mathcal{D}$
- for any morphism  $f : A \rightarrow B : \mathcal{C}$ , a morphism  $Ff : FA \rightarrow FB : \mathcal{D}$

such that:

- $F\text{id}_A = \text{id}_{FA}$
- $F(g \circ f) = Fg \circ Ff$

**Definition 3.2** (Identity Functor). For any category  $\mathcal{C}$ , the *identity functor*  $1_{\mathcal{C}} : \mathcal{C} \rightarrow \mathcal{C}$  is defined by

$$\begin{aligned} 1_{\mathcal{C}}A &= A \\ 1_{\mathcal{C}}f &= f \end{aligned}$$

**Definition 3.3** (Constant Functor). Given categories  $\mathcal{C}$ ,  $\mathcal{D}$  and an object  $D \in \mathcal{D}$ , the *constant functor*  $K^{\mathcal{C}}D : \mathcal{C} \rightarrow \mathcal{D}$  is the functor defined by

$$\begin{aligned} K^{\mathcal{C}}DC &= D \\ K^{\mathcal{C}}Df &= \text{id}_D \end{aligned}$$

### 3.1 Comma Categories

**Definition 3.4** (Comma Category). Let  $F : \mathcal{C} \rightarrow \mathcal{E}$  and  $G : \mathcal{D} \rightarrow \mathcal{E}$  be functors. The *comma category*  $F \downarrow G$  is the category with:

- objects all pairs  $(C, D, f)$  where  $C \in \mathcal{C}$ ,  $D \in \mathcal{D}$  and  $f : FC \rightarrow GD : \mathcal{E}$

- morphisms  $(u, v) : (C, D, f) \rightarrow (C', D', g)$  all pairs  $u : C \rightarrow C' : \mathcal{C}$  and  $v : D \rightarrow D' : \mathcal{D}$  such that the following diagram commutes:

$$\begin{array}{ccc} FC & \xrightarrow{f} & GD \\ \downarrow Fu & & \downarrow Gv \\ FC' & \xrightarrow{g} & GD' \end{array}$$

**Definition 3.5** (Slice Category). Let  $\mathcal{C}$  be a category and  $A \in \mathcal{C}$ . The *slice category* over  $A$ , denoted  $\mathcal{C}/A$ , is the comma category  $1_{\mathcal{C}} \downarrow K^1 A$ .

**Definition 3.6** (Coslice Category). Let  $\mathcal{C}$  be a category and  $A \in \mathcal{C}$ . The *coslice category* over  $A$ , denoted  $\mathcal{C} \backslash A$ , is the comma category  $K^1 A \downarrow 1_{\mathcal{C}}$ .

**Definition 3.7** (Pointed Sets). The *category of pointed sets*  $\mathbf{Set}_*$  is the coslice category  $\mathbf{Set} \backslash 1$ .

**Part II**

**Group Theory**



## Chapter 4

# Semigroups

**Definition 4.1** (Semigroup). A *semigroup* consists of a set  $S$  and an associative binary operation  $\cdot$  on  $S$ .



## Chapter 5

# Monoids

**Definition 5.1** (Monoid). A *monoid* consists of a semigroup  $M$  such that there exists  $e \in M$ , the *unit*, such that, for all  $x \in M$ , we have  $xe = ex = x$ .

We identify a monoid  $M$  with the category with one object whose morphisms are the elements of  $M$ , with composition given by  $\cdot$ .

**Proposition 5.2.** *The identity in a group is unique.*

PROOF: Proposition 2.2.





# Chapter 6

## Groups

**Definition 6.1** (Group). Let  $\mathcal{C}$  be a category with finite products. A *group (object)* in  $\mathcal{C}$  consists of an object  $G \in \mathcal{C}$  and morphisms

$$m : G^2 \rightarrow G, e : 1 \rightarrow G, i : G \rightarrow G$$

such that the following diagrams commute.

$$\begin{array}{ccc} G^3 & \xrightarrow{m \times \text{id}_G} & G^2 \\ \downarrow \text{id}_G \times m & & \downarrow m \\ G^2 & \xrightarrow{m} & G \end{array}$$

$$\begin{array}{ccc} 1 \times G & \xrightarrow{e \times \text{id}_G} & G^2 \\ & \searrow \cong & \downarrow m \\ & & G \end{array} \quad \begin{array}{ccc} G \times 1 & \xrightarrow{\text{id}_G \times e} & G^2 \\ & \searrow \cong & \downarrow m \\ & & G \end{array}$$

$$\begin{array}{ccccc} G & \xrightarrow{\Delta} & G^2 & \xrightarrow{\text{id}_G \times i} & G^2 \\ \downarrow & & & & \downarrow m \\ 1 & \xrightarrow{e} & G & & G \end{array} \quad \begin{array}{ccccc} G & \xrightarrow{\Delta} & G^2 & \xrightarrow{i \times \text{id}_G} & G^2 \\ \downarrow & & & & \downarrow m \\ 1 & \xrightarrow{e} & G & & G \end{array}$$

**Definition 6.2** (Group). We write just 'group' for 'group in **Set**'. Thus, a *group*  $G$  consists of a set  $G$  and a binary operation  $\cdot : G^2 \rightarrow G$  such that  $\cdot$  is associative, and there exists  $e \in G$ , the *identity* element of the group, such that:

- For all  $x \in G$  we have  $xe = ex = x$
- For all  $x \in G$ , there exists  $x^{-1} \in G$ , the *inverse* of  $x$ , such that  $xx^{-1} = x^{-1}x = e$ .

The *order* of a group  $G$ , denoted  $|G|$ , is the number of elements in  $G$  if  $G$  is finite; otherwise we write  $|G| = \infty$ .

**Proposition 6.3.** *The inverse of an element is unique.*

PROOF: If  $i$  and  $j$  are inverses of  $x$  then  $i = ixj = j$ .  $\square$

**Example 6.4.** • The *trivial* group is  $\{e\}$  under  $ee = e$ .

- $\mathbb{Z}$  is a group under addition
- $\mathbb{Q}$  is a group under addition
- $\mathbb{Q} - \{0\}$  is a group under multiplication
- $\mathbb{R}$  is a group under addition
- $\mathbb{R} - \{0\}$  is a group under multiplication
- $\mathbb{C}$  is a group under addition
- $\mathbb{C} - \{0\}$  is a group under multiplication
- $\{-1, 1\}$  is a group under multiplication
- For any category  $\mathcal{C}$  and object  $A \in \mathcal{C}$ , we have  $\text{Aut}_{\mathcal{C}}(A)$  is a group under  $gf = f \circ g$ .

For  $A$  a set, we call  $S_A = \text{Aut}_{\text{Set}}(A)$  the *symmetric group* or *group of permutations* of  $A$ .

- For  $n \geq 3$ , the *dihedral group*  $D_{2n}$  consists of the set of rigid motions that map the regular  $n$ -gon onto itself under composition.
- Let  $SL_2(\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : a, b, c, d \in \mathbb{Z}, ad - bc = 1 \right\}$  under matrix multiplication.
- The quaternionic group  $Q_8$  is the group

$$\{1, -1, i, -i, j, -j, k, -k\}$$

with multiplication table

1	-1	i	-i	j	-j	k	-k
-1	1	-i	i	-j	j	-k	k
i	-i	-1	1	k	-k	-j	j
-i	i	1	-1	-k	k	j	-j
j	-j	-k	k	-1	1	i	-i
-j	j	k	-k	1	-1	-i	i
k	-k	j	-j	-i	i	-1	1
-k	k	-j	j	i	-i	1	-1

**Example 6.5.** • The only group of order 1 is the trivial group.

- The only group of order 2 is  $\mathbb{Z}_2$ .

- The only group of order 3 is  $\mathbb{Z}_3$ .
- There are exactly two groups of order 4:  $\mathbb{Z}_4$  and  $\mathbb{Z}_2 \times \mathbb{Z}_2$  under  $(a, b)(c, d) = (ac, bd)$ .

**Proposition 6.6** (Cancellation). *Let  $G$  be a group. Let  $a, g, h \in G$ . If  $ag = ah$  or  $ga = ha$  then  $g = h$ .*

PROOF: If  $ag = ah$  then  $g = a^{-1}ag = a^{-1}ah = h$ . Similarly if  $ga = ha$ .  $\square$

**Proposition 6.7.** *Let  $G$  be a group and  $g, h \in G$ . Then  $(gh)^{-1} = h^{-1}g^{-1}$ .*

PROOF: Since  $ghh^{-1}g^{-1} = e$ .  $\square$

**Definition 6.8.** Let  $G$  be a group. Let  $g \in G$ . We define  $g^n \in G$  for all  $n \in \mathbb{Z}$  as follows:

$$\begin{aligned} g^0 &= e \\ g^{n+1} &= g^n g & (n \geq 0) \\ g^{-n} &= (g^{-1})^n & (n > 0) \end{aligned}$$

**Proposition 6.9.** *Let  $G$  be a group. Let  $g \in G$  and  $m, n \in \mathbb{Z}$ . Then*

$$g^{m+n} = g^m g^n .$$

PROOF:

$\langle 1 \rangle 1$ . For all  $k \in \mathbb{Z}$  we have  $g^{k+1} = g^k g$

$\langle 2 \rangle 1$ . For all  $k \geq 0$  we have  $g^{k+1} = g^k g$

PROOF: Immediate from definition.

$\langle 2 \rangle 2$ .  $g^{-1+1} = g^{-1} g$

PROOF: Both are equal to  $e$ .

$\langle 2 \rangle 3$ . For all  $k > 1$  we have  $g^{-k+1} = g^{-k} g$

PROOF:

$$\begin{aligned} g^{-k+1} &= (g^{-1})^{k-1} \\ &= (g^{-1})^{k-1} g^{-1} g \\ &= (g^{-1})^k g \\ &= g^{-k} g \end{aligned}$$

$\langle 1 \rangle 2$ . For all  $k \in \mathbb{Z}$  we have  $g^{k-1} = g^k g^{-1}$

PROOF: Substitute  $k = k - 1$  above and multiply by  $g^{-1}$ .

$\langle 1 \rangle 3$ .  $g^{m+0} = g^m g^0$

PROOF: Since  $g^m g^0 = g^m e = g^m$ .

$\langle 1 \rangle 4$ . If  $g^{m+n} = g^m g^n$  then  $g^{m+n+1} = g^m g^{n+1}$

PROOF:

$$\begin{aligned} g^{m+n+1} &= g^{m+n} g & (\langle 1 \rangle 1) \\ &= g^m g^n g \\ &= g^m g^{n+1} & (\langle 1 \rangle 1) \end{aligned}$$

$\langle 1 \rangle 5$ . If  $g^{m+n} = g^m g^n$  then  $g^{m+n-1} = g^m g^{n-1}$

PROOF:

$$g^{m+n-1}g = g^{m+n} \quad (\langle 1 \rangle 1)$$

$$= g^m g^n$$

$$\therefore g^{m+n-1} = g^m g^n g^{-1}$$

$$= g^m g^{n-1} \quad (\langle 1 \rangle 2)$$

□

**Proposition 6.10.** Let  $G$  be a group. Let  $g \in G$  and  $m, n \in \mathbb{Z}$ . Then

$$(g^m)^n = g^{mn} .$$

PROOF:

$\langle 1 \rangle 1$ .  $(g^m)^0 = g^0$

PROOF: Both sides are equal to  $e$ .

$\langle 1 \rangle 2$ . If  $(g^m)^n = g^{mn}$  then  $(g^m)^{n+1} = g^{m(n+1)}$ .

PROOF:

$$(g^m)^{n+1} = (g^m)^n g^m \quad (\text{Proposition 6.9})$$

$$= g^{mn} g^m$$

$$= g^{mn+m} \quad (\text{Proposition 6.9})$$

$\langle 1 \rangle 3$ . If  $(g^m)^n = g^{mn}$  then  $(g^m)^{n-1} = g^{m(n-1)}$ .

PROOF:

$$(g^m)^n = g^{mn}$$

$$\therefore (g^m)^{n-1} g^m = g^{mn-m} g^m \quad (\text{Proposition 6.9})$$

$$\therefore (g^m)^{n-1} = g^{mn-m} \quad (\text{Cancellation})$$

□

**Definition 6.11** (Commute). Let  $G$  be a group and  $g, h \in G$ . We say  $g$  and  $h$  *commute* iff  $gh = hg$ .

**Definition 6.12.** Let  $G$  be a group. Given  $g \in G$  and  $A \subseteq G$ , we define

$$gA = \{ga : a \in A\}, \quad Ag = \{ag : a \in A\} .$$

Given sets  $A, B \subseteq G$ , we define

$$AB = \{ab : a \in A, b \in B\} .$$

## 6.1 Order of an Element

**Definition 6.13** (Order). Let  $G$  be a group. Let  $g \in G$ . Then  $g$  has *finite order* iff there exists a positive integer  $n$  such that  $g^n = e$ . In this case, the *order* of  $g$ , denoted  $|g|$ , is the least positive integer  $n$  such that  $g^n = e$ .

If  $g$  does not have finite order, we write  $|g| = \infty$ .

**Proposition 6.14.** *Let  $G$  be a group. Let  $g \in G$  and  $n$  be a positive integer. If  $g^n = e$  then  $|g| \mid n$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $n = q|g| + d$  where  $0 \leq d < |g|$

PROOF: Division Algorithm.

$\langle 1 \rangle 2$ .  $g^d = e$

PROOF:

$$\begin{aligned} e &= g^n \\ &= g^{q|g|+d} \\ &= (g^{|g|})^q g^d && \text{(Propositions 6.9, 6.10)} \\ &= e^q g^d \\ &= g^d \end{aligned}$$

$\langle 1 \rangle 3$ .  $d = 0$

PROOF: By minimality of  $|g|$ .

$\langle 1 \rangle 4$ .  $n = q|g|$

□

**Corollary 6.14.1.** *Let  $G$  be a group. Let  $g \in G$  have finite order and  $n \in \mathbb{Z}$ . Then  $g^n = e$  if and only if  $|g| \mid n$ .*

**Proposition 6.15.** *Let  $G$  be a group and  $g \in G$ . Then  $|g| \leq |G|$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: w.l.o.g.  $G$  is finite.

$\langle 1 \rangle 2$ . PICK  $i, j$  with  $0 \leq i < j \leq |G|$  such that  $g^i = g^j$ .

PROOF: Otherwise  $g^0, g^1, \dots, g^{|G|}$  would be  $|G| + 1$  distinct elements of  $G$ .

$\langle 1 \rangle 3$ .  $g^{j-i} = e$

$\langle 1 \rangle 4$ .  $g$  has finite order and  $|g| \leq |G|$

PROOF: Since  $|g| \leq j - i \leq j \leq |G|$ .

□

**Proposition 6.16.** *Let  $G$  be a group. Let  $g \in G$  have finite order. Let  $m \in \mathbb{N}$ . Then*

$$|g^m| = \frac{\text{lcm}(m, |g|)}{m} = \frac{|g|}{\text{gcd}(m, |g|)}$$

PROOF: Since for any integer  $d$  we have

$$g^{md} = e \Leftrightarrow |g| \mid md \quad (\text{Corollary 6.14.1})$$

$$\Leftrightarrow \text{lcm}(m, |g|) \mid md$$

$$\Leftrightarrow \frac{\text{lcm}(m, |g|)}{m} \mid d$$

□

and so  $|g^m| = \frac{\text{lcm}(m, |g|)}{m}$  by Corollary 6.14.1. □

**Corollary 6.16.1.** *If  $g$  has odd order then  $|g^2| = |g|$ .*

**Proposition 6.17.** *Let  $G$  be a group. Let  $g, h \in G$  have finite order. Assume  $gh = hg$ . Then  $|gh|$  has finite order and*

$$|gh| \mid \text{lcm}(|g|, |h|)$$

PROOF: Since  $(gh)^{\text{lcm}(|g|, |h|)} = g^{\text{lcm}(|g|, |h|)} h^{\text{lcm}(|g|, |h|)} = e$ .  $\square$

**Example 6.18.** This example shows that we cannot remove the hypothesis that  $gh = hg$ .

In  $\text{GL}_2(\mathbb{R})$ , take

$$g = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad h = \begin{pmatrix} 0 & 1 \\ -1 & -1 \end{pmatrix}.$$

Then  $|g| = 4$ ,  $|h| = 3$  and  $|gh| = \infty$ .

**Proposition 6.19.** *Let  $G$  be a group and  $g, h \in G$  have finite order. If  $gh = hg$  and  $\gcd(|g|, |h|) = 1$  then  $|gh| = |g||h|$ .*

PROOF:

$$\langle 1 \rangle 1. \text{ LET: } N = |gh|$$

$$\langle 1 \rangle 2. g^N = (h^{-1})^N$$

$$\langle 1 \rangle 3. g^{N|g|} = e$$

$$\langle 1 \rangle 4. |g^N| \mid |g|$$

$$\langle 1 \rangle 5. h^{-N|h|} = e$$

$$\langle 1 \rangle 6. |g^N| \mid |h|$$

$$\langle 1 \rangle 7. |g^N| = 1$$

PROOF: Since  $\gcd(|g|, |h|) = 1$ .

$$\langle 1 \rangle 8. g^N = e$$

$$\langle 1 \rangle 9. |g| \mid N$$

$$\langle 1 \rangle 10. h^{-N} = e$$

$$\langle 1 \rangle 11. |h| \mid N$$

$$\langle 1 \rangle 12. N = |g||h|$$

PROOF: Using Proposition 6.17.

$\square$

**Proposition 6.20.** *Let  $G$  be a finite group. Assume there is exactly one element  $f \in G$  of order 2. Then the product of all the elements of  $G$  is  $f$ .*

PROOF: Let the elements of  $G$  be  $g_1, g_2, \dots, g_n$ . Apart from  $e$  and  $f$ , every element and its inverse are distinct elements of the list. Hence the product of the list is  $ef = f$ .  $\square$

**Proposition 6.21.** *Let  $G$  be a finite group of order  $n$ . Let  $m$  be the number of elements of  $G$  of order 2. Then  $n - m$  is odd.*

PROOF: In the list of all elements that are not of order 2, every element and its inverse are distinct except for  $e$ . Hence the list has odd length.  $\square$

**Corollary 6.21.1.** *If a finite group has even order, then it contains an element of order 2.*

**Proposition 6.22.** *Let  $G$  be a group and  $a, g \in G$ . Then  $|aga^{-1}| = |g|$ .*

PROOF: Since

$$\begin{aligned} (aga^{-1})^n = e &\Leftrightarrow ag^na^{-1} = e \\ &\Leftrightarrow g^n = e \end{aligned} \quad \square$$

**Proposition 6.23.** *Let  $G$  be a group and  $g, h \in G$ . Then  $|gh| = |hg|$ .*

PROOF: Since  $|gh| = |ghgg^{-1}| = |hg|$ .  $\square$

**Proposition 6.24.** *Let  $G$  be a group of order  $n$ . Let  $k$  be relatively prime to  $n$ . Then every element in  $G$  has the form  $x^k$  for some  $x$ .*

$\langle 1 \rangle 1$ . PICK integers  $a$  and  $b$  such that  $an + bk = 1$ .

$\langle 1 \rangle 2$ . LET:  $g \in G$

$\langle 1 \rangle 3$ .  $g = (g^b)^k$

PROOF:

$$\begin{aligned} g &= g \cdot (g^n)^{-a} & (g^n = e) \\ &= g^{1-an} \\ &= g^{bk} \end{aligned}$$

$\square$

## 6.2 Generators

**Definition 6.25** (Generator). Let  $G$  be a group and  $a \in G$ . We say  $a$  *generates* the group iff, for all  $x \in G$ , there exists an integer  $n$  such that  $x^n = a$ .

**Example 6.26.**  $\text{SL}_2(\mathbb{Z})$  is generated by

$$s = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad t = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $H = \langle s, t \rangle$

$\langle 1 \rangle 2$ . For all  $q \in \mathbb{Z}$  we have  $\begin{pmatrix} 1 & q \\ 0 & 1 \end{pmatrix} \in H$ .

PROOF: It is  $t^q$ .

$\langle 1 \rangle 3$ . For all  $q \in \mathbb{Z}$  we have  $\begin{pmatrix} 1 & 0 \\ q & 1 \end{pmatrix} \in H$ .

PROOF:

$$\begin{aligned} st^{-q}s^{-1} &= \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & -q \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & -1 \\ 1 & -q \end{pmatrix} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \\ &= \begin{pmatrix} 1 & 0 \\ q & 1 \end{pmatrix} \end{aligned}$$

⟨1⟩4.

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & q \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} a & qa+b \\ c & qc+d \end{pmatrix}$$

⟨1⟩5.

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & 0 \\ q & 1 \end{pmatrix} = \begin{pmatrix} a+qb & b \\ c+qd & d \end{pmatrix}$$

⟨1⟩6. For any  $M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \mathrm{SL}_2(\mathbb{Z})$ , if  $c$  and  $d$  are both nonzero, then there exists  $N \in H$  such that the bottom row of  $MN$  has one entry the same as  $M$  and one entry with smaller absolute value.

PROOF: From ⟨1⟩4 and ⟨1⟩5 taking  $q = -1$ .

⟨1⟩7. For any  $M \in \mathrm{SL}_2(\mathbb{Z})$ , there exists  $N \in H$  such that  $MN$  has a zero on the bottom row.

PROOF: Apply ⟨1⟩6 repeatedly.

⟨1⟩8. Any matrix in  $\mathrm{SL}_2(\mathbb{Z})$  with a zero on the bottom row is in  $H$ .

⟨2⟩1.  $\begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \in H$

PROOF: ⟨1⟩2

⟨2⟩2.  $\begin{pmatrix} -1 & b \\ 0 & -1 \end{pmatrix} \in H$

PROOF: It is  $s^2 \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix}$  since  $s^2 = -I$ .

⟨2⟩3.  $\begin{pmatrix} a & 1 \\ -1 & 0 \end{pmatrix} \in H$

PROOF: It is  $\begin{pmatrix} 1 & -a \\ 0 & 1 \end{pmatrix} s$ .

⟨2⟩4.  $\begin{pmatrix} a & -1 \\ 1 & 0 \end{pmatrix} \in H$

PROOF: It is  $s^2 \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} s$ .

⟨1⟩9. Every matrix in  $\mathrm{SL}_2(\mathbb{Z})$  is in  $H$ .

□

### 6.3 $p$ -groups

**Definition 6.27** ( $p$ -group). Let  $p$  be a prime. A  $p$ -group is a finite group whose order is a power of  $p$ .



## Chapter 7

# Group Homomorphisms

**Definition 7.1** (Homomorphism). Let  $G$  and  $H$  be groups. A (group) homomorphism  $\phi : G \rightarrow H$  is a function such that, for all  $x, y \in G$ ,

$$\phi(xy) = \phi(x)\phi(y) \text{ .}$$

**Proposition 7.2.** Let  $G$  and  $H$  be groups with identities  $e_G$  and  $e_H$ . Let  $\phi : G \rightarrow H$  be a group homomorphism. Then  $\phi(e_G) = e_H$ .

PROOF: Since  $\phi(e_G) = \phi(e_G e_G) = \phi(e_G)\phi(e_G)$  and so  $\phi(e_G) = e_H$  by Cancellation.  $\square$

**Proposition 7.3.** Let  $\phi : G \rightarrow H$  be a group homomorphism. For all  $x \in G$  we have  $\phi(x^{-1}) = \phi(x)^{-1}$ .

PROOF: Since  $\phi(x)\phi(x^{-1}) = \phi(xx^{-1}) = \phi(e_G) = e_H$ .  $\square$

**Proposition 7.4.** Let  $G, H$  and  $K$  be groups. If  $\phi : G \rightarrow H$  and  $\psi : H \rightarrow K$  are homomorphisms then  $\psi \circ \phi : G \rightarrow K$  is a homomorphism.

PROOF: For  $x, y \in G$  we have

$$\psi(\phi(xy)) = \psi(\phi(x)\phi(y)) = \psi(\phi(x))\psi(\phi(y)) \text{ .}$$

**Proposition 7.5.** Let  $G$  be a group. Then  $\text{id}_G : G \rightarrow G$  is a group homomorphism.

PROOF: For  $x, y \in G$  we have  $\text{id}_G(xy) = xy = \text{id}_G(x)\text{id}_G(y)$ .  $\square$

**Proposition 7.6.** Let  $\phi : G \rightarrow H$  be a group homomorphism. Let  $g \in G$  have finite order. Then  $|\phi(g)|$  divides  $|g|$ .

PROOF: Since  $\phi(g)^{|g|} = \phi(g^{|g|}) = e$ .  $\square$

**Definition 7.7** (Category of Groups). Let **Grp** be the category of groups and group homomorphisms.

**Example 7.8.** There are 49487365402 groups of order 1024 up to isomorphism.

**Proposition 7.9.** *A group homomorphism  $\phi : G \rightarrow H$  is an isomorphism in **Grp** if and only if it is bijective.*

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $\phi$  is bijective.

PROVE:  $\phi^{-1}$  is a group homomorphism.

$\langle 1 \rangle 2$ . LET:  $h, h' \in H$

$\langle 1 \rangle 3$ .  $\phi(\phi^{-1}(hh')) = \phi(\phi^{-1}(h)\phi^{-1}(h'))$

PROOF: Both are equal to  $hh'$ .

$\langle 1 \rangle 4$ .  $\phi^{-1}(hh') = \phi^{-1}(h)\phi^{-1}(h')$

□

**Corollary 7.9.1.**

$$D_6 \cong C_3$$

PROOF: The canonical homomorphism  $D_6 \rightarrow C_3$  is bijective. □

**Corollary 7.9.2.**

$$(\mathbb{R}, +) \cong (\{x \in \mathbb{R} : x > 0\}, \cdot)$$

PROOF: The function that maps  $x$  to  $e^x$  is a bijective homomorphism. □

**Proposition 7.10.** *The trivial group is the zero object in **Grp**.*

PROOF: For any group  $G$ , the unique function  $G \rightarrow \{e\}$  is a group homomorphism, and the only group homomorphism  $\{e\} \rightarrow G$  maps  $e$  to  $e_G$ . □

**Proposition 7.11.** *For any groups  $G$  and  $H$ , the set  $G \times H$  under  $(g, h)(g', h') = (gg', hh')$  is the product of  $G$  and  $H$  in **Grp**.*

PROOF:

$\langle 1 \rangle 1$ .  $G \times H$  is a group.

$\langle 2 \rangle 1$ . The multiplication is associative.

PROOF: Since  $(g_1, h_1)((g_2, h_2)(g_3, h_3)) = ((g_1, h_1)(g_2, h_2))(g_3, h_3) = (g_1g_2g_3, h_1h_2h_3)$ .

$\langle 2 \rangle 2$ .  $(e_G, e_H)$  is the identity.

PROOF: Since  $(g, h)(e_G, e_H) = (e_G, e_H)(g, h) = (g, h)$ .

$\langle 2 \rangle 3$ . The inverse of  $(g, h)$  is  $(g^{-1}, h^{-1})$ .

PROOF: Since  $(g, h)(g^{-1}, h^{-1}) = (g^{-1}, h^{-1})(g, h) = (e_G, e_H)$ .

$\langle 1 \rangle 2$ .  $\pi_1 : G \times H \rightarrow G$  is a group homomorphism.

PROOF: Immediate from definitions.

$\langle 1 \rangle 3$ .  $\pi_2 : G \times H \rightarrow H$  is a group homomorphism.

PROOF: Immediate from definitions.

$\langle 1 \rangle 4$ . For any group homomorphism  $\phi : K \rightarrow G$  and  $\psi : K \rightarrow H$ , the function  $\langle \phi, \psi \rangle : K \rightarrow G \times H$  where  $\langle \phi, \psi \rangle(k) = (\phi(k), \psi(k))$  is a group homomorphism.

PROOF:

$$\begin{aligned} \langle \phi, \psi \rangle(kk') &= (\phi(kk'), \psi(kk')) \\ &= (\phi(k)\phi(k'), \psi(k)\psi(k')) \\ &= (\phi(k), \psi(k))(\phi(k'), \psi(k')) \\ &= \langle \phi, \psi \rangle(k)\langle \phi, \psi \rangle(k') \end{aligned}$$

□

## 7.1 Subgroups

**Definition 7.12** (Subgroup). Let  $(G, \cdot)$  and  $(H, *)$  be groups such that  $H$  is a subset of  $G$ . Then  $H$  is a *subgroup* of  $G$  iff the inclusion  $i : H \hookrightarrow G$  is a group homomorphism.

**Proposition 7.13.** *If  $(H, *)$  is a subgroup of  $(G, \cdot)$  then  $*$  is the restriction of  $\cdot$  to  $H$ .*

PROOF: Given  $x, y \in H$  we have

$$x * y = i(x * y) = i(x) \cdot i(y) = x \cdot y . \quad \square$$

**Example 7.14.** For any group  $G$  we have  $\{e\}$  is a subgroup of  $G$ .

**Proposition 7.15.** *Let  $G$  be a group. Let  $H$  be a subset of  $G$ . Then  $H$  is a subgroup of  $G$  iff  $H$  is nonempty and, for all  $x, y \in H$ , we have  $xy^{-1} \in H$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $H$  is a subgroup of  $G$  then  $H$  is nonempty.

PROOF: Since every group has an identity element and so is nonempty.

$\langle 1 \rangle 2$ . If  $H$  is a subgroup of  $G$  then, for all  $x, y \in H$ , we have  $xy^{-1} \in H$ .

PROOF: Easy.

$\langle 1 \rangle 3$ . If  $H$  is nonempty and, for all  $x, y \in H$ , we have  $xy^{-1} \in H$ , then  $H$  is a subgroup of  $G$ .

$\langle 2 \rangle 1$ . ASSUME:  $H$  is nonempty.

$\langle 2 \rangle 2$ . ASSUME:  $\forall x, y \in H. xy^{-1} \in H$

$\langle 2 \rangle 3$ .  $e \in H$

PROOF: Pick  $x \in H$ . We have  $e = xx^{-1} \in H$ .

$\langle 2 \rangle 4$ .  $\forall x \in H. x^{-1} \in H$

PROOF: Given  $x \in H$  we have  $x^{-1} = ex^{-1} \in H$ .

$\langle 2 \rangle 5$ .  $H$  is closed under the restriction of  $\cdot$

PROOF: Given  $x, y \in H$  we have  $xy = x(y^{-1})^{-1} \in H$ .

$\langle 2 \rangle 6$ .  $H$  is a group under the restriction of  $\cdot$

PROOF: Associativity is inherited from  $G$  and the existence of an identity element and inverses follows from  $\langle 2 \rangle 3$  and  $\langle 2 \rangle 4$ .

$\langle 2 \rangle 7$ . The inclusion  $H \hookrightarrow G$  is a group homomorphism.

PROOF: For  $x, y \in H$  we have  $i(xy) = i(x)i(y) = xy$ .

$\square$

**Corollary 7.15.1.** *The intersection of a set of subgroups of  $G$  is a subgroup of  $G$ .*

**Corollary 7.15.2.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Let  $K$  be a subgroup of  $H$ . Then  $\phi^{-1}(K)$  is a subgroup of  $G$ .*

PROOF:

$\langle 1 \rangle 1$ .  $\phi^{-1}(K)$  is nonempty.

PROOF: Since  $e \in \phi^{-1}(K)$ .

$\langle 1 \rangle 2$ . LET:  $x, y \in \phi^{-1}(K)$

- $\langle 1 \rangle 3. \phi(x), \phi(y) \in K$
- $\langle 1 \rangle 4. \phi(x)\phi(y)^{-1} \in K$
- $\langle 1 \rangle 5. \phi(xy^{-1}) \in K$
- $\langle 1 \rangle 6. xy^{-1} \in \phi^{-1}(K)$

□

**Corollary 7.15.3.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Let  $K$  be a subgroup of  $G$ . Then  $\phi(K)$  is a subgroup of  $H$ .*

PROOF:

- $\langle 1 \rangle 1.$  LET:  $x, y \in \phi(K)$
- $\langle 1 \rangle 2.$  PICK  $a, b \in K$  such that  $x = \phi(a)$  and  $y = \phi(b)$
- $\langle 1 \rangle 3. xy^{-1} = \phi(ab^{-1})$
- $\langle 1 \rangle 4. xy^{-1} \in \phi(K)$

□

**Proposition 7.16.** *Let  $G$  be a subgroup of  $\mathbb{Z}$ . Then there exists  $d \geq 0$  such that  $G = d\mathbb{Z}$ .*

PROOF:

- $\langle 1 \rangle 1.$  ASSUME: w.l.o.g.  $G \neq \{0\}$

PROOF: Since  $\{0\} = 0\mathbb{Z}$ .

- $\langle 1 \rangle 2.$  LET:  $d$  be the least positive element of  $G$ .

PROVE:  $G = d\mathbb{Z}$

PROOF: If  $n \in G$  then  $-n \in G$  so  $G$  must contain a positive element.

- $\langle 1 \rangle 3. G \subseteq d\mathbb{Z}$

- $\langle 2 \rangle 1.$  LET:  $n \in G$

- $\langle 2 \rangle 2.$  LET:  $q$  and  $r$  be the integers such that  $n = qd + r$  and  $0 \leq r < d$ .

- $\langle 2 \rangle 3. r \in G$

PROOF: Since  $r = n - qd$ .

- $\langle 2 \rangle 4. r = 0$

PROOF: By minimality of  $d$ .

- $\langle 2 \rangle 5. n = qd \in d\mathbb{Z}$

- $\langle 1 \rangle 4. d\mathbb{Z} \subseteq G$

□

## 7.2 Kernel

**Definition 7.17** (Kernel). Let  $\phi : G \rightarrow H$  be a group homomorphism. The *kernel* of  $\phi$  is

$$\ker \phi = \{g \in G : \phi(g) = e\} .$$

**Proposition 7.18.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Then  $\ker \phi$  is a subgroup of  $G$ .*

PROOF: Corollary 7.15.2. □

**Proposition 7.19.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Then the inclusion  $i : \ker \phi \hookrightarrow G$  is terminal in the category of pairs  $(K, \alpha : K \rightarrow G)$  such that  $\phi \circ \alpha = 0$ .*

PROOF:

$\langle 1 \rangle 1.$   $\phi \circ i = 0$

$\langle 1 \rangle 2.$  For any group  $K$  and homomorphism  $\alpha : K \rightarrow G$  such that  $\phi \circ \alpha = 0$ , there exists a unique homomorphism  $\beta : K \rightarrow \ker \phi$  such that  $i \circ \beta = \alpha$ .

□

**Proposition 7.20.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Then the following are equivalent:*

1.  $\phi$  is monic.
2.  $\ker \phi = \{e\}$
3.  $\phi$  is injective.

PROOF:

$\langle 1 \rangle 1.$   $1 \Rightarrow 2$

$\langle 2 \rangle 1.$  ASSUME:  $\phi$  is monic.

$\langle 2 \rangle 2.$  LET:  $i : \ker \phi \hookrightarrow G, j : \{e\} \hookrightarrow \ker \phi \hookrightarrow G$  be the inclusions.

$\langle 2 \rangle 3.$   $\phi \circ i = \phi \circ j$

$\langle 2 \rangle 4.$   $i = j$

$\langle 1 \rangle 2.$   $2 \Rightarrow 3$

$\langle 2 \rangle 1.$  ASSUME:  $\ker \phi = \{e\}$

$\langle 2 \rangle 2.$  LET:  $x, y \in G$

$\langle 2 \rangle 3.$  ASSUME:  $\phi(x) = \phi(y)$

$\langle 2 \rangle 4.$   $\phi(xy^{-1}) = e$

$\langle 2 \rangle 5.$   $xy^{-1} \in \ker \phi$

$\langle 2 \rangle 6.$   $xy^{-1} = e$

$\langle 2 \rangle 7.$   $x = y$

$\langle 1 \rangle 3.$   $3 \Rightarrow 1$

PROOF: Easy.

□

**Proposition 7.21.** *A group homomorphism is an epimorphism if and only if it is surjective.*

## 7.3 Inner Automorphisms

**Proposition 7.22.** *Let  $G$  be a group and  $g \in G$ . The function  $\gamma_g : G \rightarrow G$  defined by  $\gamma_g(a) = gag^{-1}$  is an automorphism on  $G$ .*

PROOF:

$\langle 1 \rangle 1.$   $\gamma_g$  is a homomorphism.

PROOF:

$$\begin{aligned}\gamma_g(ab) &= gabg^{-1} \\ &= gag^{-1}gbg^{-1} \\ &= \gamma_g(a)\gamma_g(b)\end{aligned}$$

<1>2.  $\gamma_g$  is injective.

PROOF: By Cancellation.

<1>3.  $\gamma_g$  is surjective.

PROOF: Given  $b \in G$ , we have  $\gamma_g(g^{-1}bg) = b$ .

□

**Definition 7.23** (Inner Automorphism). Let  $G$  be a group. An *inner automorphism* on  $G$  is a function of the form  $\gamma_g(a) = gag^{-1}$  for some  $g \in G$ .

We write  $\text{Inn}(G)$  for the set of inner automorphisms of  $G$ .

**Proposition 7.24.** Let  $G$  be a group. The function  $\gamma : G \rightarrow \text{Aut}_{\mathbf{Grp}}(G)$  that maps  $g$  to  $\gamma_g$  is a group homomorphism.

PROOF: Since  $\gamma_{gh}(a) = ghah^{-1}g^{-1} = \gamma_g(\gamma_h(a))$ . □

**Corollary 7.24.1.**  $\text{Inn}(G)$  is a subgroup of  $\text{Aut}_{\mathbf{Grp}}(G)$ .

## 7.4 Direct Products

**Definition 7.25** (Direct Product). The *direct product* of groups  $G$  and  $H$  is their product in  $\mathbf{Grp}$ .

## 7.5 Free Groups

**Proposition 7.26.** Let  $A$  be a set. Let  $\mathcal{F}^A$  be the category whose objects are pairs  $(G, j)$  where  $G$  is a group and  $j$  is a function  $A \rightarrow G$ , with morphisms  $f : (G, j) \rightarrow (H, k)$  the group homomorphisms  $f : G \rightarrow H$  such that  $f \circ j = k$ . Then  $\mathcal{F}^A$  has an initial object.

PROOF:

<1>1. LET:  $W(A)$  be the set of words in the alphabet whose elements are the elements of  $A$  together with  $\{a^{-1} : a \in A\}$ .

<1>2. LET:  $r : W(A) \rightarrow W(A)$  be the function that, given a word  $w$ , removes the first pair of letters of the form  $aa^{-1}$  or  $a^{-1}a$ ; if there is no such pair, then  $r(w) = w$ .

<1>3. Let us say that a word  $w$  is a *reduced word* iff  $r(w) = w$ .

<1>4. For any word  $w$  of length  $n$ , we have  $r^{\lceil \frac{n}{2} \rceil}(w)$  is a reduced word.

PROOF: Since we cannot remove more than  $n/2$  pairs of letters from  $w$ .

<1>5. LET:  $R : W(A) \rightarrow W(A)$  be the function  $R(w) = r^{\lceil \frac{n}{2} \rceil}(w)$ , where  $n$  is the length of  $w$ .

<1>6. LET:  $F(A)$  be the set of reduced words.

<1>7. Define  $\cdot : F(A)^2 \rightarrow F(A)$  by  $w \cdot w' = R(ww')$

(1)8.  $\cdot$  is associative.

PROOF: Both  $w_1 \cdot (w_2 \cdot w_3)$  and  $(w_1 \cdot w_2) \cdot w_3$  are equal to  $R(w_1 w_2 w_3)$ .

(1)9. The empty word is the identity element in  $F(A)$

(1)10. The inverse of  $a_1^{\pm 1} a_2^{\pm 1} \dots a_n^{\pm 1}$  is  $a_n^{\mp 1} \dots a_2^{\mp 1} a_1^{\mp 1}$ .

(1)11. LET:  $j : A \rightarrow F(A)$  be the function that maps  $a$  to the word  $a$  of length

(1)12. LET:  $G$  be any group and  $k : A \rightarrow G$  any function.

(1)13. The only morphism  $f : (F(A), j) \rightarrow (G, k)$  in  $\mathcal{F}^A$  is  $f(a_1^{\pm 1} a_2^{\pm 1} \dots a_n^{\pm 1}) = k(a_1)^{\pm 1} k(a_2)^{\pm 1} \dots k(a_n)^{\pm 1}$ .

□

**Definition 7.27** (Free Group). For any set  $A$ , the *free group* on  $A$  is the initial object  $(F(A), i)$  in  $\mathcal{F}^A$ .

**Proposition 7.28.**  $i : A \rightarrow F(A)$  is injective.

PROOF:

(1)1. LET:  $x, y \in A$

(1)2. ASSUME:  $x \neq y$

PROVE:  $i(x) \neq i(y)$

(1)3. LET:  $f : A \rightarrow C_2$  be the function that maps  $x$  to 0 and all other elements of  $A$  to 1.

(1)4. LET:  $\phi : F(A) \rightarrow C_2$  be the group homomorphism such that  $f = \phi \circ i$ .

(1)5.  $f(x) \neq f(y)$

(1)6.  $\phi(i(x)) \neq \phi(i(y))$

(1)7.  $i(x) \neq i(y)$

□

**Proposition 7.29.**

$$F(0) \cong \{e\}$$

PROOF: For any set  $A$ , the unique group homomorphism  $\{e\} \rightarrow A$  makes the following diagram commute.

$$\begin{array}{ccc} \{e\} & \longrightarrow & A \\ \uparrow & \nearrow & \\ \emptyset & & \end{array}$$

**Proposition 7.30.** The free group on 1 is  $\mathbb{Z}$  with the injection mapping 0 to 1.

PROOF: Given any group  $G$  and function  $a : 1 \rightarrow G$ , the required unique homomorphism  $\phi : \mathbb{Z} \rightarrow G$  is defined by  $\phi(n) = a(0)^n$ . □

**Proposition 7.31.** For any sets  $A$  and  $B$ , we have that  $F(A + B)$  is the coproduct of  $F(A)$  and  $F(B)$  in **Grp**.

$$\begin{array}{ccccc}
& & G & & \\
& f \nearrow & \uparrow k & \nwarrow g & \\
F(A) & \xrightarrow{\kappa_1} & F(A+B) & \xleftarrow{\kappa_2} & F(B) \\
i_A \uparrow & & j \uparrow & & i_B \uparrow \\
A & \xrightarrow{k_1} & A+B & \xleftarrow{k_2} & B
\end{array}$$

PROOF:

- (1)1. LET:  $i_A : A \rightarrow F(A)$ ,  $i_B : B \rightarrow F(B)$ ,  $j : A+B \rightarrow F(A+B)$  be the canonical injections.  
 (1)2. LET:  $\kappa_1, \kappa_2$  be the unique group homomorphisms that make the diagram above commute.  
 (1)3. LET:  $G$  be any group and  $f : F(A) \rightarrow G$ ,  $g : F(B) \rightarrow G$  any group homomorphisms.  
 (1)4. LET:  $h : A+B \rightarrow G$  be the unique function such that  $h \circ k_1 = f \circ i_A$  and  $h \circ k_2 = g \circ i_B$ .  
 (1)5. LET:  $k : F(A+B) \rightarrow G$  be the unique group homomorphism such that  $k \circ j = h$ .  
 (1)6.  $k$  is the unique group homomorphism such that  $k \circ \kappa_1 \circ i_A = f \circ i_A$  and  $k \circ \kappa_2 \circ i_B = g \circ i_B$ .  
 (1)7.  $k$  is the unique group homomorphism such that  $k \circ \kappa_1 = f$  and  $k \circ \kappa_2 = g$ .  
 □

**Definition 7.32** (Subgroup Generated by a Group). Let  $G$  be a group and  $A$  a subset of  $G$ . Let  $\phi : F(A) \rightarrow G$  be the unique group homomorphism such that  $\phi(a) = a$  for all  $a \in A$ . The subgroup *generated* by  $A$  is

$$\langle A \rangle := \text{im } \phi$$

$$\begin{array}{ccc}
F(A) & \xrightarrow{\phi} & G \\
\uparrow & \nearrow & \\
A & & 
\end{array}$$

**Proposition 7.33.** Let  $G$  be a group and  $A$  a subset of  $G$ . Then  $\langle A \rangle$  is the set of all elements of the form  $a_1^{\pm 1} a_2^{\pm 1} \cdots a_n^{\pm 1}$  (where  $n \geq 0$ ) such that  $a_1, \dots, a_n \in A$ .

PROOF: Immediate from definitions. □

**Corollary 7.33.1.** Let  $G$  be a group and  $g \in G$ . Then

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

**Proposition 7.34.** Let  $G$  be a group and  $A$  a subset of  $G$ . Then  $\langle A \rangle$  is the intersection of all the subgroups of  $G$  that include  $A$ .



PROOF: Easy.  $\square$

**Definition 7.35** (Finitely Generated). Let  $G$  be a group. Then  $G$  is *finitely generated* iff there exists a finite subset  $A$  of  $G$  such that  $G = \langle A \rangle$ .

**Proposition 7.36.** *Every subgroup of a finitely generated free group is free.*

PROOF: TODO.

**Proposition 7.37.**  *$F(2)$  includes subgroups isomorphic to the free group on arbitrarily many generators.*

PROOF: TODO

**Proposition 7.38.**

$$[F(2), F(2)] \cong F(\mathbb{Z})$$

PROOF: TODO

## 7.6 Normal Subgroups

**Definition 7.39** (Normal Subgroup). A subgroup  $N$  of  $G$  is *normal* iff, for all  $g \in G$  and  $n \in N$ , we have  $gng^{-1} \in N$ .

**Example 7.40.** Every subgroup of  $Q_8$  is normal.

**Proposition 7.41.** *Let  $G$  be a group and  $N$  a subgroup of  $G$ . Then the following are equivalent.*

1.  $N$  is normal.
2.  $\forall g \in G. gNg^{-1} \subseteq N$
3.  $\forall g \in G. gNg^{-1} = N$
4.  $\forall g \in G. gN \subseteq Ng$
5.  $\forall g \in G. gN = Ng$

PROOF:

$\langle 1 \rangle 1. 1 \Leftrightarrow 2$

PROOF: Immediate from definitions.

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: If 2 holds then we have  $gNg^{-1} \subseteq N$  and  $g^{-1}Ng \subseteq N$  hence  $N = gNg^{-1}$ .

$\langle 1 \rangle 3. 3 \Rightarrow 2$

PROOF: Trivial.

$\langle 1 \rangle 4. 2 \Leftrightarrow 4$

PROOF: Easy.

$\langle 1 \rangle 5. 3 \Leftrightarrow 5$

PROOF: Easy.

□

**Proposition 7.42.** *Let  $\phi : G \rightarrow H$  be a group homomorphism. Then  $\ker \phi$  is a normal subgroup of  $G$ .*

PROOF: Given  $g \in G$  and  $n \in \ker \phi$  we have

$$\begin{aligned}\phi(gng^{-1}) &= \phi(g)\phi(n)\phi(g)^{-1} \\ &= \phi(g)\phi(g)^{-1} \\ &= e\end{aligned}$$

and so  $gng^{-1} \in \ker \phi$ . □

**Proposition 7.43.** *If  $H$  and  $K$  are normal subgroups of a group  $G$  then  $HK$  is normal in  $G$ .*

PROOF: For  $g \in G$ ,  $h \in H$  and  $k \in K$  we have  $ghkg^{-1} = (ghg^{-1})(gkg^{-1}) \in HK$ . □

## 7.7 Quotient Groups

**Definition 7.44.** Let  $G$  be a group. Let  $\sim$  be an equivalence relation on  $G$ . Then we say that  $\sim$  is *compatible* with the group operation on  $G$  iff, for all  $a, a', g \in G$ , if  $a \sim a'$  then  $ga \sim ga'$  and  $ag \sim a'g$ .

**Proposition 7.45.** *Let  $G$  be a group. Let  $\sim$  be an equivalence relation on  $G$ . Then there exists an operation  $\cdot : (G/\sim)^2 \rightarrow G/\sim$  such that*

$$\forall a, b \in G. [a][b] = [ab]$$

*iff  $\sim$  is compatible with the group operation on  $G$ . In this case,  $G/\sim$  is a group under  $\cdot$  and the canonical function  $\pi : G \rightarrow G/\sim$  is a group homomorphism, and is universal with respect to group homomorphisms  $\phi : G \rightarrow G'$  such that if  $a \sim a'$  then  $\phi(a) = \phi(a')$ .*

PROOF: Easy. □

**Definition 7.46** (Quotient Group). Let  $G$  be a group. Let  $\sim$  be an equivalence relation on  $G$  that is compatible with the group operation on  $G$ . Then  $G/\sim$  is the *quotient group* of  $G$  by  $\sim$  under  $[a][b] = [ab]$ .

**Proposition 7.47.** *Let  $G$  be a group and  $H$  a subgroup of  $G$ . Then  $H$  is normal if and only if there exists a group  $K$  and homomorphism  $\phi : G \rightarrow K$  such that  $H = \ker \phi$ .*

PROOF: One direction is given by Proposition 7.42. For the other direction, take  $K = G/H$  and  $\phi$  to be the canonical map  $G \rightarrow G/H$ . □

**Definition 7.48** (Modular Group). The *modular group*  $\text{PSL}_2(\mathbb{Z})$  is  $\text{SL}_2(\mathbb{Z})/\{I, -I\}$ .

**Proposition 7.49.**  $\text{PSL}_2(\mathbb{Z})$  is generated by  $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$  and  $\begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}$ .

PROOF: By Example 6.26.

**Proposition 7.50** (Roger Alperin).  $\text{PSL}_2(\mathbb{Z})$  is presented by  $(x, y|x^2, y^3)$ .

PROOF:

$$\langle 1 \rangle 1. \text{ LET: } x = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

$$\langle 1 \rangle 2. \text{ LET: } y = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}$$

$\langle 1 \rangle 3.$  Define an action of  $\text{PSL}_2(\mathbb{Z})$  on  $\mathbb{R} - \mathbb{Q}$  by

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} r = \frac{ar + b}{cr + d}.$$

$\langle 2 \rangle 1.$  Given  $\begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{PSL}_2(\mathbb{Z})$  and  $r$  irrational we have  $\frac{ar+b}{cr+d}$  is irrational.

$\langle 3 \rangle 1.$  ASSUME: for a contradiction  $\frac{ar+b}{cr+d} = \frac{p}{q}$  where  $p$  and  $q$  are integers with  $q > 0$ .

$$\langle 3 \rangle 2. aqr + bq = cpr + dp$$

$$\langle 3 \rangle 3. (aq - cp)r = dp - bq$$

$$\langle 3 \rangle 4. aq = cp = dp - bq = 0$$

$$\langle 3 \rangle 5. adq - cdp = 0$$

$$\langle 3 \rangle 6. cdp - cbq = 0$$

$$\langle 3 \rangle 7. (ad - cb)q = 0$$

PROOF: Since  $ad - cb = 1$ .

$$\langle 3 \rangle 8. q = 0$$

$$\langle 3 \rangle 9. \text{ Q.E.D.}$$

PROOF: This contradicts  $\langle 3 \rangle 1$ .

$$\langle 2 \rangle 2. -Ir = r$$

PROOF: Since  $-Ir = \frac{-r}{-1} = r$ .

$$\langle 2 \rangle 3. \text{ Given } A, B \in \text{PSL}_2(\mathbb{Z}) \text{ we have } A(Br) = (AB)r.$$

PROOF:

$$\begin{aligned} \begin{pmatrix} a & b \\ c & d \end{pmatrix} \left[ \begin{pmatrix} e & f \\ g & h \end{pmatrix} r \right] &= \begin{pmatrix} a & b \\ c & d \end{pmatrix} \frac{er + f}{gr + h} \\ &= \frac{a \frac{er+f}{gr+h} + b}{c \frac{er+f}{gr+h} + d} \\ &= \frac{a(er + f) + b(gr + h)}{c(er + f) + d(gr + h)} \\ &= \frac{(ae + bg)r + (af + bh)}{(ce + dg)r + (cf + dh)} \\ &= \begin{pmatrix} ae + bg & af + bh \\ ce + dg & cf + dh \end{pmatrix} r \\ &= \left[ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} e & f \\ g & h \end{pmatrix} \right] r \end{aligned}$$

$$\langle 1 \rangle 4.$$

$$yr = 1 - \frac{1}{r}$$

⟨1⟩5.

$$y^{-1}r = \frac{1}{1-r}$$

PROOF: Since  $y^{-1} = \begin{pmatrix} 0 & 1 \\ -1 & 1 \end{pmatrix}$

⟨1⟩6.

$$yxr = 1 + r$$

PROOF: Since  $yx = \begin{pmatrix} -1 & -1 \\ 0 & -1 \end{pmatrix}$ .

⟨1⟩7.

$$y^{-1}xr = \frac{r}{1+r}$$

PROOF: Since  $y^{-1}x = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$ .

⟨1⟩8. If  $r > -1$  is positive then  $yxr$  is positive.

⟨1⟩9. If  $r$  is positive then  $y^{-1}xr$  is positive.

⟨1⟩10. If  $r < -1$  then  $y^{-1}xr$  is positive.

⟨1⟩11. If  $r$  is negative then  $yr$  is positive.

⟨1⟩12. If  $r$  is negative then  $y^{-1}r$  is positive.

⟨1⟩13. No product of the form

$$(y^{\pm 1}x)(y^{\pm 1}x) \cdots (y^{\pm 1}x)$$

with one or more factors can equal the identity.

PROOF: If the last factor is  $(yx)$ , then the product maps numbers in  $(-1, 0)$  to positive numbers. If the last factor is  $(y^{-1}x)$ , then the product maps numbers  $< -1$  to positive numbers.

⟨1⟩14. No product of the form

$$(y^{\pm 1}x)(y^{\pm 1}x) \cdots (y^{\pm 1}x)y^{\pm 1}$$

with one or more factors can equal the identity.

PROOF: The product maps negative numbers to positive numbers.

⟨1⟩15.  $\text{PSL}_2(\mathbb{Z})$  is presented by  $(x, y|x^2, y^3)$ .

□

**Corollary 7.50.1.**  $\text{PSL}_2(\mathbb{Z})$  is the coproduct of  $C_2$  and  $C_3$  in **Grp**.

**Theorem 7.51.** Every group homomorphism  $\phi : G \rightarrow H$  may be decomposed as

$$G \longrightarrow G/\ker \phi \xrightarrow{\cong} \text{im } \phi \longrightarrow H$$

PROOF: Easy. □

**Corollary 7.51.1** (First Isomorphism Theorem). Let  $\phi : G \rightarrow H$  be a surjective group homomorphism. Then  $H \cong G/\ker \phi$ .

**Proposition 7.52.** Let  $H_1$  be a normal subgroup of  $G_1$  and  $H_2$  a normal subgroup of  $G_2$ . Then  $H_1 \times H_2$  is a normal subgroup of  $G_1 \times G_2$ , and

$$\frac{G_1 \times G_2}{H_1 \times H_2} \cong \frac{G_1}{H_1} \times \frac{G_2}{H_2}.$$

PROOF:  $\pi \times \pi : G_1 \times G_2 \twoheadrightarrow G_1/H_1 \times G_2/H_2$  is a surjective homomorphism with kernel  $H_1 \times H_2$ .  $\square$

**Example 7.53.**

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

PROOF: Map a real number  $r$  to  $(\cos r, \sin r)$ . The result is a surjective group homomorphism with kernel  $\mathbb{Z}$ .  $\square$

**Proposition 7.54.** *Let  $H$  be a normal subgroup of a group  $G$ . For every subgroup  $K$  of  $G$  that includes  $H$ , we have  $H$  is a normal subgroup of  $K$ , and  $K/H$  is a subgroup of  $G/H$ . The mapping*

$$u : \{\text{subgroups of } G \text{ including } H\} \rightarrow \{\text{subgroups of } G/H\}$$

*with  $u(K) = K/H$  is a poset isomorphism.*

PROOF:

- $\langle 1 \rangle 1$ . If  $K$  is a subgroup of  $G$  that includes  $H$  then  $H$  is normal in  $K$ .
- $\langle 1 \rangle 2$ . If  $K$  is a subgroup of  $G$  that includes  $H$  then  $K/H$  is a subgroup of  $G/H$ .
- $\langle 1 \rangle 3$ . If  $H \subseteq K_1 \subseteq K_2$  then  $K_1/H \subseteq K_2/H$ .
- $\langle 1 \rangle 4$ . If  $K_1/H = K_2/H$  then  $K_1 = K_2$ 
  - $\langle 2 \rangle 1$ . ASSUME:  $K_1/H = K_2/H$
  - $\langle 2 \rangle 2$ .  $K_1 \subseteq K_2$ 
    - $\langle 3 \rangle 1$ . LET:  $k \in K_1$
    - $\langle 3 \rangle 2$ .  $kH \in K_2/H$
    - $\langle 3 \rangle 3$ . PICK  $k' \in K_2$  such that  $kH = k'H$
    - $\langle 3 \rangle 4$ .  $kk'^{-1} \in H$
    - $\langle 3 \rangle 5$ .  $kk'^{-1} \in K_2$
    - $\langle 3 \rangle 6$ .  $k \in K_2$
  - $\langle 2 \rangle 3$ .  $K_2 \subseteq K_1$

PROOF: Similar.

- $\langle 1 \rangle 5$ . For any subgroup  $L$  of  $G/H$ , there exists a subgroup  $K$  of  $G$  that includes  $H$  such that  $L = K/H$ .
  - $\langle 2 \rangle 1$ . LET:  $L$  be a subgroup of  $G/H$ .
  - $\langle 2 \rangle 2$ . LET:  $K = \{k \in G : kH \in L\}$
  - $\langle 2 \rangle 3$ .  $K$  is a subgroup of  $G$ .
 

PROOF: Given  $k, k' \in K$  we have  $kH, k'H \in L$  hence  $kk'^{-1}H \in L$  and so  $kk'^{-1} \in K$ .
  - $\langle 2 \rangle 4$ .  $H \subseteq K$ 

PROOF: For all  $h \in H$  we have  $hH = H \in L$ .
  - $\langle 2 \rangle 5$ .  $L = K/H$ 

PROOF: By definition.

$\square$

**Proposition 7.55** (Third Isomorphism Theorem). *Let  $H$  be a normal subgroup of a group  $G$ . Let  $N$  be a subgroup of  $G$  that includes  $H$ . Then  $N/H$  is normal*

in  $G/H$  if and only if  $N$  is normal in  $G$ , in which case

$$\frac{G/H}{N/H} \cong \frac{G}{N}$$

PROOF:

- ⟨1⟩1. If  $N/H$  is normal in  $G/H$  then  $N$  is normal in  $G$ .
  - ⟨2⟩1. ASSUME:  $N/H$  is normal in  $G/H$ .
  - ⟨2⟩2. LET:  $g \in G$  and  $n \in N$ .
  - ⟨2⟩3.  $gng^{-1}H \in N/H$
  - ⟨2⟩4. PICK  $n' \in N$  such that  $gng^{-1}H = n'H$
  - ⟨2⟩5.  $gng^{-1}n'^{-1} \in H$
  - ⟨2⟩6.  $gng^{-1}n'^{-1} \in N$
  - ⟨2⟩7.  $gng^{-1} \in N$
- ⟨1⟩2. If  $N$  is normal in  $G$  then  $N/H$  is normal in  $G/H$  and  $(G/H)/(N/H) \cong G/N$ .
  - ⟨2⟩1. ASSUME:  $N$  is normal in  $G$ .
  - ⟨2⟩2. LET:  $\phi : G/H \rightarrow G/N$  be the homomorphism  $\phi(gH) = gN$ 
    - ⟨3⟩1. If  $gH = g'H$  then  $gN = g'N$   
 PROOF: If  $gg'^{-1} \in H$  then  $gg'^{-1} \in N$ .
    - ⟨3⟩2.  $\phi((gH)(g'H)) = \phi(gH)\phi(g'H)$   
 PROOF: Both are  $gg'N$ .
  - ⟨2⟩3.  $\phi$  is surjective.
  - ⟨2⟩4.  $\ker \phi = N/H$
  - ⟨2⟩5.  $(G/H)/(N/H) \cong G/N$   
 PROOF: By the First Isomorphism Theorem.

□

**Proposition 7.56** (Second Isomorphism Theorem). *Let  $H$  and  $K$  be subgroups of a group  $G$ . Assume that  $H$  is normal in  $G$ . Then:*

1.  $HK$  is a subgroup of  $G$ , and  $H$  is normal in  $HK$ .
2.  $H \cap K$  is normal in  $K$ , and

$$\frac{HK}{H} \cong \frac{K}{H \cap K}.$$

PROOF:

- ⟨1⟩1.  $HK$  is a subgroup of  $G$ .  
 PROOF: Since  $hkh'k' = hh'(h'^{-1}kh')k' \in HK$ .
- ⟨1⟩2.  $H$  is normal in  $HK$ .
- ⟨1⟩3.  $H \cap K$  is normal in  $K$  and  $HK/H \cong K/(H \cap K)$   
 PROOF: The function that maps  $k$  to  $kH$  is a surjective homomorphism  $K \twoheadrightarrow HK/H$  with kernel  $H \cap K$ . Surjectivity follows because  $hkh = hkh^{-1}H$ .

□

See also Proposition 7.71 for a result that holds even if  $H$  is not normal.

## 7.8 Cosets

**Proposition 7.57.** *Let  $G$  be a group. Let  $\sim$  be an equivalence relation on  $G$  such that, for all  $a, b, g \in G$ , if  $a \sim b$  then  $ga \sim gb$ . Let  $H = \{h \in G : h \sim e\}$ . Then  $H$  is a subgroup of  $G$  and, for all  $a, b \in G$ , we have*

$$a \sim b \Leftrightarrow a^{-1}b \in H \Leftrightarrow aH = bH .$$

PROOF:

$\langle 1 \rangle 1.$   $e \in H$

$\langle 1 \rangle 2.$  For all  $x, y \in H$  we have  $xy^{-1} \in H$ .

$\langle 2 \rangle 1.$  ASSUME:  $x \sim e$  and  $y \sim e$ .

$\langle 2 \rangle 2.$   $e \sim y^{-1}$

PROOF: Since  $yy^{-1} \sim ey^{-1}$ .

$\langle 2 \rangle 3.$   $xy^{-1} \sim e$

PROOF: Since  $xy^{-1} \sim ey^{-1} \sim e$ .

$\langle 1 \rangle 3.$  If  $a \sim b$  then  $a^{-1}b \in H$ .

PROOF: If  $a \sim b$  then  $a^{-1}b \sim a^{-1}a = e$ .

$\langle 1 \rangle 4.$  If  $a^{-1}b \in H$  then  $aH = bH$ .

$\langle 2 \rangle 1.$  ASSUME:  $a^{-1}b \in H$

$\langle 2 \rangle 2.$   $bH \subseteq aH$

PROOF: For any  $h \in H$  we have  $bh = aa^{-1}bh \in aH$ .

$\langle 2 \rangle 3.$   $aH \subseteq bH$

PROOF: Similar since  $b^{-1}a \in H$ .

$\langle 1 \rangle 5.$  If  $aH = bH$  then  $a \sim b$ .

$\langle 2 \rangle 1.$  ASSUME:  $aH = bH$

$\langle 2 \rangle 2.$  PICK  $h \in H$  such that  $a = bh$ .

$\langle 2 \rangle 3.$   $b^{-1}a = h$

$\langle 2 \rangle 4.$   $b^{-1}a \in H$

$\langle 2 \rangle 5.$   $b^{-1}a \sim e$

$\langle 2 \rangle 6.$   $a \sim b$

PROOF:  $a = bb^{-1}a \sim be = b$ .

□

**Definition 7.58** (Coset). Let  $G$  be a group and  $H$  a subgroup of  $G$ . A *left coset* of  $H$  is a set of the form  $aH$  for  $a \in G$ . A *right coset* of  $H$  is a set of the form  $Ha$  for some  $a \in G$ .

We write  $G/H$  for the set of all left cosets of  $H$ , and  $G \backslash H$  for the set of all right cosets of  $H$ .

**Proposition 7.59.**

$$G/H \cong G \backslash H$$

PROOF: The function that maps  $aH$  to  $Ha^{-1}$  is a bijection. □

**Proposition 7.60.** *Let  $G$  be a group and  $H$  a subgroup of  $G$ . Define  $\sim_H$  on  $G$  by:  $a \sim b$  iff  $a^{-1}b \in H$ . This defines a one-to-one correspondence between the subgroups of  $G$  and the equivalence relations  $\sim$  on  $G$  such that, for all  $a, b, g \in G$ , if  $a \sim b$ , then  $ga \sim gb$ . The equivalence class of  $a$  is  $aH$ .*

PROOF:

$\langle 1 \rangle 1$ . For any subgroup  $H$ , we have  $\sim_H$  is an equivalence relation on  $G$ .

$\langle 2 \rangle 1$ .  $\sim$  is reflexive.

PROOF: For any  $a \in G$  we have  $a^{-1}a = e \in H$ .

$\langle 2 \rangle 2$ .  $\sim$  is symmetric.

PROOF: If  $a^{-1}b \in H$  then  $b^{-1}a \in H$ .

$\langle 2 \rangle 3$ .  $\sim$  is transitive.

PROOF: If  $a^{-1}b \in H$  and  $b^{-1}c \in H$  then  $a^{-1}c = (a^{-1}b)(b^{-1}c) \in H$ .

$\langle 1 \rangle 2$ . If  $a \sim_H b$  then  $ga \sim_H gb$ .

PROOF: If  $a^{-1}b \in H$  then  $(ga)^{-1}(gb) = a^{-1}g^{-1}gb = a^{-1}b \in H$ .

$\langle 1 \rangle 3$ . For any equivalence relation  $\sim$  on  $G$  such that, whenever  $a \sim b$ , then  $ga \sim gb$ , there exists a subgroup  $H$  such that  $\sim = \sim_H$ .

PROOF: Proposition 7.57.

$\langle 1 \rangle 4$ . The  $\sim_H$ -equivalence class of  $a$  is  $aH$ .

PROOF:

$$\begin{aligned} a \sim b &\Leftrightarrow a^{-1}b \in H \\ &\Leftrightarrow \exists h \in H. a^{-1}b = h \\ &\Leftrightarrow \exists h \in H. b = aH \\ &\Leftrightarrow b \in aH \end{aligned}$$

□

**Proposition 7.61.** Let  $G$  be a group and  $H$  a subgroup of  $G$ . Define  $\sim_H$  on  $G$  by:  $a \sim b$  iff  $ab^{-1} \in H$ . This defines a one-to-one correspondence between the subgroups of  $G$  and the equivalence relations  $\sim$  on  $G$  such that, for all  $a, b, g \in G$ , if  $a \sim b$ , then  $ag \sim bg$ . The equivalence class of  $a$  is  $Ha$ .

PROOF: Similar. □

**Proposition 7.62.** Let  $G$  be a group and  $H$  be a subgroup of  $G$ . Define  $\sim_L$  and  $\sim_R$  on  $G$  by:

$$a \sim_L b \Leftrightarrow a^{-1}b \in H, \quad a \sim_R b \Leftrightarrow ab^{-1} \in H.$$

Then  $\sim_L = \sim_R$  if and only if  $H$  is normal.

PROOF:

$\langle 1 \rangle 1$ . If  $\sim_L = \sim_R$  then  $H$  is normal.

$\langle 2 \rangle 1$ . ASSUME:  $\sim_L = \sim_R$

$\langle 2 \rangle 2$ . LET:  $h \in H$  and  $g \in G$

$\langle 2 \rangle 3$ .  $g \sim_L gh^{-1}$

$\langle 2 \rangle 4$ .  $g \sim_R gh^{-1}h$

$\langle 2 \rangle 5$ .  $ghg^{-1} \in H$

$\langle 1 \rangle 2$ . If  $H$  is normal then  $\sim_L = \sim_R$ .

$\langle 2 \rangle 1$ . ASSUME:  $H$  is normal.

$\langle 2 \rangle 2$ . If  $a \sim_L b$  then  $a \sim_R b$ .

$\langle 3 \rangle 1$ . ASSUME:  $a \sim_L b$

$\langle 3 \rangle 2$ .  $a^{-1}b \in H$



- $\langle 3 \rangle 3. aa^{-1}ba^{-1} \in H$   
 $\langle 3 \rangle 4. ba^{-1} \in H$   
 $\langle 3 \rangle 5. a \sim_R b$   
 $\langle 2 \rangle 3. \text{ If } a \sim_R b \text{ then } a \sim_L b.$   
 PROOF: Similar.

□

**Corollary 7.62.1.** *Let  $G$  be a group and  $H$  be a normal subgroup of  $G$ . Define  $\sim$  on  $G$  by  $a \sim b$  iff  $a^{-1}b \in H$ . Then  $G/\sim$  is a group under  $[a][b] = [ab]$ .*

**Definition 7.63** (Quotient Group). Let  $G$  be a group and  $H$  be a normal subgroup of  $G$ . The *quotient group*  $G/H$  is  $G/\sim$  where  $a \sim b$  iff  $a^{-1}b \in H$ , under  $[a][b] = [ab]$  or  $(aH)(bH) = abH$ .

**Corollary 7.63.1.** *Let  $H$  be a normal subgroup of a group  $G$ . For every group homomorphism  $\phi : G \rightarrow G'$  such that  $H \subseteq \ker \phi$ , there exists a unique group homomorphism  $\bar{\phi} : G/H \rightarrow G'$  such that the following diagram commutes.*

$$\begin{array}{ccc}
 G & \xrightarrow{\phi} & G' \\
 \searrow \pi & & \nearrow \bar{\phi} \\
 & G/H &
 \end{array}$$

**Proposition 7.64.**  $\mathbb{Z}/n\mathbb{Z}$  has exactly  $n$  elements.

PROOF: Every integer is congruent to one of  $0, 1, \dots, n-1$  by the division algorithm, and no two of them are congruent to one another, since if  $0 \leq i < j < n$  then  $0 < j-i < n$ . □

**Proposition 7.65.** *Let  $m$  and  $n$  be integers with  $n > 0$ . The order of  $m$  in  $\mathbb{Z}/n\mathbb{Z}$  is  $\frac{n}{\gcd(m,n)}$ .*

PROOF: By Proposition 6.16 since the order of 1 is  $n$ . □

**Proposition 7.66.** *The integer  $m$  generates  $\mathbb{Z}/n\mathbb{Z}$  if and only if  $\gcd(m, n) = 1$ .*

PROOF: By Proposition 7.65. □

**Corollary 7.66.1.** *If  $p$  is prime then every non-zero element in  $\mathbb{Z}/p\mathbb{Z}$  is a generator.*

**Proposition 7.67.**

$$\text{Aut}_{\mathbf{Grp}}(\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}) \cong S_3$$

PROOF: Every permutation of  $\{(1, 0), (0, 1), (1, 1)\}$  gives an automorphism of  $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ . □

**Example 7.68.** Not all monomorphisms split in  $\mathbf{Grp}$ .

Define  $\phi : \mathbb{Z}/3\mathbb{Z} \rightarrow S_3$  by

$$\phi(0) = \text{id}_3, \quad \phi(1) = (1 \ 3 \ 2), \quad \phi(2) = (1 \ 2 \ 3) .$$

Then  $\phi$  is monic but has no retraction.

For if  $r : S_3 \rightarrow \mathbb{Z}/3\mathbb{Z}$  is a retraction, then we would have

$$r(1\ 2) + r(2\ 3) = 1, \quad r(2\ 3) + r(1\ 2) = 2$$

which is impossible.

**Proposition 7.69.** *Let  $G$  be a group,  $H$  a subgroup of  $G$ , and  $g \in G$ . The function that maps  $h$  to  $gh$  is a bijection  $H \cong gH$ .*

PROOF: By Cancellation.  $\square$

**Proposition 7.70.** *Let  $G$  be a group,  $H$  a subgroup of  $G$ , and  $g \in G$ . The function that maps  $h$  to  $hg$  is a bijection  $H \cong Hg$ .*

PROOF: By Cancellation.  $\square$

**Proposition 7.71.** *Let  $H$  and  $K$  be finite subgroups of a group  $G$ . Then*

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $f : \{hK : h \in H\} \rightarrow H/(H \cap K)$  be the function  $f(hK) = h(H \cap K)$

PROOF: This is well-defined because if  $hK = h'K$  then  $h^{-1}h' \in H \cap K$  so  $h(H \cap K) = h'(H \cap K)$ .

$\langle 1 \rangle 2$ .  $f$  is injective.

PROOF: If  $h(H \cap K) = h'(H \cap K)$  then  $hK = h'K$ .

$\langle 1 \rangle 3$ .  $f$  is surjective.

PROOF: Clear.

$\langle 1 \rangle 4$ .

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

$\square$

## 7.9 Congruence

**Definition 7.72** (Congruence). Given integers  $a, b, n$  with  $n$  positive, we say  $a$  is congruent to  $b$  modulo  $n$ , and write  $a \equiv b \pmod{n}$ , iff  $a + n\mathbb{Z} = b + n\mathbb{Z}$  in  $\mathbb{Z}/n\mathbb{Z}$ .

**Proposition 7.73.** *Given integers  $a, b, n$  with  $n$  positive, we have  $a \equiv b \pmod{n}$  iff  $n \mid a - b$ .*

PROOF: By Proposition 7.57.  $\square$

**Proposition 7.74.** *If  $a \equiv a' \pmod{n}$  and  $b \equiv b' \pmod{n}$  then  $a + b \equiv a' + b' \pmod{n}$ .*

PROOF: If  $n \mid a' - a$  and  $n \mid b' - b$  then  $n \mid (a' + b') - (a + b)$ .  $\square$

**Proposition 7.75.** *If  $a \equiv a' \pmod{n}$  and  $b \equiv b' \pmod{n}$  then  $ab \equiv a'b' \pmod{n}$ .*

PROOF: If  $n \mid a' - a$  and  $n \mid b' - b$  then  $n \mid a'b' - ab = a'(b' - b) + (a' - a)b$ .  $\square$

## 7.10 Cyclic Groups

**Definition 7.76** (Cyclic Group). The *cyclic* groups are  $\mathbb{Z}$  and  $\mathbb{Z}/n\mathbb{Z}$  for positive integers  $n$ .

**Proposition 7.77.** *If  $m$  and  $n$  are positive integers with  $\gcd(m, n) = 1$  then  $C_{mn} \cong C_m \times C_n$ .*

PROOF: The function that maps  $x$  to  $(x \bmod m, x \bmod n)$  is an isomorphism.  $\square$

**Proposition 7.78.** *Let  $G$  be a group and  $g \in G$ . Then  $\langle g \rangle$  is cyclic.*

PROOF: If  $g$  has finite order then  $\langle g \rangle \cong C_{|g|}$ , otherwise  $\langle g \rangle \cong \mathbb{Z}$ .  $\square$

**Proposition 7.79.** *Every finitely generated subgroup of  $\mathbb{Q}$  is cyclic.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $G = \langle a_1/b, \dots, a_n/b \rangle$  where  $a_1, \dots, a_n, b$  are integers with  $b > 0$

$\langle 1 \rangle 2$ . LET:  $a = \gcd(a_1, \dots, a_n)$

$\langle 1 \rangle 3$ .  $G = \langle a/b \rangle$

$\square$

**Corollary 7.79.1.**  $\mathbb{Q}$  is not finitely generated.

## 7.11 Commutator Subgroup

**Definition 7.80** (Commutator). Let  $G$  be a group and  $g, h \in G$ . The *commutator* of  $g$  and  $h$  is

$$[g, h] = ghg^{-1}h^{-1}.$$

**Definition 7.81** (Commutator Subgroup). Let  $G$  be a group. The *commutator subgroup*, denoted  $[G, G]$  or  $G'$ , is the subgroup generated by the elements of the form  $aba^{-1}b^{-1}$ .

We write  $G^{(i)}$  for the result of taking the commutator subgroup  $i$  times starting with  $G$ .

**Lemma 7.82.** *Let  $\phi : G_1 \rightarrow G_2$  be a group homomorphism. Then, for all  $g, h \in G_1$ , we have*

$$\phi([g, h]) = [\phi(g), \phi(h)]$$

and so  $\phi(G_1') \subseteq G_2'$ .

PROOF: Easy.  $\square$

## 7.12 Presentations

**Definition 7.83** (Presentation). A *presentation* of a group  $G$  is a pair  $(A, R)$  where  $A$  is a set and  $R \subseteq F(A)$  is a set of words such that

$$G \cong F(A)/N(R)$$

where  $N(R)$  is the smallest normal subgroup of  $F(A)$  that includes  $R$ .

**Example 7.84.** • The free group on a set  $A$  is presented by  $(A, \emptyset)$ .

- $S_3$  is presented by  $(x, y | x^2, y^3, xyxy)$ .
- $(a, b | a^2, b^2, (ab)^n)$  is a presentation of  $D_{2n}$ .
- $(x, y | x^2y^{-2}, y^4, xyx^{-1}y)$  is a presentation of  $Q_8$ .

**Proposition 7.85** (Word Problem). *Let  $(A, R)$  be a presentation of the group  $G$ . Let  $w_1, w_2 \in F(A)$  be two words. Then it is undecidable in general if  $w_1N(R) = w_2N(R)$  in  $G$ .*

**Definition 7.86** (Finitely Presented). A group is *finitely presented* iff it has a presentation  $(A, R)$  where both  $A$  and  $R$  are finite.

**Proposition 7.87.** *Let  $(A|R)$  be a presentation of  $G$  and  $(A'|R')$  a presentation of  $H$ . Assume w.l.o.g.  $A$  and  $A'$  are disjoint. Then the group  $G * G'$  presented by  $(A \cup A' | R \cup R')$  is the coproduct of  $G$  and  $G'$  in **Grp**.*

$$\begin{array}{ccccc}
 A & \longrightarrow & A \cup A' & \longleftarrow & A' \\
 \downarrow & & \downarrow & & \downarrow \\
 F(A) & \longrightarrow & F(A \cup A') & \longleftarrow & F(A') \\
 \downarrow & & \downarrow & & \downarrow \\
 G & \xrightarrow{\kappa_1} & G * G' & \xleftarrow{\kappa_2} & G'
 \end{array}$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $\kappa_1 : G \rightarrow G * G'$  and  $\kappa_2 : G' \rightarrow G * G'$  be the unique homomorphisms that make the diagram above commute.

$\langle 1 \rangle 2$ . LET:  $\phi : G \rightarrow H$  and  $\psi : G' \rightarrow H$  be any homomorphisms.

$\langle 1 \rangle 3$ . LET:  $[\phi, \psi] : F(A \cup A') \rightarrow H$  be the unique homomorphism such that ...

$\langle 1 \rangle 4$ .  $R \cup R' \subseteq \ker[\phi, \psi]$

$\langle 1 \rangle 5$ .  $[\phi, \psi]$  factors uniquely through the morphism  $F(A \cup A') \rightarrow G * G'$

□

## 7.13 Index of a Subgroup

**Definition 7.88** (Index). Let  $G$  be a group and  $H$  a subgroup of  $G$ . The *index* of  $H$  in  $G$ , denoted  $|G : H|$ , is the number of left cosets of  $H$  in  $G$  if this is finite, otherwise  $\infty$ .

**Theorem 7.89** (Lagrange's Theorem). *Let  $G$  be a finite group and  $H$  a subgroup of  $G$ . Then*

$$|G| = |G : H| |H| .$$

PROOF:  $G/H$  is a partition of  $G$  into  $|G : H|$  subsets, each of size  $|H|$ . □

**Corollary 7.89.1.** *For  $p$  a prime number, the only group of order  $p$  is  $C_p$ .*

PROOF: Let  $G$  be a group of order  $p$  and  $g \in G$  with  $g \neq e$ . Then  $|\langle g \rangle|$  divides  $p$  and is not 1, hence is  $p$ , that is,  $G = \langle g \rangle$ .  $\square$

**Theorem 7.90** (Cauchy's Theorem). *Let  $G$  be a finite group. If  $p$  is prime and  $p \mid |G|$  then the number of cyclic subgroups of order  $p$  is congruent to 1 modulo  $p$ . In particular, there exists an element of order  $p$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $S = \{(a_1, a_2, \dots, a_p) \in G^p : a_1 a_2 \cdots a_p = e\}$

$\langle 1 \rangle 2$ .  $|S| = |G|^{p-1}$

PROOF: Given any  $a_1, \dots, a_{p-1} \in G$ , there exists a unique  $a_p$  such that  $(a_1, \dots, a_p) \in S$ , namely  $a_p = (a_1 \cdots a_{p-1})^{-1}$ .

$\langle 1 \rangle 3$ .  $p \mid |S|$

$\langle 1 \rangle 4$ . Define an action of  $\mathbb{Z}/p\mathbb{Z}$  on  $S$  by

$$m \cdot (a_1, \dots, a_p) = (a_m, a_{m+1}, \dots, a_p, a_1, a_2, \dots, a_{m-1}) .$$

PROOF: If  $(a_1, \dots, a_p) \in S$  then  $(a_2, a_3, \dots, a_p, a_1) \in S$  since  $a_1 = (a_2 \cdots a_p)^{-1}$ .

$\langle 1 \rangle 5$ . LET:  $Z$  be the set of fixed points of this action.

$\langle 1 \rangle 6$ .  $|Z| \equiv 0 \pmod{p}$

PROOF: Corollary 9.18.1,  $\langle 1 \rangle 3$ .

$\langle 1 \rangle 7$ .  $Z = \{(a, a, \dots, a) : a^p = e\}$

$\langle 1 \rangle 8$ .  $Z \neq \emptyset$

PROOF: Since  $(e, e, \dots, e) \in Z$ .

$\langle 1 \rangle 9$ . An element  $a$  has order  $p$  iff  $(a, a, \dots, a) \in Z$  and  $a \neq e$ .

$\langle 1 \rangle 10$ . LET:  $N$  be the number of cyclic subgroups of order  $p$ .

$\langle 1 \rangle 11$ . The number of elements of order  $p$  is  $N(p-1)$

$\langle 1 \rangle 12$ .  $|Z| = N(p-1) + 1$

$\langle 1 \rangle 13$ .  $-N + 1 \equiv 0 \pmod{p}$

PROOF: From  $\langle 1 \rangle 6$ .

$\langle 1 \rangle 14$ .  $N \equiv 1 \pmod{p}$

$\square$

**Proposition 7.91.** *Let  $G$  be a group. Let  $K$  be a subgroup of  $G$  and  $H$  a subgroup of  $K$ . If  $|G : H|$ ,  $|G : K|$  and  $|K : H|$  are all finite then*

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $G/K = \{g_1 K, g_2 K, \dots, g_m K\}$

$\langle 1 \rangle 2$ . LET:  $K/H = \{k_1 H, k_2 H, \dots, k_n H\}$

$\langle 1 \rangle 3$ .  $G/H = \{g_i k_j H : 1 \leq i \leq m, 1 \leq j \leq n\}$

$\langle 2 \rangle 1$ . LET:  $g \in G$

$\langle 2 \rangle 2$ . PICK  $i$  such that  $gK = g_i K$

$\langle 2 \rangle 3$ .  $g^{-1} g_i \in K$

$\langle 2 \rangle 4$ . PICK  $j$  such that  $g^{-1} g_i H = k_j H$

$\langle 2 \rangle 5$ .  $g^{-1} g_i k_j \in H$

$\langle 2 \rangle 6$ .  $gH = g_i k_j H$

$\langle 1 \rangle 4$ . If  $g_i k_j H = g_{i'} k_{j'} H$  then  $i = i'$  and  $j = j'$ .

- $\langle 2 \rangle 1.$  ASSUME:  $g_i k_j H = g_{i'} k_{j'} H$
- $\langle 2 \rangle 2.$   $g_i K = g_{i'} K$
- $\langle 2 \rangle 3.$   $i = i'$
- $\langle 2 \rangle 4.$   $k_j H = k_{j'} H$
- $\langle 2 \rangle 5.$   $j = j'$

□

## 7.14 Cokernels

**Proposition 7.92.** *Let  $\phi : G \rightarrow H$  be a homomorphism between groups. Then there exists a group  $K$  and homomorphism  $\pi : H \rightarrow K$  that is initial with respect to all homomorphism  $\alpha : H \rightarrow L$  such that  $\alpha \circ \phi = 0$ .*

PROOF:

- $\langle 1 \rangle 1.$  LET:  $N$  be the intersection of all the normal subgroups of  $H$  that include  $\text{im } \phi$ .
- $\langle 1 \rangle 2.$  LET:  $K = H/N$  and  $\pi$  be the canonical homomorphism.
- $\langle 1 \rangle 3.$  LET:  $\pi \circ \phi = 0$
- $\langle 1 \rangle 4.$  LET:  $\alpha : H \rightarrow L$  satisfy  $\alpha \circ \phi = 0$
- $\langle 1 \rangle 5.$   $\text{im } \phi \subseteq \ker \alpha$
- $\langle 1 \rangle 6.$   $N \subseteq \ker \alpha$
- $\langle 1 \rangle 7.$  There exists a unique  $\bar{\alpha} : H/\text{im } \phi \rightarrow L$  such that  $\bar{\alpha} \circ \pi = \alpha$

□

**Definition 7.93** (Cokernel). For any homomorphism  $\phi : G \rightarrow H$  in **Grp**, the *cokernel* of  $\phi$  is the group  $\text{coker } \phi$  and homomorphism  $\pi : H \rightarrow \text{coker } \phi$  that is initial among homomorphisms  $\alpha : H \rightarrow L$  such that  $\alpha \circ \phi = 0$ .

**Example 7.94.** It is not true that a homomorphism with trivial cokernel is epi. The inclusion  $\langle (1 \ 2) \rangle \hookrightarrow S_3$  has trivial cokernel but is not epi.

## 7.15 Cayley Graphs

**Definition 7.95** (Cayley Graph). Let  $G$  be a finitely generated group. Let  $A$  be a finite set of generators for  $G$ . The *Cayley graph* of  $G$  with respect to  $A$  is the directed graph whose vertices are the elements of  $G$ , with an edge  $g_1 \rightarrow g_2$  labelled by  $a \in A$  iff  $g_2 = g_1 a$ .

**Proposition 7.96.**  *$G$  is the free group on  $A$  iff the Cayley graph with respect to  $A$  is a tree.*

PROOF: Both are equivalent to saying that the product of two different strings of elements of  $A$  and/or their inverses are not equal. □

## 7.16 Characteristic Subgroups

**Definition 7.97** (Characteristic Subgroup). Let  $G$  be a group. Let  $H$  be a subgroup of  $G$ . Then  $H$  is a *characteristic* subgroup of  $G$  iff, for every automorphism  $\phi$  of  $G$ , we have  $\phi(H) \subseteq H$ .

**Proposition 7.98.** *Characteristic subgroups are normal.*

PROOF: Take  $\phi$  to be conjugation with respect to an arbitrary element.  $\square$

**Proposition 7.99.** *Let  $G$  be a group. Let  $K$  be a normal subgroup of  $G$  and  $H$  a characteristic subgroup of  $K$ . Then  $H$  is normal in  $G$ .*

PROOF: For any  $a \in G$  we have conjugation by  $a$  is an automorphism on  $K$ , hence  $H$  is closed under it.  $\square$

**Proposition 7.100.** *Let  $G$  be a group. Let  $H$  be a subgroup of  $G$ . Suppose there is no other subgroup of  $G$  isomorphic to  $H$ . Then  $H$  is characteristic, hence normal.*

PROOF: For any automorphism  $\phi$  on  $G$ , we have  $\phi(H)$  is isomorphic to  $H$ , hence  $\phi(H) = H$ .  $\square$

**Proposition 7.101.** *Let  $G$  be a finite group. Let  $K$  be a normal subgroup of  $G$ . Assume  $|K|$  and  $|G/K|$  are relatively prime. Then  $K$  is characteristic.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $K'$  be a subgroup of  $G$  isomorphic to  $K$ .

PROVE:  $K' = K$

$\langle 1 \rangle 2$ .  $|K'/(K \cap K')|$  divides both  $|K'| = |K|$  and  $|G/K|$

$\langle 1 \rangle 3$ .  $|K'/(K \cap K')| = 1$

$\langle 1 \rangle 4$ .  $K' = K \cap K'$

$\langle 1 \rangle 5$ .  $K' = K$

$\square$

**Proposition 7.102.** *The commutator subgroup of a group is characteristic.*

PROOF: Lemma 7.82.  $\square$

## 7.17 Simple Groups

**Definition 7.103** (Simple Group). A group  $G$  is *simple* iff its only normal subgroups are  $\{e\}$  and  $G$ .

**Proposition 7.104.** *Let  $G$  be a group. Then  $G$  is simple if and only if the only homomorphic images of  $G$  are 1 and  $G$ .*

PROOF: Both are equivalent to saying that, for any surjective homomorphism  $\phi : G \rightarrow G'$ , either  $\phi$  has kernel  $\{e\}$  (in which case it is an isomorphism) or  $\phi$  has kernel  $G$  (in which case  $G' = 1$ .)  $\square$

## 7.18 Sylow Subgroups

**Definition 7.105** (Sylow Subgroup). Let  $p$  be a prime number. Let  $G$  be a finite group. A  $p$ -Sylow subgroup of  $G$  is a subgroup of order  $p^r$ , where  $r$  is the largest integer such that  $p^r$  divides  $|G|$ .

**Proposition 7.106.** Let  $p$  be prime. Let  $G$  be a finite group. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . If  $P$  is normal then  $P$  is characteristic.

PROOF: Proposition 7.101.  $\square$

**Corollary 7.106.1.** Let  $p$  be prime. Let  $G$  be a finite group. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . Let  $H$  be a subgroup of  $G$  that includes  $P$ . If  $P$  is normal in  $H$  and  $H$  is normal in  $G$  then  $P$  is normal in  $G$ .

## 7.19 Series of Subgroups

**Definition 7.107** (Series of Subgroups). Let  $G$  be a group. A *series* of subgroups of  $G$  is a sequence  $(G_n)$  of subgroups of  $G$  such that

$$G = G_0 \supsetneq G_1 \supsetneq G_2 \supsetneq \cdots$$

It is a *normal series* iff  $G_{n+1}$  is normal in  $G_n$  for all  $n$ .

**Proposition 7.108.** The maximal length of a normal series in  $G$  is 0 iff  $G$  is trivial.

PROOF: Since 1 is normal in  $G$  for every  $G$ .  $\square$

**Proposition 7.109.** The maximal length of a normal series in  $G$  is 1 iff  $G$  is non-trivial and simple.

PROOF: Immediate from definitions.  $\square$

**Example 7.110.**  $\mathbb{Z}$  has normal series of arbitrary length.

PROOF: We have  $\mathbb{Z} \supsetneq 2\mathbb{Z} \supsetneq 4\mathbb{Z} \supsetneq \cdots$ .  $\square$

**Example 7.111.** The maximal length of a normal series in  $\mathbb{Z}/n\mathbb{Z}$  is the number of primes in the prime factorization of  $n$ .

PROOF: Let  $n = p_1 p_2 \cdots p_k$ . A normal series of maximal length is  $\mathbb{Z}/p_1 p_2 \cdots p_k \mathbb{Z} \supsetneq \mathbb{Z}/p_1 p_2 \cdots p_{k-1} \mathbb{Z} \supsetneq \cdots \supsetneq \mathbb{Z}/p_1 \mathbb{Z} \supsetneq \{e\}$ .  $\square$

**Definition 7.112** (Equivalent Normal Series). Let

$$\begin{aligned} G &= G_0 \supsetneq G_1 \supsetneq G_2 \supsetneq \cdots \supsetneq G_n = \{e\} \\ G &= G'_0 \supsetneq G'_1 \supsetneq G'_2 \supsetneq \cdots \supsetneq G'_m = \{e\} \end{aligned}$$

be two normal series in a group  $G$ . Then the two series are *equivalent* iff  $m = n$  and there exists a permutation  $\sigma \in S_n$  such that, for all  $i$ , we have  $G_i/G_{i+1} \cong G'_{\sigma(i)}/G'_{\sigma(i)+1}$ .



**Definition 7.113** (Composition Series). Let  $G$  be a group. A *composition series* for  $G$  is a series of subgroups in  $G$

$$G = G_0 \supsetneq G_1 \supsetneq G_2 \supsetneq \cdots \supsetneq G_n = \{e\}$$

such that, for all  $i$ , we have  $G_i/G_{i+1}$  is simple.

**Proposition 7.114.** A normal series of maximal length in a group is a composition series.

PROOF: Easy.  $\square$

**Corollary 7.114.1.** Every finite group has a composition series.

**Corollary 7.114.2.** If a group has a composition series then every normal subgroup has a composition series.

**Definition 7.115** (Refinement). A series of subgroups  $S_1$  is a *refinement* of the series  $S_2$  iff every subgroup in  $S_2$  appears in  $S_1$ .

**Lemma 7.116.** Let  $G$  be a group. Let  $Q$ ,  $N$  and  $L$  be subgroups of  $G$ . Assume  $L$  is a normal subgroup of  $Q$  and  $qN = Nq$  for all  $q \in Q$ . Then

$$\frac{QN}{LN} \cong \frac{Q}{L(Q \cap N)} .$$

PROOF:

$\langle 1 \rangle 1$ .  $QN$  is a subgroup of  $G$ .

PROOF: Since  $QN = NQ$ .

$\langle 1 \rangle 2$ .  $LN$  is a subgroup of  $G$ .

PROOF: Since  $LN = NL$ .

$\langle 1 \rangle 3$ .  $LN$  is normal in  $QN$ .

$\langle 2 \rangle 1$ . LET:  $l \in L$ ,  $q \in Q$ , and  $n, n' \in N$ .

PROVE:  $qnl n' n^{-1} q^{-1} \in LN$

$\langle 2 \rangle 2$ . PICK  $n_1 \in N$  such that  $nl = ln_1$

$\langle 2 \rangle 3$ . PICK  $n_2 \in N$  such that  $n_1 n' n^{-1} q^{-1} = q^{-1} n_2$

$\langle 2 \rangle 4$ .  $qnl n' n^{-1} q^{-1} = ql q^{-1} n_2 \in LN$

PROOF: Since  $L$  is normal in  $Q$ .

$\langle 1 \rangle 4$ . The function  $f : Q \rightarrow QN/LN$  that maps  $q$  to  $qLN$  is a surjective homomorphism.

$\langle 1 \rangle 5$ .  $\ker f = L(Q \cap N)$

$\langle 2 \rangle 1$ .  $\ker f \subseteq L(Q \cap N)$

$\langle 3 \rangle 1$ . LET:  $x \in \ker f$

$\langle 3 \rangle 2$ .  $x \in LN$

$\langle 3 \rangle 3$ . PICK  $l \in L$  and  $n \in N$  such that  $x = ln$

$\langle 3 \rangle 4$ .  $n = l^{-1}x \in Q \cap N$

$\langle 3 \rangle 5$ .  $x \in L(Q \cap N)$

$\langle 2 \rangle 2$ .  $L(Q \cap N) \subseteq \ker f$

PROOF: Since  $L(Q \cap N) \subseteq Q$  and  $L(Q \cap N) \subseteq LN$ .

⟨1⟩6. Q.E.D.

PROOF: First Isomorphism Theorem.

□

**Theorem 7.117** (Schreier). *Any two normal series in a group have equivalent refinements.*

PROOF:

⟨1⟩1. LET:  $G$  be a group.

⟨1⟩2. LET:  $S_1 : G = G_0 \supsetneq G_1 \supsetneq G_2 \supsetneq \cdots \supsetneq G_m = \{e\}$  and  $S_2 : G = H_0 \supsetneq H_1 \supsetneq H_2 \supsetneq \cdots \supsetneq H_n = \{e\}$  be two normal series in  $G$ .

⟨1⟩3. For each  $i$ , we have

$$G_i = G_i \cap H_0 \supseteq G_i \cap H_1 \supseteq \cdots \supseteq G_i \cap H_n = \{e\}$$

is a series of subgroups in  $G_i$ .

⟨1⟩4. For each  $i$ , we have

$$G_i = (G_i \cap H_0)G_{i+1} \supseteq (G_i \cap H_1)G_{i+1} \supseteq \cdots \supseteq (G_i \cap H_n)G_{i+1} = G_{i+1}$$

is a normal series in  $G_i$ .

⟨2⟩1. LET:  $0 \leq i < m$  and  $0 \leq j < n$

PROVE:  $(G_i \cap H_{j+1})G_{i+1}$  is normal in  $(G_i \cap H_j)G_{i+1}$

⟨2⟩2. LET:  $x \in G_i \cap H_{j+1}$ ,  $y \in G_{i+1}$ ,  $a \in G_i \cap H_j$  and  $b \in G_{i+1}$

PROVE:  $abxyb^{-1}a^{-1} \in (G_i \cap H_{j+1})G_{i+1}$

⟨2⟩3.  $axa^{-1} \in G_i \cap H_{j+1}$

PROOF: Since  $a, x \in G_i$  and  $H_{j+1}$  is normal in  $H_j$ .

⟨2⟩4.  $ax^{-1}bxa^{-1} \in G_{i+1}$

PROOF: Since  $G_{i+1}$  is normal in  $G_i$ .

⟨2⟩5.  $yb^{-1} \in G_{i+1}$

⟨2⟩6.  $ayb^{-1}a^{-1} \in G_{i+1}$

PROOF: Since  $G_{i+1}$  is normal in  $G_i$ .

⟨2⟩7.  $abxyb^{-1}a^{-1} = (axa^{-1})(ax^{-1}bxa^{-1}ayb^{-1}a^{-1}) \in (G_i \cap H_{j+1})G_{i+1}$

⟨1⟩5. Let  $S$  be the series obtained by concatenating the series ⟨1⟩4 for  $G_0$  to  $G_1$ ,  $G_1$  to  $G_2$ ,  $\dots$ ,  $G_{m-1}$  to  $G_m$

⟨1⟩6.  $S$  is a refinement of  $S_1$ .

⟨1⟩7.  $S$  is normal.

⟨1⟩8. LET:  $T$  be the similarly constructed normal refinement of  $S_2$ .

⟨1⟩9. For all  $i, j$  we have

$$\frac{(G_i \cap H_j)G_{i+1}}{(G_i \cap H_{j+1})G_{i+1}} \cong \frac{G_i \cap H_j}{(G_i \cap H_{j+1})(G_{i+1} \cap H_j)}$$

⟨2⟩1.  $G_i \cap H_{j+1}$  is normal in  $G_i \cap H_j$

⟨2⟩2. For all  $q \in G_i \cap H_j$  we have  $qG_{i+1} = G_{i+1}q$

PROOF: Since for all  $q \in G_i$  we have  $qG_{i+1} = G_{i+1}q$ .

⟨2⟩3. Q.E.D.

PROOF: Lemma 7.116

⟨1⟩10. For all  $i, j$  we have

$$\frac{(G_i \cap H_j)H_{j+1}}{(G_{i+1} \cap H_j)H_{j+1}} \cong \frac{G_i \cap H_j}{(G_{i+1} \cap H_j)(G_i \cap H_{j+1})}$$

PROOF: Lemma 7.116

(1)11. For all  $i, j$  we have

$$\frac{(G_i \cap H_j)G_{i+1}}{(G_i \cap H_{j+1})G_{i+1}} \cong \frac{(G_i \cap H_j)H_{j+1}}{(G_{i+1} \cap H_j)H_{j+1}}$$

(1)12.  $S$  and  $T$  are equivalent.

□

**Corollary 7.117.1** (Jordan-Hölder). *Any two composition series for a group are equivalent.*

**Definition 7.118** (Composition Factors). Let  $G$  be a group that has a composition series. The multiset of *composition factors* of  $G$  is the multiset of quotients of any composition series.

**Example 7.119.** Non-isomorphic groups can have the same composition factors. For example,  $C_2 \times C_2$  and  $C_4$  both have composition factors  $\{[C_2, C_2]\}$ .

**Proposition 7.120.** *Let  $G$  be a group. Let  $N$  be a normal subgroup of  $G$ . Then  $G$  has a composition series if and only if  $N$  and  $G/N$  both have composition series, in which case the composition factors of  $G$  are the union of the composition factors of  $N$  and the composition factors of  $G/N$ .*

PROOF:

(1)1. If  $G$  has a composition series then  $N$  and  $G/N$  have composition series.

(2)1. LET:  $G = G_0 \supsetneq G_1 \supsetneq G_2 \supsetneq \cdots \supsetneq G_n = \{e\}$  be a composition series for  $G$ .

(2)2.  $N$  has a composition series.

(3)1. For all  $i$ , we have  $\frac{G_i \cap N}{G_{i+1} \cap N}$  is either trivial or isomorphic to  $G_i/G_{i+1}$ .

(4)1. The homomorphism  $G_i \cap N \hookrightarrow G_i \twoheadrightarrow G_i/G_{i+1}$  has kernel  $G_{i+1} \cap N$ .

(4)2. There is an injective homomorphism  $(G_i \cap N)/(G_{i+1} \cap N) \rightarrow G_i/G_{i+1}$ .

PROOF: First Isomorphism Theorem.

(4)3.  $(G_i \cap N)/(G_{i+1} \cap N)$  is either trivial or isomorphic to  $G_i/G_{i+1}$ .

PROOF: Since  $G_i/G_{i+1}$  is simple.

(3)2. Eliminating all duplicates from the series  $N = G_0 \cap N \supseteq G_1 \cap N \supseteq G_2 \cap N \supseteq \cdots \supseteq G_n \cap N = \{e\}$  gives a composition series for  $N$ .

(2)3.  $G/N$  has a composition series.

(3)1. For all  $i$  we have  $\frac{(G_i N)/N}{(G_{i+1} N)/N}$  is either trivial or isomorphic to  $G_i/G_{i+1}$ .

(4)1. LET:  $0 \leq i < n$

(4)2.  $\frac{(G_i N)/N}{(G_{i+1} N)/N} \cong G_i N/G_{i+1} N$

PROOF: Third Isomorphism Theorem.

(4)3. There exists a surjective homomorphism

$$\frac{G_i}{G_{i+1}} \twoheadrightarrow \frac{G_i N}{G_{i+1} N}.$$

(5)1. LET:  $f$  be the homomorphism  $G_i \hookrightarrow G_i N \twoheadrightarrow G_i N/G_{i+1} N$

(5)2.  $f$  is surjective.

(5)3.  $f(G_{i+1}) = \{e\}$

(5)4. Q.E.D.

PROOF: By the universal property of quotient groups.

$\langle 4 \rangle 4.$   $G_i N / G_{i+1} N$  is either trivial or isomorphic to  $G_i / G_{i+1}$ .

PROOF: Proposition 7.104.

$\langle 3 \rangle 2.$  Eliminating all duplicates from the series  $G/N = G_0 N / N \supseteq G_1 N / N \supseteq G_2 N / N \supseteq \cdots \supseteq G_n N / N = \{e\}$  gives a composition series for  $G/N$ .

$\langle 1 \rangle 2.$  If  $N$  and  $G/N$  have composition series, then  $G$  has a composition series, and the composition factors of  $G$  are the union of the composition factors of  $N$  and the composition factors of  $G/N$ .

$\langle 2 \rangle 1.$  LET:  $N = N_0 \supsetneq N_1 \supsetneq N_2 \supsetneq \cdots \supsetneq N_n = \{e\}$  be a composition series for  $N$ .

$\langle 2 \rangle 2.$  LET:  $G/N = H_0 \supsetneq H_1 \supsetneq H_2 \supsetneq \cdots \supsetneq H_m = \{e\}$  be a composition series for  $G/N$ .

$\langle 2 \rangle 3.$   $G = \pi^{-1}(H_0) \supsetneq \pi^{-1}(H_1) \supsetneq \cdots \supsetneq \pi^{-1}(H_m) = N_0 \supsetneq N_1 \supsetneq N_2 \supsetneq \cdots \supsetneq N_n$  is a composition series for  $G$ .

□

**Proposition 7.121.** *Let  $G_1$  and  $G_2$  be groups. Then  $G_1 \times G_2$  has a composition series if and only if  $G_1$  and  $G_2$  both have composition series.*

PROOF:

$\langle 1 \rangle 1.$  If  $G_1 \times G_2$  has a composition series then  $G_1$  has a composition series.

$\langle 2 \rangle 1.$  LET:  $G_1 \times G_2 = A_0 \supsetneq A_1 \supsetneq \cdots \supsetneq A_n = \{e\}$  be a composition series.

$\langle 2 \rangle 2.$  For each  $i$ , we have  $\pi_1(A_i) / \pi_1(A_{i+1})$  is either isomorphic to  $A_i / A_{i+1}$  or trivial.

$\langle 2 \rangle 3.$  Eliminating duplicates from  $G_1 = \pi_1(A_0) \supseteq \pi_1(A_1) \supseteq \cdots \supseteq \pi_1(A_n) = \{e\}$  gives a composition series for  $G_1$ .

$\langle 1 \rangle 2.$  If  $G_1 \times G_2$  has a composition series then  $G_2$  has a composition series.

PROOF: Similar.

$\langle 1 \rangle 3.$  If  $G_1$  and  $G_2$  have composition series then  $G_1 \times G_2$  has a composition series.

$\langle 2 \rangle 1.$  LET:  $G_1 = H_0 \supsetneq H_1 \supsetneq \cdots \supsetneq H_m = \{e\}$  be a composition series for  $G_1$ .

$\langle 2 \rangle 2.$  LET:  $G_2 = K_0 \supsetneq K_1 \supsetneq \cdots \supsetneq K_n = \{e\}$  be a composition series for  $G_2$ .

$\langle 2 \rangle 3.$   $G_1 \times G_2 = H_0 \times K_0 \supsetneq H_1 \times K_0 \supsetneq \cdots \supsetneq H_m \times K_0 \supsetneq H_m \times K_1 \supsetneq \cdots \supsetneq H_m \times K_n = \{e\}$  is a composition series for  $G_1 \times G_2$ .

□

**Definition 7.122** (Cyclic Series). A normal series of subgroups is *cyclic* iff every quotient is cyclic.

## Chapter 8

# Abelian Groups

**Definition 8.1** (Abelian Group). A group is *Abelian* iff any two elements commute.

In an Abelian group  $G$ , we often denote the group operation by  $+$ , the identity element by  $0$  and the inverse of an element  $g$  by  $-g$ . We write  $ng$  for  $g^n$  ( $g \in G, n \in \mathbb{Z}$ ).

**Example 8.2.** Every group of order  $\leq 4$  is Abelian.

**Example 8.3.** For any positive integer  $n$ , we have  $\mathbb{Z}/n\mathbb{Z}$  is an Abelian group under addition.

**Example 8.4.**  $S_n$  is not Abelian for  $n \geq 3$ . If  $x = \begin{pmatrix} 1 & 2 \\ 1 & 3 \end{pmatrix}$  and  $y = \begin{pmatrix} 2 & 3 \\ 1 & 3 \end{pmatrix}$  then  $xy = \begin{pmatrix} 2 & 3 \\ 1 & 3 \end{pmatrix}$  and  $yx = \begin{pmatrix} 1 & 3 \\ 1 & 3 \end{pmatrix}$ .

**Example 8.5.** There are 42 Abelian groups of order 1024 up to isomorphism.

**Proposition 8.6.** Let  $G$  be a group. If  $g^2 = e$  for all  $g \in G$  then  $G$  is Abelian.

PROOF: For any  $g, h \in G$  we have

$$ghgh = e$$

$$\therefore hgh = g \quad (\text{multiplying on the left by } g)$$

$$\therefore hg = gh \quad (\text{multiplying on the right by } h) \square$$

**Proposition 8.7.** Let  $G$  be a group. Then  $G$  is Abelian if and only if the function that maps  $g$  to  $g^{-1}$  is a group homomorphism.

PROOF:

(1)1. If  $G$  is Abelian then the function that maps  $g$  to  $g^{-1}$  is a group homomorphism.

PROOF: Since  $(gh)^{-1} = h^{-1}g^{-1} = g^{-1}h^{-1}$ .

(1)2. If the function that maps  $g$  to  $g^{-1}$  is a group homomorphism then  $G$  is Abelian.

PROOF: Since  $gh = (g^{-1})^{-1}(h^{-1})^{-1} = (g^{-1}h^{-1})^{-1} = hg$ .  
 $\square$

**Proposition 8.8.** *Let  $G$  be a group. Then  $G$  is Abelian if and only if the function that maps  $g$  to  $g^2$  is a group homomorphism.*

PROOF:

$\langle 1 \rangle 1$ . If  $G$  is Abelian then the function that maps  $g$  to  $g^2$  is a group homomorphism.

PROOF: Since  $(gh)^2 = g^2h^2$ .

$\langle 1 \rangle 2$ . If the function that maps  $g$  to  $g^2$  is a group homomorphism then  $G$  is Abelian.

PROOF: Since we have  $(gh)^2 = ghgh = g^2h^2$  and so  $hg = gh$ .

$\square$

**Proposition 8.9.** *Let  $G$  be a group. Then  $G$  is Abelian if and only if the homomorphism  $\gamma : G \rightarrow \text{Aut}_{\text{Grp}}(G)$  is the trivial homomorphism.*

PROOF:

$\langle 1 \rangle 1$ . If  $G$  is Abelian then  $\gamma$  is trivial.

PROOF: Since  $\gamma_g(a) = gag^{-1} = a$ .

$\langle 1 \rangle 2$ . If  $\gamma$  is trivial then  $G$  is Abelian.

PROOF: If  $\gamma_g(a) = gag^{-1} = a$  for all  $g$  and  $a$  then  $ga = ag$  for all  $g, a$ .

$\square$

**Proposition 8.10.** *Let  $G$  be an Abelian group. Let  $g, h \in G$ . If  $g$  has maximal finite order in  $G$ , and  $h$  has finite order, then  $|h| \mid |g|$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: for a contradiction  $|h| \nmid |g|$ .

$\langle 1 \rangle 2$ . PICK a prime  $p$  such that  $|g| = p^m r$ ,  $|h| = p^n s$  where  $p \nmid r$ ,  $p \nmid s$  and  $m < n$ .

$\langle 1 \rangle 3$ .  $|g^{p^m} h^s| = p^n r$

PROOF: Proposition 6.19.

$\langle 1 \rangle 4$ .  $|g| < |g^{p^m} h^s|$

$\langle 1 \rangle 5$ . Q.E.D.

PROOF: This contradicts the maximality of  $|g|$ .

$\square$

**Proposition 8.11.** *Given a set  $A$  and an Abelian group  $H$ , the set  $H^A$  is an Abelian group under*

$$(\phi + \psi)(a) = \phi(a) + \psi(a) \quad (\phi, \psi \in H^A, a \in A) .$$

PROOF:

$\langle 1 \rangle 1$ .  $\phi + (\psi + \chi) = (\phi + \psi) + \chi$

$\langle 1 \rangle 2$ .  $\phi + \psi = \psi + \phi$

$\langle 1 \rangle 3$ . LET:  $0 : A \rightarrow H$  be the function  $0(a) = 0$ .

$\langle 1 \rangle 4$ .  $\phi + 0 = 0 + \phi = \phi$

$\langle 1 \rangle 5$ . Given  $\phi : A \rightarrow H$ , define  $-\phi : A \rightarrow H$  by  $(-\phi)(a) = -(\phi(a))$ .

$\langle 1 \rangle 6$ .  $\phi + (-\phi) = (-\phi) + \phi = 0$

□

**Proposition 8.12.** *Given a group  $G$  and an Abelian group  $H$ , the set  $\mathbf{Grp}[G, H]$  is a subgroup of  $H^G$ .*

PROOF:

$\langle 1 \rangle 1$ . Given  $\phi, \psi : G \rightarrow H$  group homomorphisms, we have  $\phi - \psi$  is a group homomorphism.

PROOF:

$$\begin{aligned} (\phi - \psi)(g + g') &= \phi(g + g') - \psi(g + g') \\ &= \phi(g) + \phi(g') - \psi(g) - \psi(g') \\ &= \phi(g) - \psi(g) + \phi(g') - \psi(g') \\ &= (\phi - \psi)(g) + (\phi - \psi)(g') \end{aligned}$$

□

**Proposition 8.13.** *Let  $G$  be a group. The following are equivalent.*

1.  $\text{Inn}(G)$  is cyclic.
2.  $\text{Inn}(G)$  is trivial.
3.  $G$  is Abelian.

PROOF:

$\langle 1 \rangle 1$ .  $1 \Rightarrow 2$

$\langle 2 \rangle 1$ . ASSUME:  $\text{Inn}(G) = \langle \gamma_g \rangle$

$\langle 2 \rangle 2$ .  $g$  commutes with every element of  $G$

$\langle 3 \rangle 1$ . LET:  $x \in G$

$\langle 3 \rangle 2$ . PICK  $n \in \mathbb{Z}$  such that  $\gamma_x = \gamma_g^n$

$\langle 3 \rangle 3$ .  $\forall y \in G. xyx^{-1} = g^n yg^{-n}$

$\langle 3 \rangle 4$ .  $xgx^{-1} = g$

$\langle 2 \rangle 3$ .  $\gamma_g = \text{id}_G$

$\langle 1 \rangle 2$ .  $2 \Rightarrow 3$

$\langle 2 \rangle 1$ . ASSUME:  $\forall g \in G. \gamma_g = \text{id}_G$

$\langle 2 \rangle 2$ . LET:  $x, y \in G$

$\langle 2 \rangle 3$ .  $\gamma_x(y) = y$

$\langle 2 \rangle 4$ .  $xyx^{-1} = y$

$\langle 2 \rangle 5$ .  $xy = yx$

$\langle 1 \rangle 3$ .  $3 \Rightarrow 2$

PROOF: If  $xy = yx$  for all  $x, y$  then  $\gamma_x(y) = y$  for all  $x, y$ .

$\langle 1 \rangle 4$ .  $2 \Rightarrow 1$

PROOF: Easy.

□

**Corollary 8.13.1.** *If  $\text{Aut}_{\mathbf{Grp}}(G)$  is cyclic then  $G$  is Abelian.*

**Proposition 8.14.** *Every subgroup of an Abelian group is normal.*

PROOF: Let  $G$  be an Abelian group and  $N$  a subgroup of  $G$ . Given  $g \in G$  and  $n \in N$  we have  $gng^{-1} = n \in N$ .  $\square$

**Proposition 8.15.** *For any group  $G$ , the group  $G/[G, G]$  is Abelian.*

PROOF: For any  $g, h \in G$  we have

$$gh(hg)^{-1} \in [G, G]$$

$$\therefore gh[G, G] = hg[G, G] \quad \square$$

**Proposition 8.16.** *Let  $G$  be a finite Abelian group. Let  $p$  be a prime divisor of  $|G|$ . Then  $G$  has an element of order  $p$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: as induction hypothesis the result holds for all groups smaller than  $G$ .

$\langle 1 \rangle 2$ . PICK  $g \in G - \{0\}$ .

$\langle 1 \rangle 3$ . PICK an element  $h \in \langle g \rangle$  with prime order  $q$ .

$\langle 1 \rangle 4$ . CASE:  $q = p$

PROOF:  $h$  is the required element.

$\langle 1 \rangle 5$ . CASE:  $q \neq p$

$\langle 2 \rangle 1$ . PICK  $r \in G$  such that  $r + \langle h \rangle$  has order  $p$  in  $G/\langle h \rangle$ .

PROOF: By induction hypothesis since  $|G/\langle h \rangle| = |G|/q$ .

$\langle 2 \rangle 2$ .  $pr \in \langle h \rangle$

$\langle 2 \rangle 3$ . PICK  $k$  such that  $pr = kh$

$\langle 2 \rangle 4$ .  $pqr = e$

$\langle 2 \rangle 5$ .  $qr$  has order  $p$ .

$\square$

**Corollary 8.16.1.** *For  $n$  an odd integer, any Abelian group of order  $2n$  has exactly one element of order 2.*

PROOF: If  $x$  and  $y$  are distinct elements of order 2 then  $\langle x, y \rangle = \{e, x, y, xy\}$  has size 4 and so  $4 \mid 2n$  which is a contradiction.  $\square$

**Example 8.17.** It is not true that, if  $G$  is a finite group and  $d \mid |G|$ , then  $G$  has an element of order  $d$ . The quaternionic group has no element of order 4.

**Proposition 8.18.** *If  $G$  is a finite Abelian group and  $d \mid |G|$  then  $G$  has a subgroup of size  $d$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: as induction hypothesis the result is true for all  $d' < d$ .

$\langle 1 \rangle 2$ . ASSUME: w.l.o.g.  $d \neq 1$ .

$\langle 1 \rangle 3$ . PICK a prime  $p$  such that  $p \mid d$ .

$\langle 1 \rangle 4$ . PICK an element  $g \in G$  of order  $p$ .

$\langle 1 \rangle 5$ .  $d/p \mid |G/\langle g \rangle|$

$\langle 1 \rangle 6$ . PICK a subgroup  $H$  of  $G/\langle g \rangle$  of size  $d/p$ .

$\langle 1 \rangle 7$ .  $\pi^{-1}(H)$  is a subgroup of  $G$  of size  $d$ .

$\square$



**Proposition 8.19.** *Let  $(G, \cdot)$  be a group. Let  $\circ : G^2 \rightarrow G$  be a group homomorphism such that  $(G, \circ)$  is a group. Then  $\circ$  and  $\cdot$  coincide, and  $G$  is Abelian.*

PROOF:

$\langle 1 \rangle 1$ . For all  $g_1, g_2, h_1, h_2 \in G$  we have

$$(g_1 g_2) \circ (h_1 h_2) = (g_1 \circ h_1)(g_2 \circ h_2)$$

$\langle 1 \rangle 2$ .  $e \circ e = e$

PROOF:

$$\begin{aligned} e \circ e &= (ee) \circ (ee) \\ &= (e \circ e)(e \circ e) \end{aligned}$$

Hence  $e \circ e = e$  by Cancellation.

$\langle 1 \rangle 3$ .  $e$  is the identity of  $(G, \circ)$

$\langle 1 \rangle 4$ . For all  $g, h \in G$  we have

$$g \circ h = gh$$

PROOF:

$$\begin{aligned} g \circ h &= (ge) \circ (eh) \\ &= (g \circ e)(e \circ h) \\ &= gh \end{aligned}$$

$\langle 1 \rangle 5$ . For all  $g, h \in G$  we have  $gh = hg$ .

PROOF:

$$\begin{aligned} gh &= (e \circ g)(h \circ e) \\ &= (eh) \circ (ge) \\ &= h \circ g \\ &= hg \end{aligned}$$

□

**Corollary 8.19.1.** *If  $(G, m : G^2 \rightarrow G, e : 1 \rightarrow G, i : G \rightarrow G)$  is a group object in **Grp** then  $m$  is the multiplication of  $G$ ,  $e(*)$  is the identity of  $G$ ,  $i(g) = g^{-1}$ , and  $G$  is Abelian.*

*Conversely, if  $(G, m)$  is any Abelian group, then  $(G, m, e, i)$  is a group object in **Grp** where  $e(*) = e$  and  $i(g) = g^{-1}$ .*

**Proposition 8.20.** *Let  $G$  be a group. If every element of  $G$  has order  $\leq 2$  then  $G$  is Abelian.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $x, y \in G$

PROVE:  $xy = yx$

$\langle 1 \rangle 2$ . ASSUME: w.l.o.g.  $x \neq e \neq y$ .

$\langle 1 \rangle 3$ .  $x^2 = e = y^2$

$\langle 1 \rangle 4$ .  $x^{-1} = x$  and  $y^{-1} = y$ .

$\langle 1 \rangle 5$ . CASE:  $xy = e$

PROOF: Then  $y = x^{-1}$  and so  $xy = yx = e$ .

$\langle 1 \rangle 6$ . CASE:  $xy \neq e$

$\langle 2 \rangle 1$ .  $(xy)^2 = e$

$\langle 2 \rangle 2$ .  $xyxy = e$

$$\langle 2 \rangle 3. \quad xy = y^{-1}x^{-1}$$

$$\langle 2 \rangle 4. \quad xy = yx$$

□

**Proposition 8.21.** *Every Abelian group is solvable.*

PROOF: If  $G$  is Abelian then  $G' = \{e\}$ . □

**Proposition 8.22.** *The only non-trivial simple finite Abelian groups are  $\mathbb{Z}/p\mathbb{Z}$  for  $p$  a prime.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $G$  be a non-trivial simple finite Abelian group.

$\langle 1 \rangle 2$ . PICK a prime  $p$  that divides  $|G|$ .

$\langle 1 \rangle 3$ . PICK an element  $a \in G$  of order  $p$ .

PROOF: Cauchy's Theorem.

$\langle 1 \rangle 4$ .  $\langle a \rangle = G$

□

## 8.1 The Category of Abelian Groups

**Definition 8.23** (Category of Abelian Groups). Let **Ab** be the full subcategory of **Grp** whose objects are the Abelian groups.

**Proposition 8.24.** *If  $(G, m : G^2 \rightarrow G, e : 1 \rightarrow G, i : G \rightarrow G)$  is a group object in **Ab** then  $m$  is the multiplication of  $G$ ,  $e(*)$  is the identity of  $G$ ,  $i(g) = g^{-1}$ , and  $G$  is Abelian.*

*Conversely, if  $(G, m)$  is any Abelian group, then  $(G, m, e, i)$  is a group object in **Ab** where  $e(*) = e$  and  $i(g) = g^{-1}$ .*

PROOF: Immediate from Corollary 8.19.1. □

**Definition 8.25** (Direct Sum). Given Abelian groups  $G$  and  $H$ , we also call the direct product of  $G$  and  $H$  the *direct sum* and denote it  $G \oplus H$ .

**Proposition 8.26.** *Given Abelian groups  $G$  and  $H$ , the direct sum  $G \oplus H$  is the coproduct of  $G$  and  $H$  in **Ab**.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\kappa_1 : G \rightarrow G \oplus H$  be the group homomorphism  $\kappa_1(g) = (g, e_H)$ .

$\langle 1 \rangle 2$ . LET:  $\kappa_2 : H \rightarrow G \oplus H$  be the group homomorphism  $\kappa_2(h) = (e_G, h)$ .

$\langle 1 \rangle 3$ . Given group homomorphism  $\phi : G \rightarrow K$  and  $\psi : H \rightarrow K$ , define  $[\phi, \psi] : G \oplus H \rightarrow K$  by  $[\phi, \psi](g, h) = \phi(g) + \psi(h)$ .

$\langle 1 \rangle 4$ .  $[\phi, \psi]$  is a group homomorphism.

PROOF:

$$\begin{aligned} [\phi, \psi]((g, h) + (g', h')) &= [\phi, \psi](g + g', h + h') \\ &= \phi(g + g') + \psi(h + h') \\ &= \phi(g) + \phi(g') + \psi(h) + \psi(h') \\ &= \phi(g) + \psi(h) + \phi(g') + \psi(h') \\ &= [\phi, \psi](g, h) + [\phi, \psi](g', h') \end{aligned}$$

(1)5.  $[\phi, \psi] \circ \kappa_1 = \phi$

PROOF:

$$\begin{aligned} [\phi, \psi](\kappa_1(g)) &= [\phi, \psi](g, e_h) \\ &= \phi(g) + \psi(e_h) \\ &= \phi(g) + e_K \\ &= \phi(g) \end{aligned}$$

(1)6.  $[\phi, \psi] \circ \kappa_2 = \psi$

PROOF: Similar.

(1)7. If  $f : G \oplus H \rightarrow K$  is a group homomorphism with  $f \circ \kappa_1 = \phi$  and  $f \circ \kappa_2 = \psi$  then  $f = [\phi, \psi]$ .

PROOF:

$$\begin{aligned} f(g, h) &= f((g, e_H) + (e_G, h)) \\ &= f(\kappa_1(g)) + f(\kappa_2(h)) \\ &= \phi(g) + \psi(h) \end{aligned}$$

□

**Theorem 8.27.** *Every finitely generated Abelian group is a direct sum of cyclic groups.*

PROOF: TODO □

## 8.2 Free Abelian Groups

**Proposition 8.28.** *Let  $A$  be a set. Let  $\mathcal{F}^A$  be the category whose objects are pairs  $(G, j)$  where  $G$  is an Abelian group and  $j$  is a function  $A \rightarrow G$ , with morphisms  $f : (G, j) \rightarrow (H, k)$  the group homomorphisms  $f : G \rightarrow H$  such that  $f \circ j = k$ . Then  $\mathcal{F}^A$  has an initial object.*

PROOF:

(1)1. LET:  $\mathbb{Z}^{\oplus A}$  be the subgroup of  $\mathbb{Z}^A$  consisting of all functions  $\alpha : A \rightarrow \mathbb{Z}$  such that  $\alpha(a) = 0$  for only finitely many  $a \in A$ .

(1)2. LET:  $i : A \rightarrow \mathbb{Z}^{\oplus A}$  be the function such that  $i(a)(b) = 1$  if  $a = b$  and 0 if  $a \neq b$ .

(1)3. LET:  $G$  be any Abelian group and  $j : A \rightarrow G$  any function.

(1)4. The unique homomorphism  $\phi : \mathbb{Z}^{\oplus A} \rightarrow G$  required is defined by  $\phi(\alpha) = \sum_{a \in A} \alpha(a)j(a)$

□

**Definition 8.29** (Free Abelian Group). For any set  $A$ , the *free Abelian group* on  $A$  is the initial object  $(F^{ab}(A), i)$  in  $\mathcal{F}^A$ .

**Proposition 8.30.** *For any sets  $A$  and  $B$ , we have that  $F^{ab}(A + B)$  is the coproduct of  $F^{ab}(A)$  and  $F^{ab}(B)$  in **Grp**.*

$$\begin{array}{ccccc}
& & G & & \\
& \nearrow f & \uparrow k & \nwarrow g & \\
F^{ab}(A) & \xrightarrow{\kappa_1} & F^{ab}(A+B) & \xleftarrow{\kappa_2} & F^{ab}(B) \\
\uparrow i_A & & \uparrow j & & \uparrow i_B \\
A & \xrightarrow{k_1} & A+B & \xleftarrow{k_2} & B
\end{array}$$

PROOF:

- (1)1. LET:  $i_A : A \rightarrow F^{ab}(A)$ ,  $i_B : B \rightarrow F^{ab}(B)$ ,  $j : A+B \rightarrow F^{ab}(A+B)$  be the canonical injections.
  - (1)2. LET:  $\kappa_1, \kappa_2$  be the unique group homomorphisms that make the diagram above commute.
  - (1)3. LET:  $G$  be any group and  $f : F^{ab}(A) \rightarrow G$ ,  $g : F^{ab}(B) \rightarrow G$  any group homomorphisms.
  - (1)4. LET:  $h : A+B \rightarrow G$  be the unique function such that  $h \circ k_1 = f \circ i_A$  and  $h \circ k_2 = g \circ i_B$ .
  - (1)5. LET:  $k : F^{ab}(A+B) \rightarrow G$  be the unique group homomorphism such that  $k \circ j = h$ .
  - (1)6.  $k$  is the unique group homomorphism such that  $k \circ \kappa_1 \circ i_A = f \circ i_A$  and  $k \circ \kappa_2 \circ i_B = g \circ i_B$ .
  - (1)7.  $k$  is the unique group homomorphism such that  $k \circ \kappa_1 = f$  and  $k \circ \kappa_2 = g$ .
- 

**Proposition 8.31.** *For  $A$  and  $B$  finite sets, if  $F^{ab}(A) \cong F^{ab}(B)$  then  $A \cong B$ .*

PROOF:

- (1)1. For any set  $C$ , define  $\sim$  on  $F^{ab}(C)$  by:  $f \sim f'$  iff there exists  $g \in F^{ab}(C)$  such that  $f - f' = 2g$ .
- (1)2. For any set  $C$ ,  $\sim$  is an equivalence relation on  $F^{ab}(C)$ .
- (1)3. For any set  $C$ , we have  $F^{ab}(C)/\sim$  is finite if and only if  $C$  is finite, in which case  $|F^{ab}(C)/\sim| = 2^{|C|}$ .

PROOF: There is a bijection between  $F^{ab}(C)/\sim$  and the finite subsets of  $C$ , which maps  $f$  to  $\{c \in C : f(c) \text{ is odd}\}$ .

- (1)4. If  $F^{ab}(A) \cong F^{ab}(B)$  then  $A \cong B$ .

PROOF: If  $|F^{ab}(A)/\sim| = |F^{ab}(B)/\sim|$  then  $2^{|A|} = 2^{|B|}$  and so  $|A| = |B|$ .

□

**Proposition 8.32.** *Let  $G$  be an Abelian group. Then  $G$  is finitely generated if and only if there exists a surjective homomorphism  $\mathbb{Z}^{\oplus n} \twoheadrightarrow G$  for some  $n$ .*

PROOF:

- (1)1. If  $G$  is finitely generated then there exists a surjective homomorphism  $\mathbb{Z}^{\oplus n} \twoheadrightarrow G$  for some  $n$ .

PROOF: Let  $G = \langle a_1, \dots, a_n \rangle$ . Define  $\phi : \mathbb{Z}^{\oplus n} \twoheadrightarrow G$  by  $\phi(i_1, \dots, i_n) = i_1 \cdot a_1 + \dots + i_n \cdot a_n$ .

(1)2. If there exists a surjective homomorphism  $\phi : \mathbb{Z}^{\oplus n} \twoheadrightarrow G$  for some  $n$  then  $G$  is finitely generated.

PROOF:  $G$  is generated by  $\phi(1, 0, \dots, 0), \phi(0, 1, 0, \dots, 0), \dots, \phi(0, \dots, 0, 1)$ .

□

**Proposition 8.33.** *Let  $A$  be a set. Let  $i : A \hookrightarrow F(A)$  be the free group on  $A$ . Then  $\pi \circ i : A \rightarrow F(A)/[F(A), F(A)]$  is the free Abelian group on  $A$ .*

$$\begin{array}{ccc}
 & F(A)/[F(A), F(A)] & \\
 \uparrow \pi & \searrow h & \\
 F(A) & \xrightarrow{g} & G \\
 \uparrow i & \nearrow f & \\
 A & & 
 \end{array}$$

PROOF:

(1)1. LET:  $G$  be an Abelian group and  $f : A \rightarrow G$  a function.

(1)2. LET:  $g : F(A) \rightarrow G$  be the unique group homomorphism such that  $g \circ i = f$ .

(1)3.  $[F(A), F(A)] \subseteq \ker g$

PROOF: For all  $x, y \in F(A)$  we have  $g(xyx^{-1}y^{-1}) = g(x) + g(y) - g(x) - g(y) = 0$ .

(1)4. LET:  $h : F(A)/[F(A), F(A)] \rightarrow G$  be the unique group homomorphism such that  $h \circ \pi = g$ .

(1)5.  $h$  is the unique group homomorphism such that  $h \circ \pi \circ i = f$ .

□

**Corollary 8.33.1.** *Let  $A$  and  $B$  be sets. Let  $F(A)$  and  $F(B)$  be the free groups on  $A$  and  $B$  respectively. If  $F(A) \cong F(B)$  then  $A \cong B$ .*

PROOF: Proposition 8.31. □

## 8.3 Cokernels

**Proposition 8.34.** *Let  $\phi : G \rightarrow H$  be a homomorphism between Abelian groups. Then there exists an Abelian group  $K$  and homomorphism  $\pi : H \rightarrow K$  that is initial with respect to all homomorphism  $\alpha : H \rightarrow L$  such that  $\alpha \circ \phi = 0$ .*

PROOF:

(1)1. LET:  $K = H/\text{im } \phi$  and  $\pi$  be the canonical homomorphism.

(1)2. LET:  $\pi \circ \phi = 0$

(1)3. LET:  $\alpha : H \rightarrow L$  satisfy  $\alpha \circ \phi = 0$

(1)4.  $\text{im } \phi \subseteq \ker \alpha$

(1)5. There exists a unique  $\bar{\alpha} : H/\text{im } \phi \rightarrow L$  such that  $\bar{\alpha} \circ \pi = \alpha$

□

**Definition 8.35** (Cokernel). For any homomorphism  $\phi : G \rightarrow H$  in **Ab**, the *cokernel* of  $\phi$  is the Abelian group  $\text{coker } \phi$  and homomorphism  $\pi : H \rightarrow \text{coker } \phi$  that is initial among homomorphisms  $\alpha : H \rightarrow L$  such that  $\alpha \circ \phi = 0$ .

**Proposition 8.36.**  $\pi : H \rightarrow \text{coker } \phi$  is initial among functions  $f : H \rightarrow X$  such that, for all  $x, y \in H$ , if  $x + \text{im } \phi = y + \text{im } \phi$  then  $f(x) = f(y)$ .

PROOF: Easy.  $\square$

**Proposition 8.37.** Let  $\phi : G \rightarrow H$  be a homomorphism of Abelian groups. Then the following are equivalent.

- $\phi$  is an epimorphism.
- $\text{coker } \phi$  is trivial.
- $\phi$  is surjective.

PROOF:

$\langle 1 \rangle 1. 1 \Rightarrow 2$

$\langle 2 \rangle 1.$  ASSUME:  $\phi$  is epi.

$\langle 2 \rangle 2.$  LET:  $\pi : H \rightarrow \text{coker } \phi$  be the canonical homomorphism.

$\langle 2 \rangle 3.$   $\pi \circ \phi = 0 \circ \phi$

$\langle 2 \rangle 4.$   $\pi = 0$

$\langle 2 \rangle 5.$   $\text{coker } \phi = \text{im } \pi$  is trivial.

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: If  $\text{coker } \phi = H / \text{im } \phi$  is trivial then  $\text{im } \phi = H$ .

$\langle 1 \rangle 3. 3 \Rightarrow 1$

PROOF: If it is surjective then it is epi in **Set**.

$\square$

## 8.4 Commutator Subgroups

**Proposition 8.38.** Let  $G$  be a group. Let  $G'$  be the commutator subgroup of  $G$ . Then  $G/G'$  is Abelian.

PROOF: Since  $ghg^{-1}h^{-1}G' = G'$  so  $ghG' = hgG'$ .  $\square$

**Proposition 8.39.** Let  $G$  be a group and  $A$  an Abelian group. Let  $\alpha : G \rightarrow A$  be a homomorphism. Then  $G' \subseteq \ker \alpha$ .

PROOF: Since  $\phi([g, h]) = \phi(g)\phi(h)\phi(g)^{-1}\phi(h)^{-1} = e$ .  $\square$

**Corollary 8.39.1.** Let  $G$  be a group. The canonical projection  $G \twoheadrightarrow G/G'$  is initial in the category of homomorphisms from  $G$  to an Abelian group.

**Definition 8.40** (Abelian Series). A normal series of subgroups is *Abelian* iff every quotient is Abelian.

**Lemma 8.41.** Let  $G$  be a group. Let  $H$  be a normal subgroup of  $G$ . If  $G/H$  is Abelian then  $G' \subseteq H$ .

PROOF: Given  $g, h \in G$  we have

$$\begin{aligned} ghH &= hgH \\ \therefore ghg^{-1}h^{-1} &\in H \end{aligned} \quad \square$$

**Proposition 8.42.** *Let  $G$  be a finite group. The following are equivalent.*

1. *All composition factors of  $G$  are cyclic.*
2.  *$G$  has a cyclic series of subgroups ending in  $\{e\}$ .*
3.  *$G$  has an Abelian series of subgroups ending in  $\{e\}$ .*
4.  *$G$  is solvable.*

PROOF:

$\langle 1 \rangle 1. 1 \Rightarrow 2$

PROOF: Trivial.

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: Trivial.

$\langle 1 \rangle 3. 3 \Rightarrow 4$

$\langle 2 \rangle 1.$  LET:  $G = G_0 \supseteq G_1 \supseteq \cdots \supseteq G_n = \{e\}$  be an Abelian series of subgroups.

$\langle 2 \rangle 2.$  For all  $i$  we have  $G^{(i)} \subseteq G_i$ .

PROOF: Lemma 8.41.

$\langle 2 \rangle 3.$   $G^{(n)} = \{e\}$

$\langle 1 \rangle 4. 4 \Rightarrow 1$

PROOF: Extend the derived series of  $G$  to a composition series, using the fact that every simple Abelian group is cyclic.

$\square$

**Corollary 8.42.1.** *All  $p$ -groups are solvable.*

PROOF: Their composition factors are simple  $p$ -groups, hence cyclic.  $\square$

**Corollary 8.42.2.** *Let  $G$  be a group and  $N$  a normal subgroup. Then  $G$  is solvable if and only if both  $N$  and  $G/N$  are solvable.*

PROOF: By Proposition 7.120.  $\square$

**Corollary 8.42.3.** *Let  $G$  be a finite solvable group. Then the composition factors of  $G$  are exactly  $C_p$  for  $p$  a prime factor of  $G$  (with the same multiplicities).*

PROOF: Since each composition factor is simple and cyclic hence removes one prime factor in  $|G|$ .  $\square$

## 8.5 Derived Series

**Definition 8.43** (Derived Series). Let  $G$  be a group. The *derived series* of  $G$  is the series of subgroups

$$G \supseteq G' \supseteq G'' \supseteq G''' \supseteq \cdots$$

where  $G'$  is the commutator subgroup of  $G$ .

We write  $G^{(i)}$  for the  $i + 1$ st entry in the derived series

**Proposition 8.44.** *Each  $G^{(i)}$  is characteristic.*

PROOF:

$\langle 1 \rangle 1$ .  $G$  is characteristic in  $G$ .

PROOF: Trivial.

$\langle 1 \rangle 2$ . If  $G^{(i)}$  is characteristic in  $G$  then  $G^{(i+1)}$  is characteristic in  $G$ .

$\langle 2 \rangle 1$ . ASSUME:  $G^{(i)}$  is characteristic.

$\langle 2 \rangle 2$ . LET:  $\phi : G \cong G$  be an automorphism of  $G$ .

$\langle 2 \rangle 3$ . For all  $g, h \in G^{(i)}$  we have  $\phi([g, h]) \in G^{(i+1)}$ .

PROOF: Since  $\phi([g, h]) = [\phi(g), \phi(h)]$  and  $\phi(g), \phi(h) \in G^{(i)}$ .

$\langle 2 \rangle 4$ .  $\phi(G^{(i+1)}) \subseteq G^{(i+1)}$

□

## 8.6 Solvable Groups

**Definition 8.45** (Solvable). A group is *solvable* iff its derived series terminates in  $\{e\}$ .

**Theorem 8.46** (Feit-Thompson). *Every finite group of odd order is solvable.*

**Proposition 8.47.** *Let  $H$  be a nontrivial normal subgroup of a solvable group  $G$ . Then  $H$  contains a nontrivial Abelian subgroup that is normal in  $G$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $r$  be the largest number such that  $H \cap G^{(r)}$  is non-trivial.

$\langle 1 \rangle 2$ . LET:  $K = H \cap G^{(r)}$

$\langle 1 \rangle 3$ .  $K$  is Abelian.

PROOF: Since  $[K, K] \subseteq G^{(r+1)} = \{e\}$ .

$\langle 1 \rangle 4$ .  $K$  is normal.

PROOF: Proposition 8.44.

□

**Theorem 8.48** (Burnside). *Let  $p$  and  $q$  be primes. Every group of order  $p^a q^b$  is solvable.*



## Chapter 9

# Group Actions

### 9.1 Group Actions

**Definition 9.1** (Action). Let  $G$  be a group. Let  $A$  be an object of a category  $\mathcal{C}$ . A (left) action of  $G$  on  $A$  is a group homomorphism  $G \rightarrow \text{Aut}_{\mathcal{C}}(A)$ .

It is *faithful* or *effective* iff it is injective.

**Proposition 9.2.** Let  $A$  be a set. An action of the group  $G$  on the set  $A$  is given by a function  $\cdot : G \times A \rightarrow A$  such that

- $\forall a \in A. ea = a$
- $\forall g, h \in G. \forall a \in A. (gh)a = g(ha)$

PROOF: Just unfolding definitions.  $\square$

**Example 9.3.** Left multiplication defines a faithful action of any group on its own underlying set.

In fact, for any subgroup  $H$  of a group  $G$ , left multiplication defines an action of  $G$  on  $G/H$ .

**Corollary 9.3.1** (Cayley's Theorem). Every group  $G$  is a subgroup of a symmetric group, namely  $\text{Aut}_{\text{Set}}(G)$ .

**Example 9.4.** Conjugation  $g * h = ghg^{-1}$  is an action of any group on its own underlying set.

**Definition 9.5** (Transitive). An action of a group  $G$  on a set  $A$  is *transitive* iff, for all  $a, b \in A$ , there exists  $g \in G$  such that  $ga = b$ .

**Example 9.6.** Left multiplication of a group  $G$  is a transitive action of  $G$  on  $G$ .

**Definition 9.7** (Orbit). Given an action of a group  $G$  on a set  $A$  and  $a \in A$ , the *orbit* of  $a$  is

$$\text{O}_G(a) := \{ga : g \in G\} .$$

**Proposition 9.8.** *Given an action of a group  $G$  on a set  $A$ , the orbits form a partition of  $A$ .*

PROOF:

$\langle 1 \rangle 1$ . Every element of  $A$  is in some orbit.

PROOF: Since  $a \in O_G(a)$ .

$\langle 1 \rangle 2$ . Distinct orbits are disjoint.

$\langle 2 \rangle 1$ . LET:  $a \in O_G(b) \cap O_G(c)$

$\langle 2 \rangle 2$ . PICK  $g, h \in G$  such that  $a = gb = hc$ .

$\langle 2 \rangle 3$ .  $O_G(b) \subseteq O_G(c)$

PROOF: For all  $k \in G$  we have  $kb = kg^{-1}hc$ .

$\langle 2 \rangle 4$ .  $O_G(c) \subseteq O_G(b)$

PROOF: Similar.

□

**Proposition 9.9.** *Given an action of a group  $G$  on a set  $A$  and  $a \in A$ , the action is transitive on  $O_G(a)$ .*

PROOF:

$\langle 1 \rangle 1$ . The restriction of the action is an action on  $O_G(a)$ .

PROOF: Since  $g(ha) = (gh)a$ , the action maps  $O_G(a)$  to itself.

$\langle 1 \rangle 2$ . The restricted action is transitive.

PROOF: Given  $ga, ha \in O_G(a)$ , we have  $ha = (hg^{-1})(ga)$ .

□

**Definition 9.10** (Stabilizer Subgroup). Given an action of a group  $G$  on a set  $A$  and  $a \in A$ , the *stabilizer subgroup* of  $a$  is

$$\text{Stab}_G(a) := \{g \in G : ga = a\} .$$

**Proposition 9.11.** *Stabilizer subgroups are subgroups.*

PROOF: If  $g, h \in \text{Stab}_G(a)$  then  $gh^{-1}a = a$  so  $gh^{-1} \in \text{Stab}_G(a)$ . □

**Proposition 9.12.** *Let  $G$  act on a set  $A$ . Let  $a \in A$  and  $g \in G$ . Then*

$$\text{Stab}_G(ga) = g\text{Stab}_G(a)g^{-1} .$$

PROOF:

$$h \in \text{Stab}_G(ga) \Leftrightarrow hga = ga$$

$$\Leftrightarrow g^{-1}hga = a$$

$$\Leftrightarrow g^{-1}hg \in \text{Stab}_G(a)$$

$$\Leftrightarrow h \in g\text{Stab}_G(a)g^{-1}$$

□

**Corollary 9.12.1.** *Let  $G$  be an action on a set  $A$  and  $a \in A$ . If  $\text{Stab}_G(a)$  is normal in  $G$ , then for any  $b \in O_G(a)$  we have  $\text{Stab}_G(a) = \text{Stab}_G(b)$ .*

**Definition 9.13** (Free). An action of a group  $G$  on a set  $A$  is *free* iff, whenever  $ga = a$ , then  $g = e$ .

**Example 9.14.** The action of left multiplication is free.

**Proposition 9.15.** *Let  $G$  be a group. Let  $H$  be a subgroup of  $G$  of finite index  $n$ . Then  $H$  includes a subgroup  $K$  that is normal in  $G$  and such that  $|G : K|$  divides  $\gcd(|G|, n!)$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\sigma : G \rightarrow \text{Aut}_{\text{Set}}(G/H)$  be the action of left multiplication.

$\langle 1 \rangle 2$ . LET:  $K = \ker \sigma$

$\langle 1 \rangle 3$ .  $K \subseteq H$

$\langle 2 \rangle 1$ . LET:  $g \in K$

$\langle 2 \rangle 2$ .  $\sigma(g)(H) = H$

$\langle 2 \rangle 3$ .  $gH = H$

$\langle 2 \rangle 4$ .  $g \in H$

$\langle 1 \rangle 4$ .  $K$  is normal in  $G$ .

PROOF: Proposition 7.42.

$\langle 1 \rangle 5$ .  $|G : K| \mid |G|$

PROOF: Lagrange's Theorem.

$\langle 1 \rangle 6$ .  $|G : K| \mid n!$

PROOF: Since  $G/K$  is a subgroup of  $\text{Aut}_{\text{Set}}(G/H)$ .

□

**Corollary 9.15.1.** *Let  $G$  be a finite group. Let  $H$  be a subgroup of  $G$  of index  $p$  where  $p$  is the smallest prime that divides  $|G|$ . Then  $H$  is normal in  $G$ .*

PROOF:

$\langle 1 \rangle 1$ . PICK a subgroup  $K$  of  $H$  normal in  $G$  such that  $|G : K|$  divides  $\gcd(|G|, p!)$ .

$\langle 1 \rangle 2$ .  $|G : K|$  divides  $p$ .

$\langle 1 \rangle 3$ .  $|G : H| |H : K|$  divides  $p$ .

$\langle 1 \rangle 4$ .  $|H : K| = 1$

$\langle 1 \rangle 5$ .  $H = K$

$\langle 1 \rangle 6$ .  $H$  is normal.

□

**Corollary 9.15.2.** *Any subgroup of index 2 is normal.*

**Proposition 9.16.** *Let  $G$  be a group with finite set of generators  $A$ . Then left multiplication defines a free action of  $G$  on its Cayley graph.*

PROOF: Easy since if  $g_2 = g_1 a$  then  $hg_2 = hg_1 a$ . □

**Corollary 9.16.1.** *A free group acts freely on a tree.*

**Theorem 9.17.** *If a group  $G$  acts freely on a tree then  $G$  is free.*

**Corollary 9.17.1.** *Every subgroup of the free group on a finite set is free.*

PROOF: If  $H$  is a subgroup of  $F(A)$  then left multiplication defines a free action of  $H$  on the Cayley graph of  $F(A)$ , which is a tree. □

**Proposition 9.18.** *Let  $S$  be a finite set. Let  $G$  be a group acting on  $S$ . Let  $Z$  be the set of fixed points of the action:*

$$Z = \{a \in S : \forall g \in G. ga = a\} .$$

*Let  $A$  be a set of representatives for the nontrivial orbits of the action. Then*

$$|S| = |Z| + \sum_{a \in A} [G : \text{Stab}_G(a)] .$$

PROOF: Immediate from the fact that the orbits partition  $S$ .  $\square$

**Corollary 9.18.1.** *Let  $p$  be a prime. Let  $S$  be a finite set. Let  $G$  be a  $p$ -group acting on  $S$ . Let  $Z$  be the set of fixed points of the action. Then  $|Z| \equiv |S| \pmod{p}$ .*

**Corollary 9.18.2.** *Let  $p$  be a prime. Let  $S$  be a finite set. Let  $G$  be a  $p$ -group acting on  $S$ . If  $p$  does not divide  $|S|$  then the action has a fixed point.*

## 9.2 Category of $G$ -Sets

**Definition 9.19.** Given a group  $G$ , let  $G - \mathbf{Set}$  be the category with:

- objects all pairs  $(A, \rho)$  such that  $A$  is a set and  $\rho : G \times A \rightarrow A$  is an action of  $G$  on  $A$ ;
- morphisms  $f : (A, \rho) \rightarrow (B, \sigma)$  are functions  $f : A \rightarrow B$  that are  $(G-)$ equivariant, i.e.

$$\forall g \in G. \forall a \in A. f(\rho(g, a)) = \sigma(g, f(a)) .$$

**Proposition 9.20.** *A  $G$ -equivariant function  $f : A \rightarrow B$  is an isomorphism in  $G - \mathbf{Set}$  if and only if it is bijective.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $f : A \rightarrow B$  be  $G$ -equivariant and bijective.

PROVE:  $f^{-1}$  is  $G$ -equivariant.

$\langle 1 \rangle 2$ . LET:  $g \in G$  and  $b \in B$

$\langle 1 \rangle 3$ .  $f^{-1}(gb) = gf^{-1}(b)$

PROOF:

$$\begin{aligned} f(f^{-1}(gb)) &= gb \\ &= gf(f^{-1}(b)) \\ &= f(gf^{-1}(b)) \end{aligned}$$

$\square$

**Proposition 9.21.** *Let  $G$  be a group and  $A$  a transitive  $G$ -set. Let  $a \in A$ . Then  $A$  is isomorphic to  $G/\text{Stab}_G(a)$  under left multiplication.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $f : G/\text{Stab}_G(a) \rightarrow A$  be the function  $f(g\text{Stab}_G(a)) = ga$ .

$\langle 2 \rangle 1$ . ASSUME:  $g\text{Stab}_G(a) = h\text{Stab}_G(a)$

PROVE:  $ga = ha$

$\langle 2 \rangle 2$ .  $g^{-1}h \in \text{Stab}_G(a)$

$\langle 2 \rangle 3$ .  $g^{-1}ha = a$

$\langle 2 \rangle 4$ .  $ha = ga$

$\langle 1 \rangle 2$ .  $f$  is  $G$ -equivariant.

PROOF: Since  $f(gh\text{Stab}_G(a)) = gha = gf(h\text{Stab}_G(a))$ .

$\langle 1 \rangle 3$ .  $f$  is injective.

PROOF: If  $ga = ha$  then  $g^{-1}h \in \text{Stab}_G(a)$  so  $g\text{Stab}_G(a) = h\text{Stab}_G(a)$ .

$\langle 1 \rangle 4$ .  $f$  is surjective.

PROOF: Since for all  $b \in A$  there exists  $g \in G$  such that  $ga = b$ .

□

**Corollary 9.21.1.** *If  $O$  is an orbit of the action of a finite group  $G$  on a set  $A$ , then  $O$  is finite and  $|O|$  divides  $|G|$ .*

**Corollary 9.21.2.** *Let  $H$  be a subgroup of  $G$  and  $g \in G$ . Then*

$$G/H \cong G/(gHg^{-1})$$

in  $G - \mathbf{Set}$ .

PROOF: Taking  $A = G/H$  and  $a = gH$ . □

**Proposition 9.22.** *Given a family of  $G$ -sets  $\{A_i\}_{i \in I}$ , we have  $\prod_{i \in I} A_i$  is their product in  $G - \mathbf{Set}$  under*

$$g\{a_i\}_{i \in I} = \{ga_i\}_{i \in I} .$$

PROOF: Easy. □

**Proposition 9.23.** *Given a family of  $G$ -sets  $\{A_i\}_{i \in I}$ , we have  $\coprod_{i \in I} A_i$  is their product in  $G - \mathbf{Set}$  under*

$$g(i, a_i) = (i, ga_i) .$$

PROOF: Easy. □

**Proposition 9.24.** *Every finite  $G$ -set is a coproduct of  $G$ -sets of the form  $G/H$ .*

PROOF: If  $O(a_1), \dots, O(a_n)$  are the orbits of the  $G$ -set  $A$ , then  $A$  is the coproduct of  $G/\text{Stab}_G(a_1), \dots, G/\text{Stab}_G(a_n)$ . □

**Proposition 9.25.** *For any group  $G$  we have  $G \cong \text{Aut}_{G - \mathbf{Set}}(G)$  (considering  $G$  as a  $G$ -set under left multiplication).*

PROOF:

$\langle 1 \rangle 1$ . Define  $\phi : G \rightarrow \text{Aut}_{G - \mathbf{Set}}(G)$  by  $\phi(g)(g') = g'g^{-1}$ .

- ⟨2⟩1. LET:  $g \in G$   
 PROVE:  $\lambda_{g'} \in G.g'g^{-1}$  is an automorphism of  $G$  in  $G - \mathbf{Set}$ .  
 ⟨2⟩2.  $\phi(g)$  is  $G$ -equivariant.  
 PROOF: Since  $\phi(g)(h_1h_2) = h_1h_2g^{-1} = h_1\phi(g)(h_2)$ .  
 ⟨2⟩3.  $\phi(g)$  is injective.  
 PROOF: By Cancellation.  
 ⟨2⟩4.  $\phi(g)$  is surjective.  
 PROOF: For any  $h \in G$  we have  $h = \phi(g)(hg)$ .  
 ⟨1⟩2.  $\phi$  is a group homomorphism.  
 PROOF:  $\phi(g_1g_2)(h) = hg_2^{-1}g_1^{-1} = \phi(g_1)(\phi(g_2)(h))$ .  
 ⟨1⟩3.  $\phi$  is injective.  
 PROOF: If  $\phi(g) = \phi(g')$  then  $g = \phi(g)(e) = \phi(g')(e) = g'$ .  
 ⟨1⟩4.  $\phi$  is surjective.  
 ⟨2⟩1. LET:  $\sigma \in \text{Aut}_{G-\mathbf{Set}}(G)$   
 ⟨2⟩2. LET:  $g = \sigma(e)$   
 PROVE:  $\sigma = \phi(g^{-1})$   
 ⟨2⟩3.  $\sigma(h) = hg$   
 PROOF:  $\sigma(h) = \sigma(hg) = h\sigma(e) = hg$ .  
 □

### 9.3 Center

**Definition 9.26** (Center). The *center* of a group  $G$ ,  $Z(G)$ , is the kernel of the conjugation action  $\sigma : G \rightarrow S_G$ .

**Proposition 9.27.** *The center of a group  $G$  is*

$$Z(G) = \{g \in G : \forall a \in G. ag = ga\} .$$

PROOF: Immediate from definitions. □

**Lemma 9.28.** *Let  $G$  be a finite group. Assume  $G/Z(G)$  is cyclic. Then  $G$  is Abelian and so  $G/Z(G)$  is trivial.*

PROOF:

- ⟨1⟩1. PICK  $g \in G$  such that  $gZ(G)$  generates  $G/Z(G)$ .  
 ⟨1⟩2. LET:  $a, b \in G$   
 ⟨1⟩3. PICK  $r, s \in \mathbb{Z}$  such that  $aZ(G) = g^rZ(G)$  and  $bZ(G) = g^sZ(G)$   
 ⟨1⟩4. LET:  $z = g^{-r}a \in Z(G)$  and  $w = g^{-s}b \in Z(G)$   
 ⟨1⟩5.  $a = g^rz$  and  $b = g^sw$   
 ⟨1⟩6.  $ab = ba$

PROOF:

$$\begin{aligned}
 ab &= g^rzg^sw \\
 &= g^{r+s}zw \\
 &= g^swg^rz \\
 &= ba
 \end{aligned}$$

□

**Proposition 9.29.** *Let  $G$  be a group. Let  $N$  be a subgroup of  $Z(G)$ . Then  $N$  is normal in  $G$ .*

PROOF: For all  $n \in N$  and  $g \in G$  we have  $gng^{-1} = ngg^{-1} = n \in N$  since  $n \in Z(G)$ . □

**Proposition 9.30.** *For any group  $G$  we have  $G/Z(G) \cong \text{Inn}(G)$ .*

PROOF: The homomorphism  $g \mapsto \gamma_g$  is a surjective homomorphism with kernel  $Z(G)$ . □

**Proposition 9.31.** *Let  $p$  and  $q$  be prime integers. Let  $G$  be a group of order  $pq$ . Then either  $G$  is Abelian or the center of  $G$  is trivial.*

PROOF: Otherwise we would have  $|Z(G)| = p$  say and so  $|\text{Inn}(G)| = q$ , meaning  $\text{Inn}(G)$  is cyclic, hence trivial, which is a contradiction. □

**Theorem 9.32** (First Sylow Theorem). *Let  $p$  be a prime and  $k \in \mathbb{N}$ . Let  $G$  be a finite group. If  $p^k$  divides  $|G|$  then  $G$  has a subgroup of order  $p^k$ .*

PROOF:

- ⟨1⟩1. ASSUME: as induction hypothesis the statement is true for all groups smaller than  $G$ .
- ⟨1⟩2. ASSUME: w.l.o.g.  $k \neq 0$  and  $|G| \neq p$
- ⟨1⟩3. CASE: There exists a proper subgroup  $H$  of  $G$  such that  $p$  does not divide  $[G : H]$ .

PROOF: Then  $H$  has a subgroup of order  $p^k$  by induction hypothesis ⟨1⟩1.

- ⟨1⟩4. CASE: For every proper subgroup  $H$  of  $G$  we have  $p$  divides  $[G : H]$ .

- ⟨2⟩1.  $p$  divides  $|Z(G)|$ .

PROOF: By the Class Formula.

- ⟨2⟩2. PICK  $a \in Z(G)$  that has order  $p$ .

PROOF: Cauchy's Theorem.

- ⟨2⟩3. LET:  $N = \langle a \rangle$

- ⟨2⟩4.  $N$  is normal.

PROOF: Proposition 9.29.

- ⟨2⟩5.  $p^{k-1}$  divides  $|G/N|$ .

- ⟨2⟩6. PICK a subgroup  $Q$  of  $G/N$  of order  $p^{k-1}$ .

PROOF: Induction hypothesis ⟨1⟩1.

- ⟨2⟩7. LET:  $P = \pi^{-1}(Q)$

- ⟨2⟩8.  $|P| = p^k$

□

**Theorem 9.33** (Second Sylow Theorem). *Let  $G$  be a finite group. Let  $p$  be a prime. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . Let  $H$  be a subgroup of  $G$  that is a  $p$ -group. Then  $H$  is a subgroup of a conjugate of  $P$ .*

PROOF:

⟨1⟩1. PICK a fixed point  $gP$  for the action of  $H$  on the set of left cosets of  $P$  by left multiplication.

PROOF: Corollary 9.18.2.

⟨1⟩2. For all  $h \in H$  we have  $hgP = gP$

⟨1⟩3.  $H \subseteq gPg^{-1}$

□

## 9.4 Centralizer

**Definition 9.34** (Centralizer). Let  $G$  be a group. Let  $a \in G$ . The *centralizer* or *normalizer* of  $a$ , denoted  $Z_G(a)$ , is the stabilizer of  $a$  under the action of conjugation.

**Proposition 9.35.**

$$Z_G(a) = \{g \in G : ga = ag\}$$

PROOF: Immediate from definitions. □

## 9.5 Conjugacy Class

**Definition 9.36** (Conjugacy Class). Let  $G$  be a group. Let  $a \in G$ . The *conjugacy class* of  $a$ , denoted  $[a]$ , is the orbit of  $a$  under the action of conjugation.

**Proposition 9.37** (Class Formula). Let  $G$  be a finite group. Let  $A$  be a set of representatives of the non-trivial conjugacy classes. Then

$$|G| = |Z(G)| + \sum_{a \in A} [G : Z(a)] .$$

PROOF: Proposition 9.18. □

**Corollary 9.37.1.** Let  $p$  be a prime. Let  $G$  be a  $p$ -group and  $H$  a nontrivial normal subgroup of  $G$ . Then  $H \cap Z(G) \neq \{e\}$ .

PROOF: Let  $A$  be a set of representatives of the non-trivial conjugacy classes. Let  $A \cap H = \{a_1, \dots, a_n\}$ . Then

$$|H| = |H \cap Z(G)| + \sum_{i=1}^n [G : Z(a_i)] .$$

Since  $p \mid |H|$  and  $p \mid [G : Z(a_i)]$  for all  $i$ , we have  $p \mid |H \cap Z(G)|$ . □

**Corollary 9.37.2.** Let  $p$  be a prime. Every  $p$ -group has a non-trivial center.

**Corollary 9.37.3.** Let  $p$  be a prime. Every group  $G$  of order  $p^2$  is Abelian.

PROOF: By Proposition 9.31. □

**Proposition 9.38.** Let  $p$  be a prime and  $r$  a non-negative integer. Let  $G$  be a group of order  $p^r$ . Then, for  $k = 0, 1, \dots, r$ , we have  $G$  has a normal subgroup of order  $p^k$ .



PROOF:

$\langle 1 \rangle 1$ . ASSUME: as induction hypothesis the result holds for  $r' < r$ .

$\langle 1 \rangle 2$ . ASSUME: w.l.o.g.  $k > 0$

PROOF: Since  $\{e\}$  is a normal subgroup of order  $p^0$ .

$\langle 1 \rangle 3$ . PICK a subgroup  $N$  of  $Z(G)$  of order  $p$ .

$\langle 2 \rangle 1$ .  $p \mid |Z(G)|$

PROOF: From Corollary 9.37.2.

$\langle 2 \rangle 2$ .  $Z(G)$  has a subgroup of order  $p$ .

PROOF: Cauchy's Theorem.

$\langle 1 \rangle 4$ .  $N$  is normal.

PROOF: Proposition 9.29.

$\langle 1 \rangle 5$ . PICK a normal subgroup  $M$  of  $G/N$  of order  $p^{k-1}$ .

PROOF: From the induction hypothesis  $\langle 1 \rangle 1$ .

$\langle 1 \rangle 6$ .  $\pi^{-1}(M)$  is a normal subgroup of  $G$  of order  $p^k$ .

□

**Example 9.39.** The only non-Abelian group of order 6 is  $S_3$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $G$  be a non-Abelian group of order 6.

$\langle 1 \rangle 2$ .  $Z(G) = \{e\}$

PROOF: Otherwise  $Z(G)$  has order 2 or 3 and is cyclic, contradicting Lemma 9.28.

$\langle 1 \rangle 3$ .  $G$  has three conjugacy classes:  $Z(G)$ , a class of size 2 and a class of size 3.

PROOF: By the Class Formula since the only way to make 6 using non-trivial factors of 6 is  $2 + 3$ .

$\langle 1 \rangle 4$ . PICK an element  $y \in G$  of order 3.

PROOF: It cannot be that every element is of order  $\leq 2$  by Proposition 8.20.

$\langle 1 \rangle 5$ .  $\langle y \rangle$  is normal in  $G$ .

PROOF: Since it has index 2.

$\langle 1 \rangle 6$ . The conjugacy class  $y$  is  $\{y, y^2\}$ .

PROOF: Since  $\langle y \rangle$  must be a union of conjugacy classes.

$\langle 1 \rangle 7$ . The conjugacy class of size 2 is  $\{y, y^2\}$ .

PROOF: Since  $y^2$  has order 3 and so its conjugacy class is of size 2 similarly, and there is only one conjugacy class of size 2.

$\langle 1 \rangle 8$ . PICK  $x \in G$  such that  $yx = xy^2$ .

PROOF:  $y^2$  is conjugate to  $y$  so there exists  $x$  such that  $x^{-1}yx = y^2$ .

$\langle 1 \rangle 9$ .  $x$  has order 2.

PROOF:  $x$  is not in the conjugacy class of size 2 so its order cannot be 3.

$\langle 1 \rangle 10$ .  $x$  and  $y$  generate  $G$ .

PROOF: Since  $e, y, y^2, x, xy, xy^2$  are all distinct.

$\langle 1 \rangle 11$ .  $G \cong S_3$

PROOF: We now know the entire multiplication table of  $G$ .

□

**Proposition 9.40.** Let  $G$  be a finite group. Let  $H$  be a subgroup of  $G$  of order 2. Let  $a \in H$ . Let  $[a]_H$  be the conjugacy class of  $a$  in  $H$ , and  $[a]_G$  the conjugacy

class of  $a$  in  $G$ . If  $Z_G(a) \subseteq H$  then  $[a]_H$  is half the size of  $[a]_G$ ; otherwise,  $[a]_H = [a]_G$ .

PROOF:

$\langle 1 \rangle 1$ .  $H$  is normal in  $G$ .

PROOF: Corollary 9.15.2.

$\langle 1 \rangle 2$ .  $HZ_G(a)$  is a subgroup of  $G$ .

$\langle 1 \rangle 3$ .  $H$  is normal in  $HZ_G(a)$ .

$\langle 1 \rangle 4$ .  $H \cap Z_G(a)$  is normal in  $Z_G(a)$ .

$\langle 1 \rangle 5$ .

$$\frac{HZ_G(a)}{H} \cong \frac{Z_G(a)}{H \cap Z_G(a)}$$

$\langle 1 \rangle 6$ . If  $Z_G(a) \subseteq H$  then  $|[a]_H| = |[a]_G|/2$ .

PROOF: In this case we have  $Z_H(a) = Z_G(a)$  and so  $|[a]_H| = |H|/|Z_H(a)| = (|G|/2)/|Z_G(a)| = |[a]_G|/2$ .

$\langle 1 \rangle 7$ . If  $Z_G(a) \not\subseteq H$  then  $[a]_H = [a]_G$ .

PROOF:

$\langle 2 \rangle 1$ . PICK  $b \in Z_G(a) - H$

$\langle 2 \rangle 2$ .  $Hb^{-1} = G - H$

$\langle 2 \rangle 3$ .  $G = HZ_G(a)$

PROOF: For  $x \in H$  we have  $x = xe$  and for  $x \notin H$  we have  $x \in Hb^{-1}$  hence  $xb \in H$  and  $x = (xb)b$ .

$\langle 2 \rangle 4$ .  $|[a]_H| = |[a]_G|$

PROOF:

$$\begin{aligned} |[a]_H| &= \frac{|H|}{|Z_H(a)|} \\ &= \frac{|H|}{|H \cap Z_G(a)|} \\ &= \frac{|Z_G(a)||H|}{|Z_G(a)||H \cap Z_G(a)|} \\ &= \frac{|HZ_G(a)|}{|Z_G(a)|} \\ &= \frac{|G|}{|Z_G(a)|} \\ &= |[a]_G| \end{aligned}$$

□

## 9.6 Conjugation on Sets

**Definition 9.41** (Conjugation). Let  $G$  be a group. Define an action of  $G$  on  $\mathcal{P}G$  called *conjugation* that takes  $g$  and  $A$  to

$$gAg^{-1} = \{gag^{-1} : a \in A\} .$$

**Proposition 9.42.** *The conjugate of a subgroup is a subgroup.*

PROOF: Let  $H$  be a subgroup of  $G$ . Given  $gh_1g^{-1}, gh_2g^{-1} \in gHg^{-1}$ , we have  
 $(gh_1g^{-1})(gh_2g^{-1})^{-1} = gh_1h_2^{-1}g^{-1} \in gHg^{-1}$ .  $\square$

**Definition 9.43** (Normalizer). Let  $G$  be a group and  $A \subseteq G$ . The *normalizer* of  $A$ , denoted  $N_G(A)$ , is its stabilizer under conjugation.

**Proposition 9.44.** Let  $G$  be a group,  $g \in G$  and  $A$  a finite subset of  $G$ . If  $gAg^{-1} \subseteq A$  then  $gAg^{-1} = A$  and so  $g \in N_G(A)$ .

PROOF: Conjugation by  $g$  is an injection from  $A$  into  $A$ , hence a bijection.  $\square$

**Proposition 9.45.** Let  $G$  be a group and  $H$  a subgroup of  $G$ . Then  $N_G(H)$  is the largest subgroup of  $G$  that includes  $H$  such that  $H$  is normal in  $N_G(H)$ .

PROOF:

(1)1.  $N_G(H)$  is a subgroup of  $G$ .

PROOF: If  $a, b \in N_G(H)$  then  $ab^{-1}Hba^{-1} = aHa^{-1} = H$  so  $ab^{-1} \in N_G(H)$ .

(1)2.  $H \subseteq N_G(H)$

PROOF: Easy.

(1)3.  $H$  is normal in  $N_G(H)$ .

PROOF: If  $a \in N_G(H)$  then  $aHa^{-1} = H$  by definition.

(1)4. For any subgroup  $K$  of  $G$ , if  $H \subseteq K$  and  $H$  is normal in  $K$  then  $K \subseteq N_G(H)$ .

PROOF:  $H$  is normal in  $K$  means that, for all  $a \in K$ , we have  $aHa^{-1} = H$  and so  $a \in N_G(H)$ .

$\square$

**Corollary 9.45.1.** Let  $G$  be a group and  $H$  a subgroup of  $G$ . Then  $H$  is normal if and only if  $G = N_G(H)$ .

**Proposition 9.46.** Let  $G$  be a group and  $H$  a subgroup of  $G$ . If  $[G : N_G(H)]$  is finite, then it is the number of subgroups conjugate to  $H$ .

PROOF: By the Orbit-Stabilizer Theorem.  $\square$

**Corollary 9.46.1.** Let  $G$  be a group and  $H$  a subgroup of  $G$ . If  $[G : H]$  is finite, then the number of subgroups conjugate to  $H$  is finite and divides  $[G : H]$ .

**Lemma 9.47.** Let  $H$  be a  $p$ -group that is a subgroup of a finite group  $G$ . Then

$$[N_G(H) : H] \equiv [G : H] \pmod{p}.$$

PROOF:

(1)1. ASSUME: w.l.o.g.  $H$  is non-trivial.

(1)2.  $gH$  is a fixed point of the action of  $H$  on the set of left cosets of  $H$  by left multiplication if and only if  $g \in N_G(H)$ .

PROOF:

$$gH \text{ is a fixed point} \Leftrightarrow \forall h \in H. hgH = gH$$

$$\Leftrightarrow H \subseteq gHg^{-1}$$

$$\Leftrightarrow H = gHg^{-1} \quad (|gHg^{-1}| = |H|)$$

$$\Leftrightarrow g \in N_G(H)$$

$\langle 1 \rangle 3$ . The number of fixed points in  $[N_G(H) : H]$ .

$\langle 1 \rangle 4$ . Q.E.D.

PROOF: Corollary 9.18.1.

□

**Proposition 9.48.** *Let  $H$  be a  $p$ -subgroup of a finite group  $G$  that is not a  $p$ -Sylow subgroup. Then there exists a  $p$ -subgroup  $H'$  of  $G$  such that  $H$  is a normal subgroup of  $H'$  and  $[H' : H] = p$ .*

PROOF:

$\langle 1 \rangle 1$ .  $p$  divides  $[N_G(H) : H]$ .

PROOF: Lemma 9.47.

$\langle 1 \rangle 2$ . PICK  $gH \in N_G(H)/H$  of order  $p$ .

PROOF: Cauchy's Theorem.

$\langle 1 \rangle 3$ . LET:  $H' = \pi^{-1}(\langle gH \rangle)$

$\langle 1 \rangle 4$ .  $H$  is a normal subgroup of  $H'$ .

$\langle 1 \rangle 5$ .  $[H' : H] = p$

□

**Corollary 9.48.1.** *No  $p$ -group of order  $\geq p^2$  is simple.*

**Lemma 9.49.** *Let  $p$  be a prime. Let  $G$  be a finite group. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . Every  $p$ -subgroup of  $N_G(P)$  is a subgroup of  $P$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $H$  be a  $p$ -subgroup of  $N_G(P)$ .

$\langle 1 \rangle 2$ .  $P$  is normal in  $N_G(P)$ .

PROOF: Proposition 9.45.

$\langle 1 \rangle 3$ .  $PH$  is a subgroup of  $N_G(P)$ .

PROOF: Second Isomorphism Theorem.

$\langle 1 \rangle 4$ .  $|PH/P| = |H/(P \cap H)|$

PROOF: Second Isomorphism Theorem.

$\langle 1 \rangle 5$ .  $PH$  is a  $p$ -group.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $q$  is prime,  $q \mid |PH|$  and  $q \neq p$

$\langle 2 \rangle 2$ .  $q \mid |PH/P|$

$\langle 2 \rangle 3$ .  $q \mid |H/(P \cap H)|$

$\langle 2 \rangle 4$ .  $q \mid |H|$

$\langle 2 \rangle 5$ . Q.E.D.

PROOF: This contradicts the fact that  $H$  is a  $p$ -group,  $\langle 1 \rangle 1$ .

$\langle 1 \rangle 6$ .  $PH = P$

PROOF: By maximality of  $P$ .

$\langle 1 \rangle 7$ .  $H \subseteq P$

□

**Lemma 9.50.** *Let  $p$  be a prime. Let  $G$  be a finite group. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . Let  $P$  act by conjugation on the set of  $p$ -Sylow subgroups of  $G$ . Then  $P$  is the unique fixed point of this action.*

PROOF:

$\langle 1 \rangle 1.$   $P$  is a fixed point of this action.

PROOF: For any  $x \in P$  we have  $xPx^{-1} = P$ .

$\langle 1 \rangle 2.$  If  $Q$  is any fixed point of the action then  $Q = P$ .

$\langle 2 \rangle 1.$  LET:  $Q$  be a fixed point of the action.

$\langle 2 \rangle 2.$  For all  $x \in P$  we have  $xQx^{-1} = Q$ .

$\langle 2 \rangle 3.$   $P \subseteq N_G(Q)$

$\langle 2 \rangle 4.$   $P \subseteq Q$

PROOF: Lemma 9.49.

$\langle 2 \rangle 5.$   $P = Q$

PROOF: Since  $|P| = |Q|$ .

□

**Theorem 9.51** (Third Sylow Theorem). *Let  $p$  be a prime. Let  $G$  be a finite group of order  $p^r m$  where  $p$  does not divide  $m$ . Then the number of  $p$ -Sylow subgroups of  $G$  divides  $m$  and is congruent to 1 modulo  $p$ .*

PROOF:

$\langle 1 \rangle 1.$  LET:  $N_p$  be the number of  $p$ -Sylow subgroups of  $G$ .

$\langle 1 \rangle 2.$  PICK a  $p$ -Sylow subgroup  $P$ .

PROOF: One exists by the First Sylow Theorem.

$\langle 1 \rangle 3.$  The  $p$ -Sylow subgroups of  $G$  are exactly the conjugates of  $P$ .

PROOF: Second Sylow Theorem

$\langle 1 \rangle 4.$   $m = N_p [N_G(P) : P]$

PROOF: Since  $N_p = [G : N_G(P)]$  by Proposition 9.46.

$\langle 1 \rangle 5.$   $N_p$  divides  $m$ .

$\langle 1 \rangle 6.$   $mN_p \equiv m \pmod{p}$

$\langle 2 \rangle 1.$   $m \equiv [N_G(P) : P] \pmod{p}$

PROOF: Lemma 9.47.

$\langle 2 \rangle 2.$   $mN_p \equiv m \pmod{p}$

PROOF: By  $\langle 1 \rangle 4$ .

$\langle 1 \rangle 7.$   $N_p \equiv 1 \pmod{p}$

□

PROOF:

$\langle 1 \rangle 1.$  LET:  $N_p$  be the number of  $p$ -Sylow subgroups of  $G$ .

$\langle 1 \rangle 2.$  PICK a  $p$ -Sylow subgroup  $P$  of  $G$ .

PROOF: First Sylow Theorem.

$\langle 1 \rangle 3.$   $N_p$  is the number of conjugates of  $P$ .

PROOF: Second Sylow Theorem.

$\langle 1 \rangle 4.$   $N_p \mid m$

PROOF: Corollary 9.46.1.

$\langle 1 \rangle 5.$   $P$  acts on the set of conjugates of  $P$  with one fixed point.

PROOF: Lemma 9.50.

$\langle 1 \rangle 6.$   $N_p \equiv 1 \pmod{p}$

PROOF: Corollary 9.18.1.

□

**Corollary 9.51.1.** *Let  $G$  be a finite group. Let  $p$  be a prime number. If  $|G| = mp^r$  and the only divisor  $d$  of  $m$  such that  $d \equiv 1 \pmod{p}$  is  $d = 1$ , then  $G$  is not simple.*

PROOF: There must be 1  $p$ -Sylow subgroup, which has order  $p^r$  and is normal.  $\square$

**Corollary 9.51.2.** *Let  $G$  be a finite group. Let  $p$  be a prime number. If  $|G| = mp^r$  where  $1 < m < p$  then  $G$  is not simple.*

**Proposition 9.52.** *Let  $p$  and  $q$  be prime numbers with  $p < q$ . Let  $G$  be a group of order  $pq$  with a normal subgroup  $H$  of order  $p$ . Then  $G$  is cyclic.*

PROOF:

$\langle 1 \rangle 1.$  LET:  $\gamma : G \rightarrow \text{Aut}_{\mathbf{Grp}}(H)$  be the action of conjugation.

$\langle 1 \rangle 2.$   $H$  is cyclic of order  $p$ .

$\langle 1 \rangle 3.$   $|\text{Aut}_{\mathbf{Grp}}(H)| = p - 1$

$\langle 1 \rangle 4.$   $|\text{im } \gamma| \mid pq$

PROOF: Since  $\text{im } \gamma$  is a quotient group of  $G$ .

$\langle 1 \rangle 5.$   $|\text{im } \gamma| \mid p - 1$

$\langle 1 \rangle 6.$   $|\text{im } \gamma| = 1$

$\langle 1 \rangle 7.$   $\gamma = 0$

$\langle 1 \rangle 8.$   $H \subseteq Z(G)$

$\langle 1 \rangle 9.$   $G$  is Abelian.

PROOF: Lemma 9.28.

$\langle 1 \rangle 10.$  PICK an element  $g$  of order  $p$ .

PROOF: Cauchy's Theorem.

$\langle 1 \rangle 11.$  PICK an element  $g$  of order  $q$ .

PROOF: Cauchy's Theorem.

$\langle 1 \rangle 12.$   $|gh| = pq$

PROOF: Proposition 6.19.

$\square$

**Corollary 9.52.1.** *Let  $p$  and  $q$  be prime numbers with  $p < q$  and  $q \not\equiv 1 \pmod{p}$ . Then the only group of order  $pq$  is the cyclic group.*

PROOF: By the Third Sylow Theorem, such a group must have exactly one  $p$ -Sylow subgroup, which is therefore normal.  $\square$

**Proposition 9.53.** *Let  $p$  be prime. Let  $G$  be a finite group. Let  $P$  be a  $p$ -Sylow subgroup of  $G$ . Then*

$$N_G(N_G(P)) = N_G(P) \ .$$

PROOF:

$\langle 1 \rangle 1.$   $P$  is normal in  $N_G(P)$ .

PROOF: Proposition 9.45.

$\langle 1 \rangle 2.$   $N_G(P)$  is normal in  $N_G(N_G(P))$ .

PROOF: Proposition 9.45.

$\langle 1 \rangle 3.$   $P$  is normal in  $N_G(N_G(P))$ .

PROOF: Corollary 7.106.1.

(1)4.  $N_G(N_G(P)) \subseteq N_G(P)$

PROOF: Proposition 9.45.

(1)5.  $N_G(N_G(P)) = N_G(P)$

□

**Proposition 9.54.** *Let  $p, q$  and  $r$  be three distinct prime numbers. Then there is no simple group of order  $pqr$ .*

PROOF:

(1)1. LET:  $G$  be a group of order  $pqr$ .

(1)2. ASSUME: w.l.o.g.  $p < q < r$

(1)3. ASSUME: for a contradiction  $G$  is simple.

(1)4. The number of subgroups of order  $p$  is at least  $p + 1$ .

PROOF: Third Sylow Theorem

(1)5. The number of subgroups of order  $q$  is at least  $q + 1$ .

PROOF: Third Sylow Theorem

(1)6. The number of subgroups of order  $r$  is  $pq$ .

PROOF: By the Third Sylow Theorem, the number divides  $pq$ , and it cannot be 1 (lest that subgroup be normal) or  $p$  or  $q$  (as these are less than  $r$  hence not congruent to 1 modulo  $r$ ).

(1)7. There are at least  $p^2 - 1$  elements of order  $p$ .

(1)8. There are at least  $q^2 - 1$  elements of order  $q$ .

(1)9. There are at least  $pqr - pq$  elements of order  $r$ .

(1)10. Q.E.D.

PROOF: This is a contradiction as the total number of elements of order 1,  $p$ ,  $q$  and  $r$  is

$$\begin{aligned} 1 + (p^2 - 1) + (q^2 - 1) + (pqr - pq) &= p^2 + q^2 + pqr - pq - 1 \\ &> pqr + p^2 - 1 \\ &> pqr \end{aligned}$$

□

**Proposition 9.55.** *Let  $G$  be a finite simple group. Let  $H$  be a subgroup of  $G$  of index  $N > 1$ . Then  $|G|$  divides  $N!$ .*

PROOF:

(1)1. PICK a subgroup  $K$  of  $H$  that is normal in  $G$  such that  $[G : K]$  divides  $\gcd(|G|, N!)$ .

(1)2.  $K = \{e\}$

(1)3.  $[G : K] = |G|$

(1)4.  $|G|$  divides  $N!$

□

**Corollary 9.55.1.** *Let  $G$  be a finite simple group. Let  $p$  be a prime factor of  $|G|$ . Let  $N_p$  be the number of  $p$ -Sylow subgroups of  $G$ . Then  $|G|$  divides  $N_p!$ .*

PROOF: Since  $N_p = [G : N_G(P)]$  and  $N_p > 1$  since  $G$  is simple. □

**Definition 9.56** (Centralizer). Let  $G$  be a group and  $A \subseteq G$ . The *centralizer* of  $A$  is

$$Z_G(A) := \{g \in G : \forall a \in A. gag^{-1} = a\} .$$

**Proposition 9.57.** Let  $H$  and  $K$  be subgroups of  $G$  with  $H \subseteq N_G(K)$ . Then the function  $\gamma : H \rightarrow \text{Aut}_{\mathbf{Grp}}(K)$  defined by conjugation

$$\gamma_h(k) = hkh^{-1}$$

is a homomorphism of groups with  $\ker \gamma = H \cap Z_G(K)$ .

PROOF:

$\langle 1 \rangle 1$ . For all  $g, h \in H$  we have  $\gamma_{gh} = \gamma_g \circ \gamma_h$ .

PROOF: Since  $\gamma_{gh}(k) = \gamma_g(\gamma_h(k)) = ghkh^{-1}g^{-1}$ .

$\langle 1 \rangle 2$ . For all  $h \in H$  we have  $\gamma_h = \text{id}_K$  iff  $h \in Z_G(K)$ .

PROOF: Both are equivalent to  $\forall k \in K. hkh^{-1} = k$ , i.e.  $\forall k \in K. hk = kh$ .

□

## 9.7 Nilpotent Groups

**Definition 9.58** (Nilpotent). Let  $G$  be a group. Define inductively a sequence  $(Z_n)$  of subgroups of  $G$  by  $Z_0 = \{e\}$ , and  $Z_{i+1}$  is the inverse image under  $\pi$  of the center of  $G/Z_i$ .

Then  $G$  is *nilpotent* iff  $Z_n = G$  for some  $n$ .

We prove this is well-defined by proving that, for all  $i$ , we have  $Z_i$  is normal in  $G$ .

PROOF:

$\langle 1 \rangle 1$ . ASSUME: as induction hypothesis  $Z_i$  is normal in  $G$ .

PROVE:  $Z_{i+1}$  is normal in  $G$ .

$\langle 1 \rangle 2$ . LET:  $x \in Z_{i+1}$  and  $g \in G$

PROVE:  $gxg^{-1} \in Z_{i+1}$

PROVE: For all  $h \in G$  we have  $gxg^{-1}hZ_i = hgxg^{-1}Z_i$

$\langle 1 \rangle 3$ . LET:  $h \in G$

$\langle 1 \rangle 4$ .  $gxg^{-1}hZ_i = hgxg^{-1}Z_i$

PROOF:

$$\begin{aligned} gxg^{-1}hZ_i &= gg^{-1}hxZ_i \\ &= hxZ_i \\ &= hgg^{-1}xZ_i \\ &= hgxg^{-1}Z_i \end{aligned}$$

□

**Proposition 9.59.** Every Abelian group is nilpotent.

PROOF: Let  $G$  be an Abelian group. The center of  $G/Z_0$  is  $G/Z_0$ , hence  $Z_1 = G$ .

□



**Proposition 9.60.** *Let  $G$  be a group. Then  $G$  is nilpotent if and only if  $G/Z(G)$  is nilpotent.*

PROOF:

- (1)1. LET:  $(Z_n)$  be the sequence of subgroups of  $G$  where  $Z_0 = \{e\}$  and  $Z_{n+1}$  is the inverse image of the center of  $G/Z_n$ .
- (1)2.  $G/Z_0 \cong G$
- (1)3.  $Z_1 = Z(G)$
- (1)4. The corresponding sequence of subgroups for  $G/Z(G)$  is  $G/Z(G)$ ,  $Z_2/Z(G)$ ,  $Z_3/Z(G)$ ,  $\dots$
- (1)5.  $G$  is nilpotent iff  $G/Z(G)$  is nilpotent.

PROOF: Both are equivalent to  $\exists n. Z_n = G$  and to  $\exists n. Z_n/Z(G) = G/Z(G)$ .

□

**Proposition 9.61.** *Every  $p$ -group is nilpotent.*

PROOF: Each  $Z_n$  is a  $p$ -group and so has non-trivial center, hence each  $Z_{n+1}$  is larger than  $Z_n$  and so the sequence must terminate. □

**Proposition 9.62.** *Every nilpotent group is solvable.*

PROOF: Let  $(Z_n)$  be the defining sequence of subgroups. Then  $Z_{n+1}/Z_n = Z(G/Z_n)$  is Abelian for all  $n$ , hence the group is solvable by Proposition 8.42. □

**Example 9.63.** The converse is not true —  $S_3$  is solvable but not nilpotent.

**Proposition 9.64.** *Let  $G$  be a nilpotent group. Then every nontrivial normal subgroup of  $G$  intersects  $Z(G)$  non-trivially.*

PROOF:

- (1)1. LET:  $H$  be a nontrivial normal subgroup of  $G$ .
- (1)2. LET:  $(Z_n)$  be the sequence of subgroups with  $Z_0 = \{e\}$  and  $Z_{n+1}$  the inverse image of  $Z(G/Z_n)$ .
- (1)3. LET:  $r$  be least such that  $H \cap Z_r \neq \{e\}$ .
- (1)4. PICK  $h \in H \cap Z_r$  with  $h \neq e$ .
- (1)5.  $hZ_{r-1} \in Z(G/Z_{r-1})$
- (1)6. For all  $g \in G$  we have  $ghZ_{r-1} = hgZ_{r-1}$
- (1)7. For all  $g \in G$  we have  $ghg^{-1}h^{-1} \in Z_{r-1}$
- (1)8. For all  $g \in G$  we have  $ghg^{-1}h^{-1} = e$

PROOF: Since  $ghg^{-1}h^{-1} \in H$  and  $H \cap Z_{r-1} = \{e\}$ .

- (1)9. For all  $g \in G$  we have  $gh = hg$

- (1)10.  $h \in H \cap Z(G)$

□

**Example 9.65.** We cannot weaken the hypothesis to  $G$  being solvable.  $S_3$  is solvable and  $\mathbb{Z}/2\mathbb{Z}$  is a nontrivial normal subgroup but its intersection with  $Z(S_3)$  is just  $\{e\}$ .

**Proposition 9.66.** *Let  $G$  be a finite nilpotent group. Let  $H$  be a proper subgroup of  $G$ . Then  $H \subsetneq N_G(H)$ .*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: as induction hypothesis the theorem holds for all groups smaller than  $G$ .

$\langle 1 \rangle 2$ .  $Z(G)$  is non-trivial.

$\langle 1 \rangle 3$ . CASE:  $Z(G) \not\subseteq H$

$\langle 2 \rangle 1$ . PICK  $g \in Z(G) - H$

$\langle 2 \rangle 2$ .  $g \in N_G(H) - H$

$\langle 1 \rangle 4$ . CASE:  $Z(G) \subseteq H$

$\langle 2 \rangle 1$ .  $H/Z(G) \subsetneq N_{G/Z(G)}(H/Z(G))$

PROOF: By induction hypothesis  $\langle 1 \rangle 1$ .

$\langle 2 \rangle 2$ . PICK  $g$  such that  $gZ(G) \in N_{G/Z(G)}(H/Z(G)) - H/Z(G)$

$\langle 2 \rangle 3$ .  $g \in N_G(H)$

$\langle 3 \rangle 1$ . LET:  $h \in H$

PROVE:  $ghg^{-1} \in H$

$\langle 3 \rangle 2$ .  $ghg^{-1}Z(G) \in H/Z(G)$

$\langle 3 \rangle 3$ . PICK  $h_1 \in H$  such that  $ghg^{-1}Z(G) = h_1Z(G)$

$\langle 3 \rangle 4$ .  $ghg^{-1}h_1^{-1} \in Z(G)$

$\langle 3 \rangle 5$ .  $ghg^{-1}h_1^{-1} \in H$

PROOF:  $\langle 1 \rangle 4$

$\langle 3 \rangle 6$ .  $ghg^{-1} \in H$

$\langle 2 \rangle 4$ .  $g \notin H$

□

**Corollary 9.66.1.** *Every Sylow subgroup of a finite nilpotent group is normal.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $G$  be a finite nilpotent group.

$\langle 1 \rangle 2$ . LET:  $P$  be Sylow subgroup of  $G$

$\langle 1 \rangle 3$ .  $N_G(P) = N_G(N_G(P))$

PROOF: Proposition 9.53.

$\langle 1 \rangle 4$ .  $N_G(P) = G$

PROOF: Proposition 9.66.

$\langle 1 \rangle 5$ .  $P$  is normal.

□

## Chapter 10

# Classification of Groups

**Example 10.1.**     • The only group of order 1 is the trivial group.

- The only group of order 2 is  $C_2$ .
- The only group of order 3 is  $C_3$ .
- There are two groups of order 4:  $C_4$  and  $C_2 \times C_2$ .
- The only group of order 5 is  $C_5$ .
- There are two groups of order 6:  $C_6$  and  $S_3$ .
- The only group of order 7 is  $C_7$ .
- There are two groups of order 9:  $C_9$  and  $C_3 \times C_3$ .
- There are two groups of order 10:  $C_{10}$  and  $D_{10}$ .
- The only group of order 11 is  $C_{11}$ .
- The only group of order 13 is  $C_{13}$ .
- There are two groups of order 14:  $C_{14}$  and  $D_{14}$ .
- The only group of order 15 is  $C_{15}$ .

**Proposition 10.2.** *The only non-Abelian groups of order 8 are  $D_8$  and  $Q_8$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $G$  be a non-Abelian group of order 8.

$\langle 1 \rangle 2$ .  $G$  has no element of order 8.

PROOF: If it does then it is  $C_8$  and hence Abelian.

$\langle 1 \rangle 3$ . PICK an element  $y$  of order 4.

$\langle 2 \rangle 1$ . PICK an element  $a$  of order 2.

$\langle 2 \rangle 2$ .  $G/\langle a \rangle$  is isomorphic to  $C_4$  or  $C_2 \times C_2$ .

$\langle 2 \rangle 3$ . PICK an element  $y\langle a \rangle$  of order 2 in  $G/\langle a \rangle$

$\langle 2 \rangle 4. y^2 \in \langle a \rangle$

$\langle 2 \rangle 5. \text{ CASE:}$

$$y^2 = a$$

PROOF: In this case  $y$  is of order 4.

$\langle 2 \rangle 6. \text{ CASE:}$

$$y^2 = e$$

PROOF: In this case  $G \cong C_2^3$  which is Abelian.

$\langle 1 \rangle 4. \text{ PICK } x \notin \langle y \rangle \text{ such that } x^2 = e \text{ or } x^2 = y^2$

$\langle 2 \rangle 1. G/\langle y \rangle \cong C_2$

$\langle 2 \rangle 2. \text{ PICK } x\langle y \rangle \in G/\langle y \rangle \text{ of order 2.}$

$\langle 2 \rangle 3. x^2 \in \langle y \rangle$

$\langle 2 \rangle 4. x^2 \neq y \text{ and } x^2 \neq y^3$

$\langle 2 \rangle 5. x^2 = e \text{ or } x^2 = y^2$

$\langle 1 \rangle 5. xy = y^3x$

$\langle 2 \rangle 1. xy \neq e$

PROOF: Since  $y^{-1} = y^3 \neq x$ .

$\langle 2 \rangle 2. xy \neq y$

PROOF:  $xy = y$  implies  $x = e$ .

$\langle 2 \rangle 3. xy \neq y^2$

PROOF:  $xy = y^2$  implies  $x = y$ .

$\langle 2 \rangle 4. xy \neq y^3$

PROOF:  $xy = y^3$  implies  $x = y^2$ .

$\langle 2 \rangle 5. xy \neq x$

PROOF:  $xy = x$  implies  $y = e$ .

$\langle 2 \rangle 6. xy \neq yx$

PROOF:  $xy = yx$  implies  $G$  is Abelian.

$\langle 2 \rangle 7. xy \neq y^2x$

$\langle 3 \rangle 1. \text{ ASSUME: for a contradiction } xy = y^2x$

$\langle 3 \rangle 2. xy^2 = x$

PROOF:

$$\begin{aligned} xy^2 &= y^2xy \\ &= y^4x \\ &= x \end{aligned}$$

$\langle 3 \rangle 3. y^2 = e$

$\langle 1 \rangle 6. \text{ The multiplication table of } G \text{ is one of the following.}$

$e$	$y$	$y^2$	$y^3$	$x$	$yx$	$y^2x$	$y^3x$
$y$	$y^2$	$y^3$	$e$	$yx$	$y^2x$	$y^3x$	$x$
$y^2$	$y^3$	$e$	$y$	$y^2x$	$y^3x$	$x$	$yx$
$y^3$	$e$	$y$	$y^2$	$y^3x$	$x$	$yx$	$y^2x$
$x$	$y^3x$	$y^2x$	$yx$	$e$	$y^3$	$y^2$	$y$
$yx$	$x$	$y^3x$	$y^2x$	$y$	$e$	$y^3$	$y^2$
$y^2x$	$yx$	$x$	$y^3x$	$y^2$	$y$	$e$	$y^3$
$y^3x$	$y^2x$	$yx$	$x$	$y^3$	$y^2$	$y$	$e$

$e$	$y$	$y^2$	$y^3$	$x$	$yx$	$y^2x$	$y^3x$
$y$	$y^2$	$y^3$	$e$	$yx$	$y^2x$	$y^3x$	$x$
$y^2$	$y^3$	$e$	$y$	$y^2x$	$y^3x$	$x$	$yx$
$y^3$	$e$	$y$	$y^2$	$y^3x$	$x$	$yx$	$y^2x$
$x$	$y^3x$	$y^2x$	$yx$	$y^2$	$y$	$e$	$y^3$
$yx$	$x$	$y^3x$	$y^2x$	$y^3$	$y^2$	$y$	$e$
$y^2x$	$yx$	$x$	$y^3x$	$e$	$y^3$	$y^2$	$y$
$y^3x$	$y^2x$	$yx$	$x$	$y$	$e$	$y^3$	$y^2$

$\langle 1 \rangle 7. G \cong D_8$  or  $G \cong Q_8$ .

□

**Proposition 10.3.** *Let  $q$  be an odd prime. Then  $D_{2q}$  is the only non-Abelian group of order  $2q$ .*

PROOF:

$\langle 1 \rangle 1.$  LET:  $G$  be a non-Abelian group of order  $2q$ .

$\langle 1 \rangle 2.$  PICK  $y \in G$  of order  $q$ .

PROOF: Cauchy's Theorem

$\langle 1 \rangle 3.$   $\langle y \rangle$  is the only subgroup of order  $q$ .

PROOF: Third Sylow Theorem

$\langle 1 \rangle 4.$   $\langle y \rangle$  is normal.

$\langle 1 \rangle 5.$  PICK  $x \in G - \langle y \rangle - \{e\}$

$\langle 1 \rangle 6.$   $|x| = 2$

PROOF: We cannot have  $|x| = 2q$  since  $G$  is not cyclic, and  $|x| \neq q$  since  $\langle x \rangle$  is not the subgroup of order  $q$ .

$\langle 1 \rangle 7.$   $xyx^{-1} \in \langle y \rangle$

PROOF: Since  $x\langle y \rangle x^{-1} = \langle y \rangle$  by  $\langle 1 \rangle 3$ .

$\langle 1 \rangle 8.$  PICK  $r$  such that  $0 \leq r < q$  and  $xyx^{-1} = y^r$ .

$\langle 1 \rangle 9.$   $y^{r^2} = y$

PROOF:

$$y^{r^2} = (xyx^{-1})^r \quad (\langle 1 \rangle 8)$$

$$= xy^r x^{-1}$$

$$= x^2 y x^{-2} \quad (\langle 1 \rangle 8)$$

$$= y \quad (\langle 1 \rangle 6)$$

$\langle 1 \rangle 10.$   $q \mid (r-1)(r+1)$

PROOF: Since  $y^{(r-1)(r+1)} = e$  and  $|y| = q$  by  $\langle 1 \rangle 2$ .

$\langle 1 \rangle 11.$   $r = 1$  or  $r = q-1$

PROOF: Since  $0 \leq r < q$  by  $\langle 1 \rangle 8$ .

$\langle 1 \rangle 12.$   $r \neq 1$

$\langle 2 \rangle 1.$  ASSUME: for a contradiction  $r = 1$ .

$\langle 2 \rangle 2.$   $xy = yx$

PROOF:  $\langle 1 \rangle 8$

$\langle 2 \rangle 3.$   $|xy| = 2q$

PROOF: Proposition 6.19

$\langle 2 \rangle 4.$   $G$  is cyclic.

$\langle 2 \rangle 5.$  Q.E.D.

PROOF: This contradicts  $\langle 1 \rangle 1$ .

$\langle 1 \rangle 13$ .  $x^2 = e$  and  $y^q = e$  and  $yx = xy^{q-1}$

$\langle 1 \rangle 14$ .  $G \cong D_{2q}$

□

**Corollary 10.3.1.** *For  $q$  an odd prime, the only groups of order  $2q$  are  $C_{2q}$  and  $D_{2q}$ .*

**Proposition 10.4.** *There is no non-Abelian simple group of order less than 60.*

PROOF: We rule out the other sizes as follows:

- 1 — Only group is the trivial group.
- 2 — Prime therefore cyclic
- 3 — Prime therefore cyclic
- 4 — Corollary 9.48.1
- 5 — Prime therefore cyclic
- 6 — Corollary 9.51.2
- 7 — Prime therefore cyclic
- 8 — Corollary 9.48.1
- 9 — Corollary 9.48.1
- 10 — Corollary 9.51.2
- 11 — Prime therefore cyclic
- 12 —

$\langle 1 \rangle 1$ . There is no simple non-Abelian group of order 12.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 12.

$\langle 2 \rangle 2$ .  $G$  has 4 3-Sylow subgroups.

$\langle 2 \rangle 3$ .  $G$  has 8 elements of order 3.

$\langle 2 \rangle 4$ .  $G$  has 3 elements of order 2 or 4.

$\langle 2 \rangle 5$ .  $G$  has one 2-Sylow subgroup.

$\langle 2 \rangle 6$ . The 2-Sylow subgroup of  $G$  is normal.

$\langle 2 \rangle 7$ . Q.E.D.

PROOF: This contradicts  $\langle 2 \rangle 1$ .

- 13 — Prime therefore cyclic
- 14 — Corollary 9.51.2
- 15 — Corollary 9.51.2

- 16 — Corollary 9.48.1
  - 17 — Prime therefore cyclic
  - 18 — Corollary 9.51.2
  - 19 — Prime therefore cyclic
  - 20 — Corollary 9.51.2
  - 21 — Corollary 9.51.2
  - 22 — Corollary 9.51.2
  - 23 — Prime therefore cyclic
  - 24 —
- (1)2. There is no simple non-Abelian group of order 24.
- ⟨2⟩1. ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 24.
- ⟨2⟩2.  $G$  has 3 2-Sylow subgroups.
- ⟨2⟩3. LET:  $\gamma : G \rightarrow S_3$  be the action of conjugation of  $G$  on the set of 2-Sylow subgroups.
- ⟨2⟩4.  $\ker \gamma \neq \{e\}$   
PROOF:  $\gamma$  cannot be injective since  $|G| > |S_3|$ .
- ⟨2⟩5.  $\ker \gamma \neq G$
- ⟨2⟩6.  $\ker \gamma$  is a proper non-trivial normal subgroup of  $G$ .
- ⟨2⟩7. Q.E.D.  
PROOF: This contradicts ⟨2⟩1.
- 25 — Corollary 9.48.1
  - 26 — Corollary 9.51.2
  - 27 — Corollary 9.48.1
  - 28 — Corollary 9.51.2
  - 29 — Prime therefore cyclic
  - 30 — Proposition 9.54
  - 31 — Prime therefore cyclic
  - 32 — Corollary 9.48.1
  - 33 — Corollary 9.51.2
  - 34 — Corollary 9.51.2
  - 35 — Corollary 9.51.2

- 36 —

⟨1⟩3. There is no simple non-Abelian group of order 36.

⟨2⟩1. ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 36.

⟨2⟩2.  $G$  has 4 3-Sylow subgroups.

⟨2⟩3. LET:  $\gamma : G \rightarrow S_4$  be the action of conjugation of  $G$  on the set of 2-Sylow subgroups.

⟨2⟩4.  $\ker \gamma \neq \{e\}$

PROOF:  $\gamma$  cannot be injective since  $|G| > |S_4|$ .

⟨2⟩5.  $\ker \gamma \neq G$

⟨2⟩6.  $\ker \gamma$  is a proper non-trivial normal subgroup of  $G$ .

⟨2⟩7. Q.E.D.

PROOF: This contradicts ⟨2⟩1.

- 37 — Prime therefore cyclic

- 38 — Corollary 9.51.2

- 39 — Corollary 9.51.2

- 40 — There can be only 1 5-Sylow subgroup.

- 41 — Prime therefore cyclic

- 42 — Proposition 9.54

- 43 — Prime therefore cyclic

- 44 — Corollary 9.51.2

- 45 — There can be only 1 5-Sylow subgroup.

- 46 — Corollary 9.51.2

- 47 — Prime therefore cyclic

- 48 —

⟨1⟩4. There is no simple non-Abelian group of order 48.

⟨2⟩1. ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 48.

⟨2⟩2.  $G$  has 3 2-Sylow subgroups.

⟨2⟩3. LET:  $\gamma : G \rightarrow S_3$  be the action of conjugation of  $G$  on the set of 2-Sylow subgroups.

⟨2⟩4.  $\ker \gamma \neq \{e\}$

PROOF:  $\gamma$  cannot be injective since  $|G| > |S_3|$ .

⟨2⟩5.  $\ker \gamma \neq G$

⟨2⟩6.  $\ker \gamma$  is a proper non-trivial normal subgroup of  $G$ .

⟨2⟩7. Q.E.D.

PROOF: This contradicts ⟨2⟩1.



- 49 — Corollary 9.48.1
- 50 — Corollary 9.51.2
- 51 — Corollary 9.51.2
- 52 — Corollary 9.51.2
- 53 — Prime therefore cyclic
- 54 — Corollary 9.51.2
- 55 — Corollary 9.51.2
- 56 — Corollary 9.51.2
- 57 — Corollary 9.51.2
- 58 — Corollary 9.51.2
- 59 — Prime therefore cyclic

**Proposition 10.5.** *Every simple group of order 60 has a subgroup of index 5.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $G$  be a simple group of order 60.

$\langle 1 \rangle 2$ . The number of 2-Sylow subgroups of  $G$  is either 5 or 15.

$\langle 2 \rangle 1$ . LET:  $n$  be the number of 2-Sylow subgroups.

$\langle 2 \rangle 2$ .  $60 \mid n!$

PROOF: Corollary 9.55.1.

$\langle 2 \rangle 3$ .  $n \geq 5$

$\langle 2 \rangle 4$ .  $n \mid 15$

PROOF: Third Sylow Theorem

$\langle 2 \rangle 5$ .  $n = 5$  or  $n = 15$

$\langle 1 \rangle 3$ . ASSUME: w.l.o.g.  $G$  has 15 2-Sylow subgroups.

$\langle 1 \rangle 4$ .  $G$  has 4 or 10 3-Sylow subgroups.

$\langle 1 \rangle 5$ .  $G$  has 10 3-Sylow subgroups.

PROOF: Corollary 9.55.1.

$\langle 1 \rangle 6$ .  $G$  has exactly 6 5-Sylow subgroups.

$\langle 1 \rangle 7$ . The number of elements of order 3 is 20.

$\langle 1 \rangle 8$ . The number of elements of order 5 is 24.

$\langle 1 \rangle 9$ . The number of elements of order 2 or 4 is 15.

$\langle 1 \rangle 10$ . PICK two 2-Sylow subgroups  $H_1$  and  $H_2$  with non-trivial intersection.

$\langle 1 \rangle 11$ . LET:  $g \in G$  be such that  $H_1 \cap H_2 = \{e, g\}$ .

$\langle 1 \rangle 12$ . LET:  $K = Z_G(H_1 \cap H_2)$

$\langle 1 \rangle 13$ .  $|K| = 12$  or  $|K| = 20$

PROOF: We have  $4 \mid |K|$  since  $H_1 \leq K$ , and  $|K| \geq 6$  since  $H_1 \cup H_2 \subseteq K$ . We also have  $|K| \mid 60$ .

$\langle 1 \rangle 14$ .  $[G : K] \neq 3$

PROOF: There cannot be an embedding of  $G$  in  $S_3$ .

$\langle 1 \rangle 15. [G : K] = 5$

□

**Proposition 10.6.** *There is no non-Abelian simple group of order between 60 and 168.*

PROOF: We rule out the other sizes as follows:

- 61 — prime therefore cyclic
- 62 — Corollary 9.51.2
- 63 — Corollary 9.51.1
- 64 — Corollary 9.48.1
- 65 — Corollary 9.51.2
- 66 — Corollary 9.51.2
- 67 — prime therefore cyclic
- 68 — Corollary 9.51.2
- 69 — Corollary 9.51.2
- 70 — Proposition 9.54
- 71 — prime therefore cyclic
- 72

$\langle 1 \rangle 1.$  There is no simple non-Abelian group of order 72

PROOF:

$\langle 2 \rangle 1.$  ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 72.

$\langle 2 \rangle 2.$   $G$  has 4 3-Sylow subgroups.

$\langle 2 \rangle 3.$  LET:  $\gamma : G \rightarrow S_4$  be the action of conjugation on the set of 3-Sylow subgroups.

$\langle 2 \rangle 4.$   $\ker \gamma \neq 1$

PROOF: Since  $|G| > |S_4|$ .

$\langle 2 \rangle 5.$   $\ker \gamma$  is a non-trivial proper subgroup of  $G$ .

$\langle 2 \rangle 6.$  Q.E.D.

PROOF: This is a contradiction.

- 73 — prime therefore cyclic
- 74 — Corollary 9.51.2
- 75 — Corollary 9.51.2
- 76 — Corollary 9.51.2

- 77 — Corollary 9.51.2
- 78 — Corollary 9.51.2
- 79 — prime therefore cyclic
- 80

$\langle 1 \rangle 2$ . There is no simple non-Abelian group of order 80.

PROOF:

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 80.

$\langle 2 \rangle 2$ .  $G$  has 5 2-Sylow subgroups.

$\langle 2 \rangle 3$ . LET:  $\gamma : G \rightarrow S_5$  be the action of conjugation on the set of 2-Sylow subgroups.

$\langle 2 \rangle 4$ .  $\ker \gamma \neq 1$

PROOF: Otherwise  $\text{im } \gamma$  would be a subgroup of  $S_5$  of order 80, contradicting Lagrange's Theorem.

$\langle 2 \rangle 5$ .  $\ker \gamma$  is a non-trivial normal subgroup of  $G$ .

$\langle 2 \rangle 6$ . Q.E.D.

PROOF: This is a contradiction.

- 81 — Corollary 9.48.1
- 82 — Corollary 9.51.2
- 83 — prime therefore cyclic
- 84 — Corollary 9.51.1
- 85 — Corollary 9.51.2
- 86 — Corollary 9.51.2
- 87 — Corollary 9.51.2
- 88 — Corollary 9.51.2
- 89 — prime therefore cyclic
- 90 — Corollary 9.51.1
- 91 — Corollary 9.51.2
- 92 — Corollary 9.51.2
- 93 — Corollary 9.51.2
- 94 — Corollary 9.51.2
- 95 — Corollary 9.51.2

- 96 — There are 3 2-Sylow subgroups. The kernel of the action of conjugation  $G \rightarrow S_3$  is a non-trivial normal subgroup of  $G$ .
- 97 — prime therefore cyclic
- 98 — Corollary 9.51.2
- 99 — Corollary 9.51.2
- 100 — Corollary 9.51.2
- 101 — prime therefore cyclic
- 102 — Proposition 9.54
- 103 — prime therefore cyclic
- 104 — Corollary 9.51.2
- 105 — Proposition 9.54
- 106 — Corollary 9.51.2
- 107 — prime therefore cyclic
- 108 — There are 4 3-Sylow subgroups. The kernel of the action of conjugation  $G \rightarrow S_4$  is a non-trivial normal subgroup of  $G$ .
- 109 — prime therefore cyclic
- 110 — Proposition 9.54
- 111 — Corollary 9.51.2
- 112
  - $\langle 1 \rangle 3$ . There is no simple non-Abelian group of order 112.
  - $\langle 2 \rangle 1$ . ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 112.
  - $\langle 2 \rangle 2$ .  $G$  has exactly 7 2-Sylow subgroups.
  - $\langle 2 \rangle 3$ . LET:  $\gamma : G \rightarrow A_7$  be the action of conjugation of  $G$  on the set of 2-Sylow subgroups.
  - PROOF:  $\gamma(g)$  is always an even permutation since  $G$  has no subgroup of index 2.
  - $\langle 2 \rangle 4$ .  $\ker \gamma \neq 1$
  - PROOF: Since  $|G|$  does not divide  $|A_7| = 7!/2$ .
  - $\langle 2 \rangle 5$ .  $\ker \gamma$  is a non-trivial normal subgroup of  $G$ .
  - $\langle 2 \rangle 6$ . Q.E.D.
- 113 — prime therefore cyclic
- 114 — Proposition 9.54

- 115 — Corollary 9.51.2
- 116 — Corollary 9.51.2
- 117 — Corollary 9.51.2
- 118 — Corollary 9.51.2
- 119 — Corollary 9.51.2
- 120

$\langle 1 \rangle 4$ . There is no simple non-Abelian group of order 120.

PROOF:

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 120.

$\langle 2 \rangle 2$ . There are exactly 6 5-Sylow subgroups.

$\langle 2 \rangle 3$ . LET:  $\gamma : G \rightarrow A_6$  be the action of conjugation on the set of 5-Sylow subgroups.

$\langle 2 \rangle 4$ .  $\text{im } \gamma$  is a subgroup of  $A_6$  of order 120.

$\langle 2 \rangle 5$ . Q.E.D.

PROOF: This is a contradiction by inspection of the list of subgroups of  $A_6$ .

- 121 — Corollary 9.48.1
- 122 — Corollary 9.51.2
- 123 — Corollary 9.51.2
- 124 — Corollary 9.51.2
- 125 — Corollary 9.48.1
- 126 — Corollary 9.51.1
- 127 — prime therefore cyclic
- 128 — Corollary 9.48.1
- 129 — Corollary 9.51.2
- 130 — Proposition 9.54
- 131 — prime therefore cyclic
- 132

$\langle 1 \rangle 5$ . There is no simple non-Abelian group of order 132.

$\langle 2 \rangle 1$ . ASSUME: for a contradiction  $G$  is a simple non-Abelian group of order 132.

$\langle 2 \rangle 2$ . There are at least 4 3-Sylow subgroups.

- $\langle 2 \rangle 3$ . There are at least 8 elements of order 3.
- $\langle 2 \rangle 4$ . There are exactly 12 11-Sylow subgroups.
- $\langle 2 \rangle 5$ . There are exactly 120 elements of order 11.
- $\langle 2 \rangle 6$ . There are exactly 3 elements of order 2.
- $\langle 2 \rangle 7$ . There is a unique 2-Sylow subgroups.
- $\langle 2 \rangle 8$ . Q.E.D.

PROOF: This is a contradiction.

- 133 — Corollary 9.51.2
- 134 — Corollary 9.51.2
- 135 — Corollary 9.51.1
- 136 — Corollary 9.51.2
- 137 — prime therefore cyclic
- 138 — Proposition 9.54
- 139 — prime therefore cyclic
- 140 — Corollary 9.51.1
- 141 — Corollary 9.51.2
- 142 — Corollary 9.51.2
- 143 — Corollary 9.51.2
- 144 — Burnside's Theorem
- 145 — Burnside's Theorem
- 146 — Burnside's Theorem
- 147 — Burnside's Theorem
- 148 — Burnside's Theorem
- 149 — prime therefore cyclic
- 150 — There are exactly 6 5-Sylow subgroups. The kernel of the action of conjugation  $G \rightarrow A_5$  is a non-trivial normal subgroup since 150 does not divide  $|A_5| = 60$ .
- 151 — prime therefore cyclic
- 152 — Burnside's Theorem
- 153 — Burnside's Theorem
- 154 — Proposition 9.54

- 155 — Burnside's Theorem
- 156 — Corollary 9.51.2
- 157 — prime therefore cyclic
- 158 — Burnside's Theorem
- 159 — Burnside's Theorem
- 160 — Burnside's Theorem
- 161 — Burnside's Theorem
- 162 — Burnside's Theorem
- 163 — prime therefore cyclic
- 164 — Burnside's Theorem
- 165 — Proposition 9.54
- 166 — Burnside's Theorem
- 167 — prime therefore cyclic





**Part III**

**Ring Theory**



# Chapter 11

## Rngs

**Definition 11.1** (Ring). A *rng* consists of a set  $R$  and binary operations  $+, \cdot : R^2 \rightarrow R$  such that:

- $(R, +)$  is an Abelian group
- $\cdot$  is associative.
- The *distributive properties* hold: for all  $r, s, t \in R$  we have

$$(r + s)t = rt + st, \quad r(s + t) = rs + rt .$$

**Example 11.2.**     • The *zero rng* is  $\{0\}$ .

- $\mathbb{Z}, \mathbb{Q}, \mathbb{R}$  and  $\mathbb{C}$  are rngs.
- $2\mathbb{Z}$  is a rng.
- Given a rng  $R$  and natural number  $n$ , then the set  $\mathfrak{gl}_n(R)$  of all  $n \times n$  matrices with entries in  $R$  is a rng under matrix addition and matrix multiplication.
- For any set  $S$ , the power set  $\mathcal{P}S$  is a rng under  $A + B = (A \cup B) - (A \cap B)$  and  $AB = A \cap B$ .
- Given a rng  $R$  and a set  $S$ , then  $R^S$  is a rng under  $(f + g)(s) = f(s) + g(s)$  and  $(fg)(s) = f(s)g(s)$  for all  $f, g \in R^S$  and  $s \in S$ .
- The set  $\mathfrak{sl}_n(\mathbb{R}) = \{M \in \mathfrak{gl}_n(\mathbb{R}) : \text{tr } M = 0\}$  is a rng.
- The set  $\mathfrak{sl}_n(\mathbb{C}) = \{M \in \mathfrak{gl}_n(\mathbb{C}) : \text{tr } M = 0\}$  is a rng.
- $\mathbb{Z}/n\mathbb{Z}$  is a rng.

- The ring  $\mathbb{H}$  of *quaternions* is  $\mathbb{R}^4$  under the following operations, where we write  $(a, b, c, d)$  as  $a + bi + cj + dk$ :

$$\begin{aligned}
 (a + bi + cj + dk) + (a' + b'i + c'j + d'k) &= (a + a') + (b + b')i \\
 &\quad + (c + c')j + (d + d')k \\
 (a + bi + cj + dk)(a' + b'i + c'j + d'k) &= (aa' - bb' - cc' - dd') \\
 &\quad + (ab' + ba' + cd' - dc')i \\
 &\quad + (ac' - bd' + ca' + db')j \\
 &\quad + (ad' + bc' - cb' + da')k
 \end{aligned}$$

- For any Abelian group  $G$ , the set  $\text{End}_{\mathbf{Ab}}(G)$  is a ring under pointwise addition and composition.

**Proposition 11.3.** *In any rng  $R$  we have*

$$\forall x \in R. x0 = 0x = 0.$$

PROOF:

$$\begin{aligned}
 x0 &= x(0 + 0) \\
 &= x0 + x0
 \end{aligned}$$

and so  $x0 = 0$  by Cancellation. Similarly  $0x = 0$ .  $\square$

**Definition 11.4** (Zero Divisor). Let  $R$  be a rng and  $a \in R$ .

Then  $a$  is a *left-zero-divisor* iff there exists  $b \in R - \{0\}$  such that  $ab = 0$ .

The element  $a$  is a *right-zero-divisor* iff there exists  $b \in R - \{0\}$  such that  $ba = 0$ .

**Example 11.5.** 0 is a left- and right-zero-divisor in every non-zero rng.

The zero rng is the only ring with no zero-divisors.

**Proposition 11.6.** *Let  $R$  be a rng and  $a \in R$ . Then  $a$  is not a left-zero-divisor if and only if left multiplication by  $a$  is an injective function  $R \rightarrow R$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $a$  is not a left-zero-divisor then left multiplication by  $a$  is injective.

$\langle 2 \rangle 1$ . ASSUME:  $a$  is not a left-zero-divisor.

$\langle 2 \rangle 2$ . LET:  $ab = ac$

$\langle 2 \rangle 3$ .  $a(b - c) = 0$

$\langle 2 \rangle 4$ .  $b - c = 0$

$\langle 2 \rangle 5$ .  $b = c$

$\langle 1 \rangle 2$ . If  $a$  is a left-zero-divisor then left multiplication by  $a$  is not injective.

$\langle 2 \rangle 1$ . PICK  $b \neq 0$  such that  $ab = 0$ .

$\langle 2 \rangle 2$ .  $ab = a0$  but  $b \neq 0$

$\square$

## 11.1 Commutative Rings

**Definition 11.7** (Commutative). A rng  $R$  is *commutative* iff  $\forall x, y \in R. xy = yx$ .

**Example 11.8.** • The zero rng is commutative.

- $\mathbb{Z}$ ,  $\mathbb{Q}$ ,  $\mathbb{R}$  and  $\mathbb{C}$  are commutative.
- $2\mathbb{Z}$  is commutative.
- $\mathfrak{gl}_2(\mathbb{R})$  is not commutative.
- For any set  $S$ , the rng  $\mathcal{P}S$  is commutative.
- If  $R$  is commutative then  $R^S$  is commutative.

## 11.2 Rng Homomorphisms

**Definition 11.9.** Let  $R$  and  $S$  be rngs. A *rng homomorphism*  $\phi : R \rightarrow S$  is a function such that, for all  $x, y \in R$ , we have

$$\begin{aligned}\phi(x + y) &= \phi(x) + \phi(y) \\ \phi(xy) &= \phi(x)\phi(y)\end{aligned}$$

Let **Rng** be the category of rngs and rng homomorphisms.

## 11.3 Quaternions

**Definition 11.10** (Norm). The *norm* of a quaternion is defined by

$$N(a + bi + cj + dk) = a^2 + b^2 + c^2 + d^2 \ .$$



# Chapter 12

## Rings

**Definition 12.1** (Ring). A *ring*  $R$  is a rng such that there exists  $1 \in R$ , the *multiplicative identity*, such that

$$\forall x \in R. x1 = 1x = x \text{ .}$$

**Example 12.2.**     • The zero rng is a ring with  $1 = 0$ .

- $\mathbb{Z}$ ,  $\mathbb{Q}$ ,  $\mathbb{R}$  and  $\mathbb{C}$  are rngs.
- $2\mathbb{Z}$  is not a ring.
- If  $R$  is a ring then  $\mathfrak{gl}_n(R)$  is a ring.
- For any set  $S$ , the rng  $\mathcal{P}S$  is a ring with  $1 = S$ .
- If  $R$  is a ring then  $R^S$  is a ring.
- $\mathfrak{sl}_n(\mathbb{R})$  is not a ring for  $n > 0$ .
- $\mathfrak{sl}_n(\mathbb{C})$  is not a ring for  $n > 0$ .
- $\mathfrak{so}_n(\mathbb{R}) = \{M \in \mathfrak{sl}_n(\mathbb{R}) : M + M^T = 0\}$  is not a ring.
- $\mathbb{Z}/n\mathbb{Z}$  is a ring.

**Proposition 12.3.** *In any ring  $R$ , if  $0 = 1$  then  $R$  is the zero ring.*

PROOF: For any  $x \in R$  we have  $x = 1x = 0x = 0$ .  $\square$

**Proposition 12.4.** *In any ring we have  $(-1)x = -x$ .*

PROOF: Since

$$\begin{aligned} x + (-1)x &= 1x + (-1)x \\ &= (1 + (-1))x \\ &= 0x \\ &= 0 \end{aligned}$$

$\square$

## 12.1 Units

**Definition 12.5** (Left-Unit, Right-Unit). Let  $R$  be a ring and  $a \in R$ . Then  $a$  is a *left-unit* iff there exists  $b \in R$  such that  $ab = 1$ . The element  $a$  is a *right-unit* iff there exists  $b \in R$  such that  $ba = 1$ .

An element is a *unit* iff it is a left-unit and a right-unit.

**Proposition 12.6.** *Let  $R$  be a ring and  $a \in R$ . Then  $a$  is a left-unit iff left multiplication by  $a$  is a surjective function  $R \rightarrow R$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $a$  is a left-unit then left multiplication by  $a$  is surjective.

$\langle 2 \rangle 1$ . PICK  $b \in R$  such that  $ab = 1$ .

$\langle 2 \rangle 2$ . For all  $c \in R$  we have  $c = a(bc)$ .

$\langle 1 \rangle 2$ . If left multiplication by  $a$  is surjective then  $a$  is a left-unit.

PROOF: Immediate.

□

**Proposition 12.7.** *Let  $R$  be a ring and  $a \in R$ . Then  $a$  is a right-unit iff right multiplication by  $a$  is a surjective function  $R \rightarrow R$ .*

PROOF: Similar. □

**Proposition 12.8.** *No left-unit is a right-zero-divisor.*

PROOF:

$\langle 1 \rangle 1$ . ASSUME: for a contradiction  $ab = 1$  and  $ca = 0$  where  $c \neq 0$ .

$\langle 1 \rangle 2$ .  $c = 0$

PROOF:

$$0 = 0b$$

$$= cab$$

$$= c1$$

$$= c$$

$\langle 1 \rangle 3$ . Q.E.D.

PROOF: This is a contradiction.

□

**Proposition 12.9.** *No right-unit is a left-zero-divisor.*

PROOF: Similar. □

**Proposition 12.10.** *The inverse of a unit is unique.*

PROOF: If  $ba = 1$  and  $ac = 1$  then  $b = bac = c$ . □

**Proposition 12.11.** *The units of a ring form a group under multiplication.*

PROOF:

$\langle 1 \rangle 1$ . If  $a$  and  $b$  are units then  $ab$  is a unit.

PROOF: We have  $b^{-1}a^{-1}ab = 1$  and  $abb^{-1}a^{-1} = 1$ .



⟨1⟩2. 1 is a unit.

PROOF: Since  $1 \cdot 1 = 1$ .

⟨1⟩3. If  $a$  is a unit then its inverse is a unit.

PROOF: Immediate from definitions.

□

**Definition 12.12** (Group of Units). For any ring  $R$ , we write  $R^*$  for the group of the units of  $R$  under multiplication.

**Example 12.13.** The quaternionic group is a subgroup of  $\mathbb{H}^*$ .

**Example 12.14.** The norm is a group homomorphism  $\mathbb{H}^* \rightarrow \mathbb{R}^+$  where  $\mathbb{R}^+$  is the group of positive real numbers under multiplication with kernel isomorphic to  $\text{SU}_2(\mathbb{C})$ . The isomorphism maps a quaternion  $a + bi + cj + dk$  to

$$\begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix}.$$

**Theorem 12.15** (Fermat's Little Theorem). *Let  $p$  be a prime number and  $a$  any integer. Then  $a^p \equiv a \pmod{p}$ .*

PROOF: If  $p \mid a$  then  $a^p \equiv a \equiv 0 \pmod{p}$ . Otherwise, we have  $a^{p-1} \equiv 1 \pmod{p}$  by applying Lagrange's Theorem to  $(\mathbb{Z}/p\mathbb{Z})^*$ . □

**Example 12.16.** It is not true that, if  $n \mid |G|$ , then  $G$  has a subgroup of order  $n$ . The group  $A_4$  has order 12 but no subgroup of order 6.

**Proposition 12.17.** *If  $p$  is prime then  $(\mathbb{Z}/p\mathbb{Z})^*$  is cyclic.*

PROOF:

⟨1⟩1. LET:  $g$  be an element of maximal order in  $(\mathbb{Z}/p\mathbb{Z})^*$ .

⟨1⟩2. For all  $h \in (\mathbb{Z}/p\mathbb{Z})^*$  we have  $h^{|g|} = 1$ .

PROOF: Proposition 8.10.

⟨1⟩3. There are at most  $|g|$  elements  $x$  such that  $x^{|g|} = 1$  in  $\mathbb{Z}/p\mathbb{Z}$

⟨1⟩4.  $p - 1 \leq |g|$

⟨1⟩5.  $|g| = p - 1$

⟨1⟩6.  $g$  generates  $(\mathbb{Z}/p\mathbb{Z})^*$ .

□

**Example 12.18.**  $(\mathbb{Z}/12\mathbb{Z})^*$  is not cyclic. Its elements are 1, 5, 7 and 11 with orders 1, 2, 2 and 2.

**Theorem 12.19** (Wilson's Theorem). *A positive integer  $p$  is prime if and only if  $(p - 1)! \equiv 1 \pmod{p}$ .*

⟨1⟩1. If  $p$  is prime then  $(p - 1)! \equiv 1 \pmod{p}$ .

⟨2⟩1. ASSUME:  $p$  is prime.

⟨2⟩2.  $(p - 1)!$  is the product of all the elements of  $(\mathbb{Z}/p\mathbb{Z})^*$

⟨2⟩3. The only element of  $(\mathbb{Z}/p\mathbb{Z})^*$  with order 2 is  $-1$ .

⟨2⟩4.  $(p - 1)! \equiv -1 \pmod{p}$

PROOF: Proposition 6.20.

$\langle 1 \rangle 2$ . If  $(p-1)! \equiv -1 \pmod{p}$  then  $p$  is prime.

$\langle 2 \rangle 1$ . ASSUME:  $(p-1)! \equiv -1 \pmod{p}$

$\langle 2 \rangle 2$ . LET:  $d$  be a proper divisor of  $p$ .

PROVE:  $d = 1$

$\langle 2 \rangle 3$ .  $d \mid (p-1)!$

$\langle 2 \rangle 4$ .  $d \mid 1$

PROOF: Since  $d \mid p \mid (p-1)! + 1$ .

$\langle 2 \rangle 5$ .  $d = 1$

□

**Proposition 12.20.** *If  $p$  and  $q$  are distinct odd primes then  $(\mathbb{Z}/pq\mathbb{Z})^*$  is not cyclic.*

PROOF:

$\langle 1 \rangle 1$ .  $|(\mathbb{Z}/pq\mathbb{Z})^*| = (p-1)(q-1)$

$\langle 1 \rangle 2$ . LET:  $g \in (\mathbb{Z}/pq\mathbb{Z})^*$

PROVE:  $g$  does not have order  $(p-1)(q-1)$

$\langle 1 \rangle 3$ .  $g^{(p-1)(q-1)/2} \equiv 1 \pmod{p}$

$\langle 1 \rangle 4$ .  $g^{(p-1)(q-1)/2} \equiv 1 \pmod{q}$

$\langle 1 \rangle 5$ .  $pq \mid g^{(p-1)(q-1)/2} - 1$

$\langle 1 \rangle 6$ .  $g^{(p-1)(q-1)/2} \equiv 1 \pmod{pq}$

$\langle 1 \rangle 7$ .  $|g| \mid (p-1)(q-1)/2$

□

**Proposition 12.21.** *For any prime  $p$ , we have  $\text{Aut}_{\mathbf{Grp}}(C_p) \cong C_{p-1}$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\phi : \text{Aut}_{\mathbf{Grp}}(C_p) \rightarrow (\mathbb{Z}/p\mathbb{Z})^*$  be the function  $\phi(\alpha) = \alpha(1)$ .

PROOF:  $\alpha(1)$  has order  $p$  in  $C_p$  and so is coprime with  $p$ .

$\langle 1 \rangle 2$ .  $\phi$  is a homomorphism.

PROOF:  $\phi(\alpha \circ \beta) = \alpha(\beta(1)) = \alpha(\beta(1)1) = \beta(1)\alpha(1) = \phi(\alpha)\phi(\beta)$

$\langle 1 \rangle 3$ .  $\phi$  is injective.

PROOF: If  $\phi(\alpha) = \phi(\beta)$  then for any  $n$  we have  $\alpha(n) = n\alpha(1) = n\phi(\alpha) = n\phi(\beta) = n\beta(1) = \beta(n)$ .

$\langle 1 \rangle 4$ .  $\phi$  is surjective.

PROOF: For any  $r \in (\mathbb{Z}/p\mathbb{Z})^*$  we have  $r = \phi(\alpha)$  where  $\alpha(n) = nr \pmod{p}$ .

$\langle 1 \rangle 5$ .  $(\mathbb{Z}/p\mathbb{Z})^* \cong C_{p-1}$

□

## 12.2 Euler's $\phi$ -function

**Proposition 12.22.** *For  $n$  a positive integer, we have  $(\mathbb{Z}/n\mathbb{Z})^* = \{m \in \mathbb{Z}/n\mathbb{Z} : \gcd(m, n) = 1\}$ .*

PROOF:

$$\begin{aligned} m \in (\mathbb{Z}/n\mathbb{Z})^* &\Leftrightarrow \exists a.am \equiv 1 \pmod{n} \\ &\Leftrightarrow \exists a, b.am + bn = 1 \\ &\Leftrightarrow \gcd(m, n) = 1 \quad \square \end{aligned}$$

**Definition 12.23** (Euler's Totient Function). For  $n$  a positive integer, let  $\phi(n) = |(\mathbb{Z}/n\mathbb{Z})^*|$ .

**Proposition 12.24.** *If  $n$  is an odd positive integer then  $\phi(2n) = \phi(n)$ .*

PROOF:

(1)1. LET:  $n$  be an odd positive integer.

(1)2. For any integer  $m$ , if  $\gcd(m, n) = 1$  then  $\gcd(2m + n, 2n) = 1$

PROOF: For  $p$  a prime, if  $p \mid 2m + n$  and  $p \mid 2n$  then  $p \neq 2$  (since  $2m + n$  is odd) so  $p \mid n$  and hence  $p \mid m$ , which is a contradiction.

(1)3. For any integer  $r$ , if  $\gcd(r, 2n) = 1$  then  $\gcd(\frac{r+n}{2}, n) = 1$

PROOF: If  $p \mid n$  and  $p \mid \frac{r+n}{2}$  then  $p \mid r + n$  so  $p \mid r$  which is a contradiction.

(1)4. The function that maps  $m$  to  $2m + n$  is a bijection between  $(\mathbb{Z}/n\mathbb{Z})^*$  and  $(\mathbb{Z}/2n\mathbb{Z})^*$ .

□

**Theorem 12.25.** *For any positive integer  $n$  we have*

$$\sum_{m>0, m|n} \phi(m) = n.$$

PROOF:

(1)1. Define  $\chi : \{0, 1, \dots, n-1\} \rightarrow \{(m, d) : m > 0, m \mid n, d \text{ generates } \langle n/m \rangle\}$   
by:  $\chi(x) = (\gcd(x, n), x)$ .

(1)2.  $\chi$  is injective.

(1)3.  $\chi$  is surjective.

PROOF: Given  $(m, d)$  such that  $d$  generates  $\langle n/m \rangle$  we have  $\chi(d) = (m, d)$ .

(1)4.  $n = \sum_{m>0, m|n} \phi(m)$

PROOF: Since  $\langle n/m \rangle \cong C_m$  and so has  $\phi(m)$  generators.

□

**Proposition 12.26.** *For any positive integers  $a$  and  $n$ , we have  $n \mid \phi(a^n - 1)$ .*

PROOF: Since the order of  $a$  is  $n$  in  $(\mathbb{Z}/(a^n - 1)\mathbb{Z})^*$ . □

**Theorem 12.27** (Euler's Theorem). *For any coprime integers  $a$  and  $n$  we have  $a^{\phi(n)} \equiv a \pmod{n}$ .*

PROOF: Immediate from Lagrange's Theorem. □

**Proposition 12.28.**

$$|\text{Aut}_{\mathbf{Grp}}(C_n)| = \phi(n)$$

PROOF: An automorphism  $\alpha$  is determined by  $\alpha(1)$  which is any element of order  $n$ , and  $g$  has order  $n$  iff  $\gcd(g, n) = 1$ . □

**Example 12.29.**

$$\text{Aut}_{\mathbf{Grp}}(\mathbb{Z}) \cong C_2$$

PROOF: The only automorphisms are the identity and multiplication by -1.  $\square$

## 12.3 Nilpotent Elements

**Definition 12.30** (Nilpotent). Let  $R$  be a ring and  $a \in R$ . Then  $a$  is *nilpotent* iff there exists  $n$  such that  $a^n = 0$ .

**Proposition 12.31.** *Let  $R$  be a ring and  $a, b \in R$ . If  $a$  and  $b$  are nilpotent and  $ab = ba$  then  $a + b$  is nilpotent.*

PROOF:

$\langle 1 \rangle 1$ . PICK  $m$  and  $n$  such that  $a^m = b^n = 0$ .

$\langle 1 \rangle 2$ .  $(a + b)^{m+n} = 0$

PROOF: Since  $(a + b)^{m+n} = \sum_k \binom{m+n}{k} a^k b^{m+n-k}$  and every term in this sum is 0 since, for every  $k$ , either  $k \geq m$  or  $m + n - k \geq n$ .

$\square$

**Proposition 12.32.**  *$m$  is nilpotent in  $\mathbb{Z}/n\mathbb{Z}$  if and only if  $m$  is divisible by all the prime factors of  $n$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $m$  is nilpotent then  $m$  is divisible by all the prime factors of  $n$ .

$\langle 2 \rangle 1$ . ASSUME:  $m^a \equiv 0 \pmod{n}$

$\langle 2 \rangle 2$ . For every prime  $p$ , if  $p \mid n$  then  $p \mid m^a$ .

$\langle 2 \rangle 3$ . For every prime  $p$ , if  $p \mid n$  then  $p \mid m$ .

$\langle 1 \rangle 2$ . If  $m$  is divisible by all the prime factors of  $n$  then  $m$  is nilpotent in  $\mathbb{Z}/n\mathbb{Z}$ .

$\langle 2 \rangle 1$ . ASSUME:  $m$  is divisible by all the prime factors of  $n$ .

$\langle 2 \rangle 2$ . LET:  $a$  be the largest number such that  $p^a \mid n$  for some prime  $p$ .

$\langle 2 \rangle 3$ . For every prime  $p$  that divides  $n$  we have  $p^a \mid m^a$

$\langle 2 \rangle 4$ .  $n \mid m^a$

$\langle 2 \rangle 5$ .  $m^a \equiv 0 \pmod{n}$

$\langle 2 \rangle 6$ .  $m$  is nilpotent in  $\mathbb{Z}/n\mathbb{Z}$ .

$\square$

## Chapter 13

# Ring Homomorphisms

**Definition 13.1** (Ring Homomorphism). Let  $R$  and  $S$  be rings. A *ring homomorphism*  $\phi : R \rightarrow S$  is a rng homomorphism such that  $\phi(1) = 1$ .

**Proposition 13.2.** *The zero-ring is terminal in **Ring**.*

PROOF: Easy.  $\square$

**Proposition 13.3.** *The ring  $\mathbb{Z}$  is initial in **Ring**.*

PROOF: Easy.  $\square$

**Proposition 13.4.** *Let  $R$  and  $S$  be rings and  $\phi : R \rightarrow S$  be a rng homomorphism. If  $\phi$  is surjective, then  $\phi$  is a ring homomorphism.*

PROOF:

$\langle 1 \rangle 1$ . PICK  $a \in R$  such that  $\phi(a) = 1$

$\langle 1 \rangle 2$ .  $\phi(1) = 1$

PROOF:

$$\begin{aligned}\phi(1) &= \phi(1)\phi(a) \\ &= \phi(1a) \\ &= \phi(a) \\ &= 1\end{aligned}$$

$\square$

**Example 13.5.** For any set  $S$  we have  $\mathcal{P}S \cong (\mathbb{Z}/2\mathbb{Z})^S$  in **Ring** with the isomorphism

$$\begin{aligned}\phi : \mathcal{P}S &\cong (\mathbb{Z}/2\mathbb{Z})^S \\ \phi(A)(s) &= \begin{cases} 1 & \text{if } s \in A \\ 0 & \text{if } s \notin A \end{cases}\end{aligned}$$

**Example 13.6.** The function  $\mathbb{H} \rightarrow \mathfrak{gl}_4(\mathbb{R})$  that maps  $a + bi + cj + dk$  to

$$\begin{pmatrix} a & b & c & d \\ -b & a & -d & c \\ -c & d & a & -b \\ -d & -c & b & a \end{pmatrix}$$

is a monomorphism in **Ring**, as is the function  $\mathbb{H} \rightarrow \mathfrak{sl}_2(\mathbb{C})$  that maps  $a + bi + cj + dk$  to

$$\begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix}.$$

**Proposition 13.7.** *Ring homomorphisms preserve units.*

PROOF: If  $uv = 1$  then  $\phi(u)\phi(v) = 1$ .  $\square$

**Proposition 13.8.** *Let  $\phi : R \rightarrow S$  be a ring homomorphism. Then the following are equivalent.*

1.  $\phi$  is a monomorphism.
2.  $\ker \phi = \{0\}$
3.  $\phi$  is injective.

PROOF:

$\langle 1 \rangle 1. 1 \Rightarrow 2$

$\langle 2 \rangle 1.$  ASSUME:  $\phi$  is a monomorphism.

$\langle 2 \rangle 2.$  LET:  $r \in \ker \phi$

$\langle 2 \rangle 3.$  LET:  $\text{ev}_r : \mathbb{Z}[x] \rightarrow R$  be the unique ring homomorphism such that  $\text{ev}_r(x) = r$ .

$\langle 2 \rangle 4.$  LET:  $\text{ev}_0 : \mathbb{Z}[x] \rightarrow R$  be the unique ring homomorphism such that  $\text{ev}_0(x) = 0$ .

$\langle 2 \rangle 5.$   $\phi \circ \text{ev}_r = \phi \circ \text{ev}_0$

$\langle 2 \rangle 6.$   $\text{ev}_r = \text{ev}_0$

$\langle 2 \rangle 7.$   $r = 0$

$\langle 1 \rangle 2. 2 \Rightarrow 3$

PROOF: Proposition 7.20.

$\langle 1 \rangle 3. 3 \Rightarrow 1$

PROOF: Easy.

$\square$

**Example 13.9.** It is not true that every epimorphism in **Ring** is surjective. The inclusion  $\mathbb{Z} \hookrightarrow \mathbb{Q}$  is an epimorphism but not surjective.

The same example shows that a ring homomorphism may be a monomorphism and an epimorphism but not be an isomorphism.

**Example 13.10.**

$$\text{End}_{\mathbf{Ab}}(\mathbb{Z}) \cong \mathbb{Z}$$

The isomorphism maps any group endomorphism  $\phi : \mathbb{Z} \rightarrow \mathbb{Z}$  to  $\phi(1)$ .

**Example 13.11.** The group of units of  $\text{End}_{\mathbf{Ab}}(G)$  is  $\text{Aut}_{\mathbf{Ab}}(G)$ .

**Example 13.12.** Let  $R$  be a ring. Then the function  $\lambda : R \rightarrow \text{End}_{\mathbf{Ab}}(R)$  defined by

$$\lambda(a)(b) = ab$$

is a ring monomorphism.

PROOF: Easy.  $\square$

## 13.1 Products

**Proposition 13.13.** *Let  $R$  and  $S$  be rings. Then  $R \times S$  is a ring under componentwise addition and multiplication, and this ring is the product of  $R$  and  $S$  in **Ring**.*

PROOF: Easy.  $\square$





## Chapter 14

# Subrings

**Definition 14.1** (Subring). Let  $S$  be a ring. A *subring* of  $S$  is a ring  $R$  such that  $R$  is a subset of  $S$  and the inclusion  $R \hookrightarrow S$  is a ring homomorphism.

**Proposition 14.2.** *Let  $R$  and  $S$  be rings. Then  $R$  is a subring of  $S$  if and only if  $R$  is a subset of  $S$ , the unit  $1$  of  $S$  is an element of  $R$ , and the operations of  $R$  are the restrictions of the operations of  $S$  to  $R$ .*

PROOF: Easy.  $\square$

**Corollary 14.2.1.** *The zero ring is not a subring of any non-zero ring.*

**Proposition 14.3.** *Let  $\phi : R \rightarrow S$  be a ring homomorphism. Then  $\phi(R)$  is a subring of  $S$ .*

PROOF: Easy.  $\square$

### 14.1 Centralizer

**Definition 14.4** (Centralizer). Let  $R$  be a ring and  $a \in R$ . The *centralizer* of  $a$  is  $\{r \in R : ar = ra\}$ .

**Proposition 14.5.** *The centralizer of  $a$  is a subring of  $R$ .*

PROOF: Easy.  $\square$

### 14.2 Center

**Definition 14.6** (Center). The *center* of a ring  $R$  is  $\{x \in R : \forall y \in R. xy = yx\}$ .

**Proposition 14.7.** *The center of a ring is a subring.*

PROOF: Easy.  $\square$

**Proposition 14.8.** *Let  $R$  be a ring. The center of  $\text{End}_{\mathbf{Ab}}(R)$  is isomorphic to the center of  $R$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\lambda : R \rightarrow \text{End}_{\mathbf{Ab}}(R)$  be left multiplication.

$\langle 1 \rangle 2$ .  $\lambda$  maps  $Z(R)$  to  $Z(\text{End}_{\mathbf{Ab}}(R))$ .

$\langle 2 \rangle 1$ . LET:  $a \in Z(R)$

$\langle 2 \rangle 2$ . LET:  $\phi \in \text{End}_{\mathbf{Ab}}(R)$

PROVE:  $\lambda(a) \circ \phi = \phi \circ \lambda(a)$

$\langle 2 \rangle 3$ . LET:  $x \in R$

$\langle 2 \rangle 4$ .  $a + \phi(x) = \phi(a + x)$

$\langle 1 \rangle 3$ .  $\lambda(Z(R)) = Z(\text{End}_{\mathbf{Ab}}(R))$

$\langle 2 \rangle 1$ . LET:  $\phi \in Z(\text{End}_{\mathbf{Ab}}(R))$

$\langle 2 \rangle 2$ . For all  $r \in R$ ,

LET:  $\mu_r \in \text{End}_{\mathbf{Ab}}(R)$  be right multiplication by  $r$ .

$\langle 2 \rangle 3$ . For all  $r \in R$  we have  $\phi \circ \mu_r = \mu_r \circ \phi$ .

$\langle 2 \rangle 4$ . For all  $r, x \in R$  we have  $\phi(xr) = \phi(x)r$

$\langle 2 \rangle 5$ . For all  $r \in R$  we have  $\phi(r) = \phi(1)r$

$\langle 2 \rangle 6$ .  $\phi = \lambda(\phi(1))$

□

**Corollary 14.8.1.** *If  $R$  is a commutative ring then  $R$  is isomorphic to the center of  $\text{End}_{\mathbf{Ab}}(R)$ .*

**Example 14.9.** For  $n$  a positive integer we have  $\mathbb{Z}/n\mathbb{Z} \cong \text{End}_{\mathbf{Ab}}(\mathbb{Z}/n\mathbb{Z})$ .

Since, for any  $\phi \in \text{End}_{\mathbf{Ab}}(\mathbb{Z}/n\mathbb{Z})$  we have  $\phi(m) = m\phi(1)$  and so the whole of  $\text{End}_{\mathbf{Ab}}(\mathbb{Z}/n\mathbb{Z})$  is the image of  $\lambda$ .

## Chapter 15

# Monoid Rings

**Definition 15.1** (Monoid Ring). Let  $R$  be a ring and  $M$  a monoid. Define  $R[M]$  to be the ring whose elements are the families  $\{a_m\}_{m \in M}$  such that  $a_m = 0$  for all but finitely many  $m \in M$ , written

$$\sum_{m \in M} a_m m ,$$

under

$$\begin{aligned} \sum_m a_m m + \sum_m b_m m &= \sum_m (a_m + b_m) m \\ \left( \sum_m a_m m \right) \left( \sum_m b_m m \right) &= \sum_{m \in M} \sum_{m_1 m_2 = m} a_{m_1} b_{m_2} m \end{aligned}$$

**Example 15.2.** Ring homomorphisms do not necessarily preserve zero-divisors. The canonical homomorphism  $\pi : \mathbb{Z} \rightarrow \mathbb{Z}/6\mathbb{Z}$  maps the non-zero-divisor 2 to a zero-divisor.

### 15.1 Polynomials

**Definition 15.3** (Polynomial). Let  $R$  be a ring. The ring of *polynomials*  $R[x]$  is  $R[\mathbb{N}]$ . We write

$$\sum_n a_n x^n \text{ for } \sum_n a_n n .$$

Concretely, a *polynomial* in  $R$  is a sequence  $(a_n)$  in  $R$  such that there exists  $N$  such that  $\forall n \geq N. a_n = 0$ . We write the polynomial as

$$\sum_{n=0}^{N-1} a_n x^n = a_0 + a_1 x + a_2 x^2 + \cdots + a_{N-1} x^{N-1} .$$

We write  $R[x]$  for the set of all polynomials in  $R$ .

Define addition and multiplication on  $R[x]$  by

$$\begin{aligned}\sum_n a_n x^n + \sum_n b_n x^n &= \sum_n (a_n + b_n) x^n \\ \left( \sum_n a_n x^n \right) \left( \sum_n b_n x^n \right) &= \sum_n \sum_{i+j=n} a_i b_j x^n\end{aligned}$$

A *constant* is a polynomial of the form  $a + 0x + 0x^2 + \cdots$  for some  $a \in R$ . We write  $R[x_1, \dots, x_n]$  for  $R[x_1][x_2] \cdots [x_n]$ .

**Proposition 15.4.** *For any ring  $R$ , the set of polynomials  $R[x]$  is a ring.*

PROOF: Easy.  $\square$

**Definition 15.5** (Degree). The *degree* of a polynomial  $\sum_n a_n x^n$  is the largest integer  $d$  such that  $a_d \neq 0$ . We take the degree of the zero polynomial to be  $-\infty$ .

**Proposition 15.6.** *Let  $R$  be a ring and  $f, g \in R[x]$  be nonzero polynomials. Then*

$$\deg(f + g) \leq \max(\deg f, \deg g) .$$

PROOF: If  $a_n + b_n \neq 0$  then  $a_n \neq 0$  or  $b_n \neq 0$ .  $\square$

**Proposition 15.7.** *The function  $i : n \rightarrow \mathbb{Z}[x_1, \dots, x_n]$  that maps  $k$  to  $x_k$  is initial in the category with:*

- *objects all pairs  $j : n \rightarrow R$  where  $R$  is a commutative ring and  $j$  a function*
- *morphisms  $\phi : (j_1, R_1) \rightarrow (j_2, R_2)$  are ring homomorphisms  $\phi : R_1 \rightarrow R_2$  such that  $\phi \circ j_1 = j_2$ .*

PROOF: The unique morphism  $(i, \mathbb{Z}[x_1, \dots, x_n]) \rightarrow (j, R)$  maps a polynomial  $p$  to  $p(j(0), j(1), \dots, j(n-1))$ .  $\square$

**Proposition 15.8.** *Let  $\alpha : R \rightarrow S$  be a ring homomorphism. Let  $s \in S$  commute with  $\alpha(r)$  for all  $r \in R$ . Then there exists a unique ring homomorphism  $\bar{\alpha} : R[x] \rightarrow S$  such that  $\bar{\alpha}(x) = s$  and the following diagram commutes:*

$$\begin{array}{ccc} R[x] & \xrightarrow{\bar{\alpha}} & S \\ \uparrow & \nearrow \alpha & \\ R & & \end{array}$$

PROOF: The map  $\bar{\alpha}$  is given by

$$\bar{\alpha}(a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n) = \alpha(a_0) + \alpha(a_1)s + \alpha(a_2)s^2 + \cdots + \alpha(a_n)s^n .$$

$\square$

**Definition 15.9.** Let  $R$  be a commutative ring. Given a polynomial  $p \in R[x]$ , the *polynomial function*  $p : R \rightarrow R$  is the function given by:  $p(r) = \alpha_r(p)$ , where  $\alpha_r : R[x] \rightarrow R$  is the unique ring homomorphism such that the following diagram commutes.

$$\begin{array}{ccc} R[x] & \xrightarrow{\alpha_r} & R \\ x \uparrow & \nearrow r & \\ 1 & & \end{array}$$

**Proposition 15.10.**  $\mathbb{Z}[x, y]$  is the coproduct of  $\mathbb{Z}[x]$  and  $\mathbb{Z}[y]$  in the category of commutative rings.

PROOF: Given ring homomorphisms  $f : \mathbb{Z}[x] \rightarrow R$  and  $g : \mathbb{Z}[y] \rightarrow R$ , the required morphism  $\mathbb{Z}[x, y] \rightarrow R$  maps  $p(x, y)$  to  $p(f(x), g(y))$ .  $\square$

**Example 15.11.**  $\mathbb{Z}[x, y]$  is not the coproduct of  $\mathbb{Z}[x]$  and  $\mathbb{Z}[y]$  in **Ring**. Given  $f : \mathbb{Z}[x] \rightarrow R$  and  $g : \mathbb{Z}[y] \rightarrow R$  with  $f(x) \neq g(y)$ , the mediating morphism  $\mathbb{Z}[x, y] \rightarrow R$  cannot exist since it must map  $xy$  to both  $f(x)g(y)$  and  $g(y)f(x)$ .  $\square$

**Definition 15.12.** A polynomial is *monic* iff its last non-zero coefficient is 1.

**Proposition 15.13.** A monic polynomial is not a left- or right-zero-divisor.

PROOF: Easy.  $\square$

**Proposition 15.14.** Let  $R$  be a ring. Let  $f, g \in R[x]$  with  $f$  monic. Then there exist unique polynomials  $q, r \in R[x]$  with  $\deg r < \deg f$  such that

$$g = qf + r \text{ .}$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $d = \deg f$

$\langle 1 \rangle 2$ . For all  $a \in R$  and  $n > d$ , there exists  $h \in R[x]$  with  $\deg h < n$  such that

$$ax^n = ax^{n-d}f + h \text{ .}$$

PROOF: Take  $h = ax^n - ax^{n-d}f$ .

$\langle 1 \rangle 3$ . For all  $a \in R$  and  $n > d$ , there exists  $q, h \in R[x]$  with  $\deg h \leq d$  such that

$$ax^n = qf + h \text{ .}$$

PROOF: Repeating  $\langle 1 \rangle 2$  by induction.

$\langle 1 \rangle 4$ . LET:  $g = \sum_{i=0}^n a_i x^i$

$\langle 1 \rangle 5$ . For  $i > d$ , PICK  $q_i h_i \in R[x]$  with  $\deg h < \deg f$  such that  $a_i x^i = q_i f + h_i$

$\langle 1 \rangle 6$ .  $g = (\sum_{i=d+1}^n q_i) f + \sum_{i=d+1}^n h_i$

$\langle 1 \rangle 7$ .  $q$  and  $r$  are unique.

PROOF: If  $q_1 f + r_1 = q_2 f + r_2$  then  $r_1 - r_2 = (q_2 - q_1)f$  and so  $r_1 - r_2 = (q_2 - q_1)f = 0$  since  $\deg(r_1 - r_2) < \deg f$ .

$\square$

## 15.2 Laurent Polynomials

**Definition 15.15** (Laurent Polynomial). Let  $R$  be a ring. The ring of *Laurent polynomials* is the group ring  $R[\mathbb{Z}]$ . We write  $\sum_{n \in \mathbb{Z}} a_n x^n$  for  $\sum_n a_n n$ .

### 15.3 Power Series

**Definition 15.16** (Power Series). Let  $R$  be a ring. A *power series* in  $R$  is a sequence  $(a_n)$  in  $R$ . We write the power series as

$$\sum_{n=0}^{\infty} a_n x^n = a_0 + a_1 x + a_2 x^2 + \cdots .$$

We write  $R[[x]]$  for the set of all power series in  $R$ .

Define addition and multiplication on  $R[[x]]$  by

$$\begin{aligned} \sum_n a_n x^n + \sum_n b_n x^n &= \sum_n (a_n + b_n) x^n \\ \left( \sum_n a_n x^n \right) \left( \sum_n b_n x^n \right) &= \sum_n \sum_{i+j=n} a_i b_j x^n \end{aligned}$$

**Proposition 15.17.** *For any ring  $R$ , the set of power series  $R[[x]]$  is a ring.*

PROOF: Easy.  $\square$

**Proposition 15.18.** *A power series  $\sum_n a_n x^n$  is a unit in  $R[[x]]$  if and only if  $a_0$  is a unit in  $R$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $\sum_n a_n x^n$  is a unit then  $a_0$  is a unit.

$\langle 2 \rangle 1$ . LET:  $\sum_n b_n x^n$  be the inverse of  $\sum_n a_n x^n$ .

$\langle 2 \rangle 2$ .  $a_0 b_0 = b_0 a_0 = 1$

$\langle 1 \rangle 2$ . If  $a_0$  is a unit then  $\sum_n a_n x^n$  is a unit.

PROOF: Define the sequence  $(b_n)$  in  $R$  by

$$b_n = -a_0^{-1} \sum_{i=1}^n a_i b_{n-i}$$

Then  $\sum_n b_n x^n$  is the inverse of  $\sum_n a_n x^n$ .

$\square$

# Chapter 16

## Ideals

**Definition 16.1** (Left-Ideal). Let  $R$  be a ring.

A subgroup  $I$  of  $R$  is a *left-ideal* iff, for all  $r \in R$ , we have  $rI \subseteq I$ .

A subgroup  $I$  of  $R$  is a *right-ideal* iff, for all  $r \in R$ , we have  $Ir \subseteq I$ .

A subgroup  $I$  of  $R$  is a (*two-sided*) *ideal* iff it is a left-ideal and a right-ideal.

**Example 16.2.** Let  $R$  be a ring and  $a \in R$ . Then  $Ra$  is a left-ideal and  $aR$  is a right-ideal.

In particular,  $\{0\}$  is always a two-sided ideal.

**Example 16.3.** Let  $S$  be a set and  $T \subseteq S$ . Then  $\{X \in \mathcal{P}S : X \subseteq T\}$  is an ideal in  $\mathcal{P}S$ .

**Proposition 16.4.** Let  $S$  be a finite set. Then every ideal in  $\mathcal{P}S$  is of the form  $\{X \in \mathcal{P}S : X \subseteq T\}$  for some  $T \subseteq S$ .

PROOF:

$\langle 1 \rangle 1$ . LET:  $I$  be an ideal in  $\mathcal{P}S$ .

$\langle 1 \rangle 2$ . LET:  $T = \bigcup I$

$\langle 1 \rangle 3$ . For all  $i \in T$  we have  $\{i\} \in I$ .

$\langle 2 \rangle 1$ . LET:  $i \in T$

$\langle 2 \rangle 2$ . PICK  $X \in I$  such that  $i \in X$

$\langle 2 \rangle 3$ .  $\{i\} = \{i\} \cap X \in I$

$\langle 1 \rangle 4$ . For all  $X \subseteq T$  we have  $X \in I$ .

PROOF: If  $X = \{x_1, \dots, x_n\}$  then  $X = \{x_1\} + \dots + \{x_n\} \in I$ .

□

**Example 16.5.** If  $S$  is an infinite set, then there is always an ideal in  $\mathcal{P}S$  that is not of the form  $\{X \in \mathcal{P}S : X \subseteq T\}$  for some  $T \subseteq S$ , namely the set of all finite subsets of  $S$ .

**Proposition 16.6.** Let  $\phi : R \twoheadrightarrow S$  be a surjective ring homomorphism. Let  $J$  be an ideal in  $R$ . Then  $\phi(J)$  is an ideal in  $S$ .

PROOF:

- $\langle 1 \rangle 1$ . LET:  $j \in J$  and  $s \in S$   
 PROVE:  $s\phi(j), \phi(j)s \in \phi(J)$   
 $\langle 1 \rangle 2$ . PICK  $r \in R$  such that  $\phi(r) = s$   
 $\langle 1 \rangle 3$ .  $rj, jr \in J$   
 $\langle 1 \rangle 4$ .  $s\phi(j), \phi(j)s \in \phi(J)$   
 $\square$

**Example 16.7.** We cannot remove the hypothesis that  $\phi$  is surjective.

Let  $i : \mathbb{Z} \hookrightarrow \mathbb{Q}$  be the inclusion. Then  $i(2\mathbb{Z}) = 2\mathbb{Z}$  is not an ideal in  $\mathbb{Q}$ .

**Proposition 16.8.** Let  $\phi : R \rightarrow S$  be a ring homomorphism and  $I$  a (left-, right-)ideal in  $S$ . Then  $\phi^{-1}I$  is a (left-, right-)ideal in  $R$ .

PROOF: Easy.  $\square$

**Corollary 16.8.1.** Let  $\phi : R \rightarrow S$  be a ring homomorphism. Then  $\ker \phi$  is an ideal in  $R$ .

**Definition 16.9** (Quotient Ring). Let  $I$  be an ideal in  $R$ . The *quotient ring*  $R/I$  is the quotient group  $R/I$  under

$$(a + I)(b + I) = ab + I.$$

This is well-defined as, if  $a + I = a' + I$  and  $b + I = b' + I$  then

$$\begin{aligned}
 a - a' &\in I \\
 b - b' &\in I \\
 \therefore ab - a'b &\in I \\
 a'b - a'b' &\in I \\
 \therefore ab - a'b' &\in I
 \end{aligned}$$

**Proposition 16.10.** Let  $I$  be an ideal in  $R$ . Then the canonical group homomorphism  $\pi : R \rightarrow R/I$  is a ring homomorphism.

PROOF: By construction.  $\square$

**Proposition 16.11.** Let  $I$  be an ideal in a ring  $R$ . For every ring homomorphism  $\phi : R \rightarrow S$  such that  $I \subseteq \ker \phi$ , there exists a unique ring homomorphism  $\bar{\phi} : R/I \rightarrow S$  such that the following diagram commutes.

$$\begin{array}{ccc}
 R & \xrightarrow{\phi} & S \\
 \searrow \pi & & \nearrow \bar{\phi} \\
 & R/I &
 \end{array}$$

PROOF: Easy.  $\square$

**Corollary 16.11.1.** Every ring homomorphism  $\phi : R \rightarrow S$  decomposes as follows.



$$\begin{array}{ccccc}
 & & \phi & & \\
 & \searrow & \text{---} & \nearrow & \\
 R & \twoheadrightarrow & R/\ker \phi & \xrightarrow{\cong} & \text{im } \phi & \hookrightarrow & S
 \end{array}$$

**Corollary 16.11.2** (First Isomorphism Theorem). *Let  $\phi : R \rightarrow S$  be a surjective ring homomorphism. Then*

$$S \cong R/\ker \phi .$$

**Theorem 16.12** (Third Isomorphism Theorem). *Let  $I$  and  $J$  be ideals in  $R$  with  $I \subseteq J$ . Then  $J/I$  is an ideal in  $R/I$ , and*

$$\frac{R/I}{J/I} \cong R/J$$

PROOF: Since the function  $R/I \rightarrow R/J$  that maps  $r + I$  to  $r + J$  is a surjective ring homomorphism with kernel  $J/I$ .  $\square$

**Corollary 16.12.1.** *Let  $\phi : R \rightarrow S$  be a surjective ring homomorphism. Let  $J$  be an ideal in  $R$ . Then*

$$\frac{S}{\phi(J)} \cong \frac{R}{\ker \phi + J}$$

**Proposition 16.13.** *Let  $R$  be a ring and  $J$  an ideal in  $\mathfrak{gl}_n(R)$ . Let  $A \in \mathfrak{gl}_n(R)$ . Then  $A \in J$  if and only if the matrices obtained by placing any entry of  $A$  in any position and zeros elsewhere all belong to  $J$ .*

PROOF: Each such matrix can be obtained by pre- and post-multiplying  $A$  by matrices which have a single 1 and 0s elsewhere. Conversely,  $A$  is a sum of such matrices.  $\square$

**Corollary 16.13.1.** *Let  $R$  be a ring. Let  $J$  be an ideal in  $\mathfrak{gl}_n(R)$ . Let  $I$  be the set of all entries of elements of  $J$ . Then  $I$  is an ideal in  $R$ , and  $J$  is the set of all matrices whose entries are in  $I$ .*

**Proposition 16.14.** *Let  $R$  be a ring. Let  $\{I_\alpha\}_{\alpha \in A}$  be a family of ideals in  $R$ . Let*

$$\sum_{\alpha \in A} I_\alpha = \left\{ \sum_{\alpha \in A} r_\alpha : \forall \alpha, r_\alpha \in I_\alpha, r_\alpha = 0 \text{ for all but finitely many } \alpha \in A \right\} .$$

*Then  $\sum_{\alpha \in A} I_\alpha$  is an ideal, and is the smallest ideal that includes every  $I_\alpha$ .*

PROOF: Easy.  $\square$

**Proposition 16.15.** *The intersection of a set of ideals is an ideal.*

PROOF: Easy.  $\square$

## 16.1 Characteristic

**Definition 16.16** (Characteristic). The *characteristic* of a ring  $R$  is the non-negative integer  $n$  such that  $n\mathbb{Z}$  is the kernel of the unique ring homomorphism  $\mathbb{Z} \rightarrow R$ .

**Proposition 16.17.** *Let  $R$  be a ring. If the unit 1 has finite order in  $R$ , then its order is the characteristic of  $R$ ; otherwise, the characteristic of  $R$  is 0.*

PROOF: Easy.  $\square$

**Example 16.18.** The zero ring is the only ring with characteristic 1.

## 16.2 Nilradical

**Definition 16.19** (Nilradical). Let  $R$  be a commutative ring. The *nilradical* of  $R$  is the set of all nilpotent elements.

**Proposition 16.20.** *Let  $R$  be a commutative ring. The nilradical of  $R$  is an ideal in  $R$ .*

PROOF: If  $a^n = 0$  then for any  $b$  we have  $(ba)^n = 0$ .  $\square$

**Example 16.21.** We cannot remove the assumption that  $R$  is commutative. In  $\mathfrak{gl}_2(\mathbb{R})$  we have that  $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$  is nilpotent but  $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 1 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 0 & 0 \end{pmatrix}$  is not.

## 16.3 Principal Ideals

**Definition 16.22** (Principal Ideal). Let  $R$  be a commutative ring and  $a \in R$ . The *principal ideal* generated by  $a$  is  $(a) = Ra = aR$ .

**Example 16.23.**  $\{0\} = (0)$  and  $R = \{1\}$  are principal ideals.

**Definition 16.24.** Let  $R$  be a commutative ring and  $\{a_\alpha\}_{\alpha \in A}$  be a family of elements of  $R$ . The *ideal generated by the elements  $a_\alpha$*  is

$$(a_\alpha)_{\alpha \in A} := \sum_{\alpha \in A} (a_\alpha) \ .$$

An ideal is *finitely generated* iff it is generated by a finite family of elements.

**Definition 16.25.** Let  $R$  be a commutative ring and  $I, J$  be ideals in  $R$ . Then  $IJ$  is the ideal generated by  $\{ij\}_{i \in I, j \in J}$ .

**Proposition 16.26.**

$$IJ \subseteq I \cap J$$

PROOF: Easy.  $\square$

**Proposition 16.27.** *Let  $R$  be a commutative ring. Let  $I$  and  $J$  be ideals in  $R$ . If  $I + J = R$  then  $IJ = I \cap J$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $r \in I \cap J$

$\langle 1 \rangle 2$ . PICK  $i \in I$  and  $j \in J$  such that  $i + j = 1$ .

$\langle 1 \rangle 3$ .  $ri, rj \in IJ$

$\langle 1 \rangle 4$ .  $r = ri + rj \in IJ$

$\square$

**Proposition 16.28.** *Let  $R$  be a commutative ring. Let  $f \in R[x]$  be a monic polynomial of degree  $d$ . Then the function*

$$\phi : R[x] \rightarrow R^{\oplus d}$$

*that sends a polynomial  $g$  to the remainder of the division of  $g$  by  $f$  induces an isomorphism of Abelian groups*

$$\frac{R[x]}{(f(x))} \cong R^{\oplus d}.$$

PROOF: It is clearly a group homomorphism; it is surjective since it maps any polynomial of degree  $< d$  to itself, and its kernel is  $(f(x))$  since these are the polynomials with remainder 0.  $\square$

**Corollary 16.28.1.** *Let  $R$  be a commutative ring and  $a \in R$ . Then we have*

$$\frac{R[x]}{(x - a)} \cong R$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $\phi : R[x] \rightarrow R$  be evaluation at  $a$ .

$\langle 1 \rangle 2$ .  $\phi(g)$  is the remainder when dividing  $g$  by  $x - a$ .

PROOF: If  $g = (x - a)q + r$  then  $g(a) = (a - a)q(a) + r = r$ .

$\langle 1 \rangle 3$ .  $\phi$  induces a group isomorphism  $R[x]/(x - a) \cong R$

PROOF: By the theorem.

$\langle 1 \rangle 4$ . This isomorphism is a ring isomorphism.

PROOF: Since evaluation at  $a$  is a ring homomorphism.

$\square$

**Example 16.29.** We have

$$\frac{\mathbb{R}[x]}{(x^2 + 1)} \cong \mathbb{C}$$

as rings.

## 16.4 Maximal Ideals

**Definition 16.30** (Maximal Ideal). Let  $R$  be a ring and  $I$  an ideal in  $R$ . Then  $I$  is a *maximal ideal* iff  $I \neq R$  and, whenever  $J$  is an ideal with  $I \subseteq J$ , then either  $I = J$  or  $J = R$ .



## Chapter 17

# Integral Domains

**Definition 17.1** (Integral Domain). An *integral domain* is a non-trivial commutative ring with no nonzero zero-divisors.

**Example 17.2.**  $\mathbb{Z}$ ,  $\mathbb{Q}$ ,  $\mathbb{R}$  and  $\mathbb{C}$  are integral domains.

**Proposition 17.3.**  $\mathbb{Z}/n\mathbb{Z}$  is an integral domain if and only if  $n$  is prime.

PROOF:

$$\begin{aligned} n \text{ is prime} &\Leftrightarrow \forall a, b \in \mathbb{Z} (n \mid ab \Rightarrow n \mid a \vee n \mid b) \\ &\Leftrightarrow \forall a, b \in \mathbb{Z}/n\mathbb{Z} (ab \cong 0(\text{mod } n) \Rightarrow a \cong 0(\text{mod } n) \vee b \cong 0(\text{mod } n)) \\ &\Leftrightarrow \mathbb{Z}/n\mathbb{Z} \text{ is an integral domain} \quad \square \end{aligned}$$

**Proposition 17.4.** In an integral domain, if  $x^2 = 1$  then  $x = \pm 1$ .

PROOF: We have  $x^2 - 1 = (x - 1)(x + 1) = 0$  so  $x - 1 = 0$  or  $x + 1 = 0$ .  $\square$

**Proposition 17.5.** Let  $R$  be an integral domain and  $f, g \in R[x]$ . Then

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

PROOF:

$\langle 1 \rangle 1$ . LET:  $f = \sum_n a_n x^n$  and  $g = \sum_n b_n x^n$ .

$\langle 1 \rangle 2$ . LET:  $d = \deg f$  and  $e = \deg g$ .

$\langle 1 \rangle 3$ . The  $d + e$ th term of  $fg$  is

$$a_d b_e x^{d+e}$$

which is non-zero.

$\langle 1 \rangle 4$ . For  $n > d + e$  the  $n$ th term of  $fg$  is 0.

$\square$

**Corollary 17.5.1.** Let  $R$  be a ring. Then  $R[x]$  is an integral domain if and only if  $R$  is an integral domain.

**Proposition 17.6.** Let  $R$  be a ring. Then  $R[[x]]$  is an integral domain if and only if  $R$  is an integral domain.

PROOF:

$\langle 1 \rangle 1$ . If  $R[[x]]$  is an integral domain then  $R$  is an integral domain.

PROOF: Easy.

$\langle 1 \rangle 2$ . If  $R$  is an integral domain then  $R[[x]]$  is an integral domain.

$\langle 2 \rangle 1$ . ASSUME:  $R$  is an integral domain.

$\langle 2 \rangle 2$ . LET:  $(\sum_n a_n x^n)(\sum_n b_n x^n) = 0$

$\langle 2 \rangle 3$ .  $a_0 b_0 = 0$

$\langle 2 \rangle 4$ .  $a_0 = 0$  or  $b_0 = 0$

$\langle 2 \rangle 5$ . ASSUME: w.l.o.g.  $b_0 \neq 0$

PROVE: For all  $n$  we have  $a_n = 0$

$\langle 2 \rangle 6$ . ASSUME: as induction hypothesis  $a_0 = a_1 = \cdots = a_{n-1} = 0$

$\langle 2 \rangle 7$ .  $\sum_{i=0}^n a_i b_{n-i} = 0$

$\langle 2 \rangle 8$ .  $a_n b_0 = 0$

$\langle 2 \rangle 9$ .  $a_n = 0$

□

**Proposition 17.7.** *Let  $R$  be a ring and  $S$  an integral domain. Every ring homomorphism  $\phi : R \rightarrow S$  is a ring homomorphism.*

PROOF:

$$\begin{aligned}\phi(1) &= \phi(1 \cdot 1) \\ &= \phi(1)\phi(1)\end{aligned}$$

and so  $\phi(1) = 1$  by Cancellation. □

**Proposition 17.8.** *The characteristic of an integral domain is either 0 or a prime number.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $D$  be an integral domain.

$\langle 1 \rangle 2$ . LET:  $n$  be the characteristic of  $D$

$\langle 1 \rangle 3$ . ASSUME:  $n \neq 0$

$\langle 1 \rangle 4$ . ASSUME:  $n = ab$

$\langle 1 \rangle 5$ .  $ab = 0$  in  $D$

$\langle 1 \rangle 6$ .  $a = 0$  or  $b = 0$  in  $D$

$\langle 1 \rangle 7$ .  $n \mid a$  or  $n \mid b$

$\langle 1 \rangle 8$ . One of  $a, b$  is 1 and the other is  $n$ .

□

## 17.1 Prime Ideals

**Definition 17.9** (Prime Ideal). Let  $I$  be an ideal in a commutative ring  $R$ . Then  $I$  is a *prime ideal* iff  $R/I$  is an integral domain.

**Example 17.10.** Let  $R$  be a commutative ring and  $a \in R$ . Then  $(x - a)$  is a prime ideal in  $R$  iff  $R$  is an integral domain.

**Proposition 17.11.** *Let  $R$  be a commutative ring and  $I$  a proper ideal in  $R$ . Then  $I$  is prime iff, whenever  $ab \in I$ , then  $a \in I$  or  $b \in I$ .*

PROOF: The condition is the same as saying that, if  $(a + I)(b + I) = I$ , then  $a + I = I$  or  $b + I = I$ .  $\square$

**Definition 17.12** (Spectrum). The *spectrum* of a commutative ring  $R$ ,  $\text{Spec } R$ , is the set of prime ideals.

**Proposition 17.13.** Let  $\phi : R \rightarrow S$  be a ring homomorphism. If  $I$  is a prime ideal in  $S$  then  $\phi^{-1}(I)$  is a prime ideal in  $R$ .

PROOF: If  $ab \in \phi^{-1}(I)$  then  $\phi(a)\phi(b) \in I$  so either  $\phi(a) \in I$  or  $\phi(b) \in I$ , i.e. either  $a \in \phi^{-1}(I)$  or  $b \in \phi^{-1}(I)$ .  $\square$

**Proposition 17.14.** Let  $R$  be a commutative ring. Suppose there exists a prime ideal  $P$  in  $R$  such that the only zero-divisor in  $P$  is 0. Then  $R$  is an integral domain.

PROOF:

$\langle 1 \rangle$ 1. ASSUME:  $ab = 0$  in  $R$

$\langle 1 \rangle$ 2.  $ab \in P$

$\langle 1 \rangle$ 3.  $a \in P$  or  $b \in P$

$\langle 1 \rangle$ 4.  $a = 0$  or  $b = 0$

$\square$

**Proposition 17.15.** Let  $R$  be a commutative ring. The nilradical of  $R$  is included in every prime ideal of  $R$ .

PROOF: Let  $P$  be a prime ideal. If  $a^n = 0$  then  $a^n \in P$  hence  $a \in P$ .  $\square$

**Definition 17.16** (Krull Dimension). The (*Krull*) *dimension* of a commutative ring  $R$  is the length of the longest chain of prime ideals in  $R$ .

**Example 17.17.**  $\mathbb{Z}[x]$  has Krull dimension 2.





## Chapter 18

# Unique Factorization Domains

**Example 18.1.**  $\mathbb{Z}$  is a UFD.



## Chapter 19

# Noetherian Rings

**Definition 19.1** (Noetherian Ring). A commutative ring is *Noetherian* iff every ideal is finitely generated.

**Proposition 19.2.** *The homomorphic image of a Noetherian ring is Noetherian.*

PROOF:

⟨1⟩1. LET:  $R$  be a Noetherian ring,  $S$  be a commutative ring, and  $\phi : R \rightarrow S$  a surjective ring homomorphism.

⟨1⟩2. LET:  $I$  be an ideal in  $S$ .

⟨1⟩3. LET:  $\phi^{-1}(I) = (a_1, \dots, a_n)$

⟨1⟩4.  $I = (\phi(a_1), \dots, \phi(a_n))$

□



## Chapter 20

# Principal Ideal Domains

**Definition 20.1** (Principal Ideal Domain). A commutative ring is a *principal ideal domain* (PID) iff every ideal is principal.

**Example 20.2.**  $\mathbb{Z}$  is a PID by Proposition 7.16.

**Example 20.3.**  $\mathbb{Z}[x]$  is not a PID. The ideal  $(2, x)$  is not principal.

**Proposition 20.4.** *Every PID is Noetherian.*

PROOF: Trivial.  $\square$

**Proposition 20.5.** *Every nonzero prime ideal in a PID is maximal.*

PROOF:

$\langle 1 \rangle$ 1. LET:  $R$  be a PID.

$\langle 1 \rangle$ 2. LET:  $I$  be a nonzero prime ideal in  $R$ .

$\langle 1 \rangle$ 3. PICK  $a \in R$  such that  $I = (a)$ .

$\langle 1 \rangle$ 4. LET:  $J$  be an ideal such that  $I \subseteq J$

$\langle 1 \rangle$ 5. PICK  $b \in R$  such that  $J = (b)$ .

$\langle 1 \rangle$ 6. PICK  $t \in R$  such that  $a = bt$ .

$\langle 1 \rangle$ 7.  $b \in I$  or  $t \in I$

$\langle 1 \rangle$ 8. CASE:  $b \in I$

PROOF: Then  $J \subseteq I$  so  $I = J$ .

$\langle 1 \rangle$ 9. CASE:  $t \in I$

$\langle 2 \rangle$ 1. PICK  $s \in R$  such that  $t = as$ .

$\langle 2 \rangle$ 2.  $a = ast$

$\langle 2 \rangle$ 3.  $st = 1$

PROOF: Since  $R$  is an integral domain.

$\langle 2 \rangle$ 4.  $1 \in I$

$\langle 2 \rangle$ 5.  $I = R$

$\square$

**Corollary 20.5.1.** *Any PID has Krull dimension 1.*



## Chapter 21

# Euclidean Domains

**Example 21.1.**  $\mathbb{Z}$  is a Euclidean domain.





## Chapter 22

# Division Rings

**Definition 22.1** (Division Ring). A *division ring* is a ring in which every nonzero element is a two-sided unit.

**Example 22.2.** The quaternions form a division ring, with the inverse of a non-zero element  $a + bi + cj + dk$  being

$$\frac{1}{a^2 + b^2 + c^2 + d^2}(a - bi - cj - dk) .$$

**Example 22.3.** For any ring  $R$ , the ring of polynomials  $R[x]$  is not a division ring, since  $x$  has no inverse.

**Proposition 22.4.** *Every centralizer in a division ring is a division ring.*

PROOF: If  $ar = ra$  then  $ra^{-1} = a^{-1}r$ .  $\square$

**Proposition 22.5.** *A non-trivial ring  $R$  is a division ring if and only if its only left-ideals and right-ideals are  $\{0\}$  and  $R$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $R$  is a division ring then the only left-ideals and right-ideals are  $\{0\}$  and  $R$ .

$\langle 2 \rangle 1$ . ASSUME:  $R$  is a division ring.

$\langle 2 \rangle 2$ . The only left-ideals are  $\{0\}$  and  $R$ .

$\langle 3 \rangle 1$ . LET:  $I$  be a left-ideal that is not  $\{0\}$ .

PROVE:  $I = R$

$\langle 3 \rangle 2$ . PICK  $a \in I - \{0\}$

$\langle 3 \rangle 3$ . PICK a left inverse  $b$  for  $a$

$\langle 3 \rangle 4$ .  $1 \in I$

PROOF: Since  $1 = ba$ .

$\langle 3 \rangle 5$ .  $I = R$

PROOF: For any  $r \in R$  we have  $r = r1 \in I$ .

$\langle 2 \rangle 3$ . The only right-ideals are  $\{0\}$  and  $R$ .

PROOF: Similar.

⟨1⟩2. If the only left-ideals and right-ideals are  $\{0\}$  and  $R$  then  $R$  is a division ring.

□

**Proposition 22.6.** *Let  $K$  be a division ring and  $R$  a non-trivial ring. Every ring homomorphism  $K \rightarrow R$  is injective.*

PROOF:

⟨1⟩1. LET:  $\phi : K \rightarrow R$  be a ring homomorphism.

PROVE:  $\ker \phi = \{0\}$

⟨1⟩2. LET:  $x \in \ker \phi$

⟨1⟩3. ASSUME: for a contradiction  $x \neq 0$ .

⟨1⟩4.  $\phi(xx^{-1}) = 1$

⟨1⟩5.  $0 = 1$

⟨1⟩6. Q.E.D.

PROOF: This contradicts the assumption that  $R$  is non-trivial.

□

## Chapter 23

# Simple Rings

**Definition 23.1** (Simple Ring). A non-trivial ring is *R simple* iff its only two-sided ideals are  $\{0\}$  and  $R$ .

**Example 23.2.** For any simple ring  $R$  we have  $\mathfrak{gl}_n(R)$  is simple, by Corollary 16.13.1.

**Proposition 23.3.** *Let  $R$  be a ring and  $I$  an ideal in  $R$ . Then  $I$  is maximal iff  $R/I$  is simple.*

PROOF:

$$\begin{aligned} R/I \text{ is simple} &\Leftrightarrow \text{the only ideals in } R/I \text{ are } \{I\} \text{ and } R/I \\ &\Leftrightarrow \text{the only ideals in } R \text{ that include } I \text{ are } I \text{ and } R \\ &\Leftrightarrow I \text{ is maximal} \end{aligned}$$

□



## Chapter 24

# Reduced Rings

**Definition 24.1** (Reduced Ring). A ring is *reduced* iff it has no non-zero nilpotent elements.

**Proposition 24.2.** *Let  $R$  be a commutative ring. Let  $N$  be its nilradical. Then  $R/N$  is reduced.*

PROOF:

- $\langle 1 \rangle 1.$  LET:  $r + N$  be nilpotent.
- $\langle 1 \rangle 2.$  PICK  $n$  such that  $(r + N)^n = N$
- $\langle 1 \rangle 3.$   $r^n \in N$
- $\langle 1 \rangle 4.$  PICK  $k$  such that  $(r^n)^k = 0$
- $\langle 1 \rangle 5.$   $r^{nk} = 0$
- $\langle 1 \rangle 6.$   $r \in N$
- $\langle 1 \rangle 7.$   $r + N = N$

□

**Proposition 24.3.** *Let  $R$  be a commutative ring. Let  $I$  and  $J$  be ideals in  $R$ . If  $R/IJ$  is reduced then  $IJ = I \cap J$ .*

PROOF:

- $\langle 1 \rangle 1.$  LET:  $r \in I \cap J$   
PROVE:  $r \in IJ$
- $\langle 1 \rangle 2.$   $r^2 \in IJ$
- $\langle 1 \rangle 3.$   $(r + IJ)^2 = IJ$
- $\langle 1 \rangle 4.$   $r + IJ = IJ$

PROOF: Since  $R/IJ$  is reduced.

- $\langle 1 \rangle 5.$   $r \in IJ$

□



## Chapter 25

# Boolean Rings

**Definition 25.1** (Boolean). A ring is *Boolean* iff  $a^2 = a$  for every element  $a$ .

**Example 25.2.** For any set  $S$ , the ring  $\mathcal{P}S$  is Boolean.

**Proposition 25.3.** *Every non-trivial Boolean ring has characteristic 2.*

PROOF: We have  $4 = 2$  and so  $2 = 0$ .  $\square$

**Proposition 25.4.** *Every Boolean ring is commutative.*

PROOF:

$$\begin{aligned}(a+b)^2 &= a+b \\ \therefore a^2 + ab + ba + b^2 &= a+b \\ \therefore a + ab + ba + b &= a+b \\ \therefore ab + ba &= 0 \\ \therefore ab &= -ba \\ &= ba \quad (\text{Proposition 25.3})\end{aligned}$$

**Example 25.5.** The only Boolean integral domain is  $\mathbb{Z}/2\mathbb{Z}$ . For, if  $D$  is a Boolean integral domain and  $x \in D$ , we have  $x^2 = x$ , so  $x^2 - x = x(x-1) = 0$  and so  $x = 0$  or  $x = 1$ , i.e.  $D = \{0, 1\}$ .

**Proposition 25.6.** *Every Boolean ring has Krull dimension 0.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $R$  be a Boolean ring.

$\langle 1 \rangle 2$ . LET:  $I$  be a prime ideal in  $R$ .

PROVE:  $I$  is maximal.

$\langle 1 \rangle 3$ . LET:  $J$  be an ideal with  $I \subsetneq J$

$\langle 1 \rangle 4$ . PICK  $a \in J$  with  $a \notin I$

$\langle 1 \rangle 5$ .  $a^2 - a = 0 \in I$

$\langle 1 \rangle 6$ .  $a(a-1) \in I$

$$\langle 1 \rangle 7. \ a - 1 \in I$$

$$\langle 1 \rangle 8. \ a - 1 \in J$$

$$\langle 1 \rangle 9. \ 1 \in J$$

$$\langle 1 \rangle 10. \ J = R$$

□



# Chapter 26

## Modules

**Definition 26.1** (Left Module). Let  $R$  be a ring and  $M$  an Abelian group. A *left-action* of  $R$  on  $M$  is a ring homomorphism

$$R \rightarrow \text{End}_{\mathbf{Ab}}(M) \quad .$$

A *left  $R$ -module* consists of an Abelian group  $M$  and a left-action of  $R$  on  $M$ .

**Proposition 26.2.** *Let  $R$  be a ring and  $M$  an Abelian group. Let  $\cdot : R \times M \rightarrow M$ . Then  $\cdot$  defines a left-action of  $R$  on  $M$  if and only if, for all  $r, s \in R$  and  $m, n \in M$ :*

- $r(m + n) = rm + rn$
- $(r + s)m = rm + sm$
- $(rs)m = r(sm)$
- $1m = m$

PROOF: Immediate from definitions.  $\square$

**Proposition 26.3.** *In any  $R$ -module  $M$  we have  $0m = 0$  for all  $m \in M$ .*

PROOF: Since  $0m = (0 + 0)m = 0m + 0m$  and so  $0m = 0$  by cancellation in  $M$ .  $\square$

**Proposition 26.4.** *In any  $R$ -module  $M$  we have  $(-1)m = -m$  for all  $m \in M$ .*

PROOF: Since  $m + (-1)m = 1m + (-1)m = (1 + (-1))m = 0m = 0$ .  $\square$

**Proposition 26.5.** *Every Abelian group is a  $\mathbb{Z}$ -module in exactly one way.*

PROOF: Since  $\mathbb{Z}$  is initial in **Ring**.  $\square$

**Definition 26.6** (Right Module). Let  $R$  be a ring. A *right  $R$ -module* consists of an Abelian group  $M$  and a function  $\cdot : M \times R \rightarrow M$  such that, for all  $r, s \in R$  and  $m, n \in M$ :

- $(m + n)r = mr + nr$
- $m(r + s) = mr + ms$
- $m(rs) = (mr)s$
- $m1 = m$

## 26.1 Homomorphisms

**Definition 26.7** (Homomorphism of Left-Modules). Let  $R$  be a ring. Let  $M$  and  $N$  be left- $R$ -modules. A *homomorphism of left- $R$ -modules*  $\phi : M \rightarrow N$  is a group homomorphism such that, for all  $r \in R$  and  $m \in M$ , we have  $\phi(rm) = r\phi(m)$ .

Let  $R - \mathbf{Mod}$  be the category of left- $R$ -modules and left- $R$ -module homomorphisms.

**Example 26.8.**

$$\mathbb{Z} - \mathbf{Mod} \cong \mathbf{Ab}$$

**Example 26.9.** The trivial group  $0$  is the zero object in  $R - \mathbf{Mod}$ .

**Proposition 26.10.** *Every bijective  $R$ -module homomorphism is an isomorphism.*

PROOF: Easy.  $\square$

**Proposition 26.11.** *Let  $R$  be a ring. Let  $M$  be an  $R$ -module. Then*

$$M \cong R - \mathbf{Mod}[R, M]$$

*as  $R$ -modules.*

PROOF: The isomorphism maps  $m$  to the function  $\lambda r.rm$ . Its inverse maps an  $R$ -module homomorphism  $\alpha$  to  $\alpha(1)$ .  $\square$

**Proposition 26.12.** *Let  $R$  be a commutative ring. Let  $M$  be an  $R$ -module. Then there is a bijection between the set of  $R[x]$ -module structures on  $M$  that extend the given  $R$ -module structure and  $\text{End}_{R - \mathbf{Mod}}(M)$ .*

PROOF:

- (1)1. LET:  $\alpha : R \rightarrow \text{End}_{\mathbf{Ab}}(M)$  be the given  $R$ -module structure on  $M$ .
- (1)2. An  $R[x]$ -module structure on  $M$  that extends  $\alpha$  is a ring homomorphism  $\beta : R[x] \rightarrow \text{End}_{\mathbf{Ab}}(M)$  such that  $\beta \circ i = \alpha$ , where  $i$  is the inclusion  $R \rightarrow R[x]$ .
- (1)3. There is a bijection between the  $R[x]$ -module structures on  $M$  that extend  $\alpha$  and the elements  $s \in \text{End}_{\mathbf{Ab}}(M)$  that commute with  $\alpha(r)$  for all  $r \in R$ .

PROOF: By the universal property for polynomials.

- (1)4. There is a bijection between the  $R[x]$ -module structures on  $M$  that extend  $\alpha$  and the  $R$ -module homomorphisms  $(M, \alpha) \rightarrow (M, \alpha)$ .

□

**Proposition 26.13.** *Let  $R$  be a commutative ring. Let  $M$  and  $N$  be  $R$ -modules. Then  $R - \mathbf{Mod}[M, N]$  is an  $R$ -module under*

$$\begin{aligned}(\phi + \psi)(m) &= \phi(m) + \psi(m) \\ (r\phi)(m) &= r\phi(m)\end{aligned}$$

PROOF: Easy. □

**Proposition 26.14.** *Let  $R$  be an integral domain. Let  $I$  be a nonzero principal ideal of  $R$ . Then  $I \cong R$  in  $R - \mathbf{Mod}$ .*

PROOF:

⟨1⟩1. PICK  $a \in R$  such that  $I = (a)$ .

⟨1⟩2. LET:  $\phi : R \rightarrow I$  be the map  $\phi(r) = ra$ .

⟨1⟩3.  $\phi$  is an  $R$ -module homomorphism.

PROOF: Since  $(r + s)a = ra + sa$  and  $(rs)a = r(sa)$ .

⟨1⟩4.  $\phi$  is surjective.

⟨1⟩5.  $\phi$  is injective.

PROOF: If  $ra = sa$  then  $(r - s)a = 0$  so  $r - s = 0$  and  $r = s$ .

⟨1⟩6.  $\phi : R \cong I$

□

## 26.2 Submodules

**Definition 26.15** (Submodule). Let  $M$  be a left- $R$ -module and  $N \subseteq M$ . Then  $N$  is a *submodule* of  $M$  iff  $N$  is a subgroup of  $M$  and  $\forall r \in R, \forall n \in N, rn \in N$ .

**Proposition 26.16.** *Let  $R$  be a ring and  $I \subseteq R$ . Then  $I$  is a left-ideal in  $R$  iff  $I$  is a submodule of  $R$  as an  $R$ -module.*

PROOF: Immediate from definitions. □

**Proposition 26.17.** *Let  $R$  be a ring. Let  $M$  and  $N$  be left- $R$ -modules and  $\phi : M \rightarrow N$  an  $R$ -module homomorphism. Then  $\ker \phi$  is a submodule of  $M$  and  $\text{im } \phi$  is a submodule of  $N$ .*

PROOF: Easy. □

**Proposition 26.18.** *Let  $R$  be a commutative ring. Let  $M$  be a left- $R$ -module. Let  $r \in R$ . Then  $rM = \{rm : m \in M\}$  is a submodule of  $M$ .*

PROOF: Easy. □

**Proposition 26.19.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $I$  be a left-ideal in  $R$ . Then  $IM = \{rm : r \in I, m \in M\}$  is a submodule of  $M$ .*

PROOF:

- $\langle 1 \rangle 1.$   $IM$  is a subgroup of  $M$ .  
 $\langle 2 \rangle 1.$  LET:  $r, s \in I$  and  $m, n \in M$ .  
 PROVE:  $rm + sn \in IM$   
 $\langle 2 \rangle 2.$   $rm + sn = r(m - n) + (s - r)n$   
 $\langle 1 \rangle 2.$  For all  $r \in R$  and  $x \in IM$  we have  $rx \in IM$ .  
 $\square$

## 26.3 Quotient Modules

**Definition 26.20** (Quotient Module). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $N$  be a submodule of  $M$ . Then the *quotient module*  $M/N$  is the quotient group  $M/N$  under

$$r(m + N) = rm + N \ .$$

**Proposition 26.21.** Let  $R$  be a ring. Let  $M$  and  $P$  be left- $R$ -modules. Let  $N$  be a submodule of  $M$ . Let  $\phi : M \rightarrow P$  be an  $R$ -module homomorphism. If  $N \subseteq \ker \phi$ , then there exists a unique  $R$ -module homomorphism  $\bar{\phi} : M/N \rightarrow P$  such that the following diagram commutes.

$$\begin{array}{ccc}
 M & \xrightarrow{\phi} & P \\
 & \searrow & \nearrow \bar{\phi} \\
 & M/N &
 \end{array}$$

PROOF: Easy.  $\square$

**Theorem 26.22.** Every  $R$ -module homomorphism  $\phi : M \rightarrow M'$  may be decomposed as:

$$M \longrightarrow M/\ker \phi \xrightarrow{\cong} \text{im } \phi \longrightarrow M'$$

PROOF: Easy.  $\square$

**Corollary 26.22.1** (First Isomorphism Theorem). Let  $\phi : M \rightarrow M'$  be a surjective  $R$ -module homomorphism. Then

$$M' \cong \frac{M}{\ker \phi} \ .$$

**Proposition 26.23** (Second Isomorphism Theorem). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $N$  and  $P$  be submodules of  $M$ . Then  $N + P$  is a submodule of  $M$ ,  $N \cap P$  is a submodule of  $P$ , and

$$\frac{N + P}{N} \cong \frac{P}{N \cap P}$$

PROOF: The function that maps  $P$  to  $p + N$  is a surjective homomorphism  $P \rightarrow (N + P)/N$  with kernel  $N \cap P$ .  $\square$

**Proposition 26.24** (Third Isomorphism Theorem). *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $N$  be a submodule of  $M$  and  $P$  a submodule of  $N$ . Then  $N/P$  is a submodule of  $M/P$  and*

$$\frac{M/P}{N/P} \cong \frac{M}{N}$$

PROOF: The canonical map  $M \rightarrow M/N$  induces a surjective homomorphism  $M/P \rightarrow M/N$  which has kernel  $N/P$ .  $\square$

**Proposition 26.25.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. The sum and intersection of a family of submodules of  $M$  are submodules of  $M$ .*

PROOF: Easy.  $\square$

## 26.4 Products

**Proposition 26.26.**  *$R - \mathbf{Mod}$  has products.*

PROOF: Given a family  $\{M_\alpha\}_{\alpha \in A}$  of left- $R$ -modules, we make  $\prod_{\alpha \in A} M_\alpha$  into a left- $R$ -module by

$$\begin{aligned} (f + g)(\alpha) &= f(\alpha) + g(\alpha) \\ (rf)(\alpha) &= rf(\alpha) \end{aligned} \quad \square$$

## 26.5 Coproducts

**Proposition 26.27.**  *$R - \mathbf{Mod}$  has coproducts.*

PROOF: Given a family  $\{M_\alpha\}_{\alpha \in A}$  of left- $R$ -modules, take  $\bigoplus_{\alpha \in A} M_\alpha$  to be  $\{f \in \prod_{\alpha \in A} M_\alpha : f(\alpha) = 0 \text{ for all but finitely many } \alpha \in A\}$ .  $\square$

## 26.6 Direct Sum

**Definition 26.28** (Direct Sum). *Let  $R$  be a ring. Let  $M$  and  $N$  be left- $R$ -modules. Then the direct sum  $M \oplus N$  is an  $R$ -module under*

$$r(m, n) = (rm, rn) .$$

**Proposition 26.29.**  *$M \oplus N$  is the biproduct of  $M$  and  $N$  in  $R - \mathbf{Mod}$ .*

PROOF: Easy.  $\square$

**Example 26.30.** Infinite products and coproducts are in general different. We have  $\mathbb{Z}^{\mathbb{N}} \not\cong \mathbb{Z}^{\oplus \mathbb{N}}$  since  $\mathbb{Z}^{\mathbb{N}}$  is uncountable but  $\mathbb{Z}^{\oplus \mathbb{N}}$  is countable.

## 26.7 Kernels and Cokernels

**Proposition 26.31.** *Let  $R$  be a ring. Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then  $\ker \phi \hookrightarrow M$  is terminal in the category of left- $R$ -module homomorphisms  $\alpha : P \rightarrow M$  such that  $\phi \circ \alpha = 0$ .*

PROOF: Easy.  $\square$

**Proposition 26.32.** *Let  $R$  be a ring. Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then  $N \twoheadrightarrow \operatorname{coker} \phi$  is initial in the category of left- $R$ -module homomorphisms  $\alpha : N \rightarrow P$  such that  $\alpha \circ \phi = 0$ .*

PROOF: Easy.  $\square$

**Proposition 26.33.** *Let  $R$  be a ring. Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then the following are equivalent.*

- $\phi$  is a monomorphism.
- $\ker \phi$  is trivial.
- $\phi$  is injective.

PROOF: Easy.  $\square$

**Proposition 26.34.** *Let  $R$  be a ring. Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then the following are equivalent.*

- $\phi$  is an epimorphism.
- $\operatorname{coker} \phi$  is trivial.
- $\phi$  is surjective.

PROOF: Easy.  $\square$

**Proposition 26.35.** *Every monomorphism in  $R - \mathbf{Mod}$  is the kernel of some homomorphism.*

PROOF: If  $\phi : M \rightarrow N$  is a monomorphism then it is the kernel of  $N \twoheadrightarrow N/\operatorname{im} \phi$ .  $\square$

**Proposition 26.36.** *Every epimorphism in  $R - \mathbf{Mod}$  is the cokernel of some homomorphism.*

PROOF: If  $\phi : M \rightarrow N$  is epi then it is the cokernel of  $\ker \phi \hookrightarrow M$ .  $\square$

**Example 26.37.** Monomorphisms do not split in  $R - \mathbf{Mod}$ . Multiplication by 2 is a monomorphism  $\mathbb{Z} \rightarrow \mathbb{Z}$  but has no left inverse.

**Example 26.38.** Epimorphisms do not split in  $R - \mathbf{Mod}$ . The canonical map  $\mathbb{Z} \rightarrow \mathbb{Z}/2\mathbb{Z}$  is an epimorphism without a right inverse.

## 26.8 Free Modules

**Proposition 26.39.** *Let  $R$  be a ring and  $A$  a set. Then there exists a left- $R$ -module  $F^R(A)$  and function  $j : A \rightarrow F^R(A)$  such that, for any left- $R$ -module  $M$  and function  $f : A \rightarrow M$ , there exists a unique left- $R$ -module homomorphism  $\bar{f} : F^R(A) \rightarrow M$  such that the following diagram commutes.*

$$\begin{array}{ccc} F^R(A) & \xrightarrow{\bar{f}} & M \\ j \uparrow & \nearrow f & \\ A & & \end{array}$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $R^{\oplus A} = \{\alpha : A \rightarrow R : \alpha(a) = 0 \text{ for all but finitely many } a \in A\}$   
under the operations

$$\begin{aligned} (\alpha + \beta)(a) &= \alpha(a) + \beta(a) \\ (r\alpha)(a) &= r\alpha(a) \end{aligned}$$

$\langle 1 \rangle 2$ .  $R^{\oplus A}$  is a left- $R$ -module.

$\langle 1 \rangle 3$ . LET:  $j : A \rightarrow R^{\oplus A}$  be the function

$$j(a)(a') = \begin{cases} 1 & \text{if } a = a' \\ 0 & \text{if } a \neq a' \end{cases}$$

$\langle 1 \rangle 4$ . LET:  $M$  be any left- $R$ -module.

$\langle 1 \rangle 5$ . LET:  $f : A \rightarrow M$  be a function.

$\langle 1 \rangle 6$ . LET:  $\bar{f} : R^{\oplus A} \rightarrow M$  be the function

$$\bar{f}(\alpha) = \sum_{a \in A, \alpha(a) \neq 0} \alpha(a)f(a)$$

$\langle 1 \rangle 7$ .  $\bar{f}$  is a left- $R$ -module homomorphism.

$\langle 1 \rangle 8$ .  $\bar{f} \circ j = f$

$\langle 1 \rangle 9$ .  $\bar{f}$  is unique.

**Definition 26.40.** We call  $j : A \rightarrow F^R(A)$  the *free* left- $R$ -module over  $A$ .

**Proposition 26.41.**  $j$  is injective.

PROOF: By the proof of the previous proposition.  $\square$

**Proposition 26.42.** *Let  $R$  be a ring. Let  $F$  be a non-zero free left- $R$ -module. Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then  $\phi$  is onto if and only if, for every left- $R$ -module homomorphism  $\alpha : F \rightarrow N$ , there exists a left- $R$ -module homomorphism  $\beta : F \rightarrow M$  such that the diagram below commutes.*

$$\begin{array}{ccc} M & \xrightarrow{\phi} & N \\ \beta \uparrow & \nearrow \alpha & \\ F & & \end{array}$$

PROOF:

- (1)1. LET:  $F$  be the free left- $R$ -module over  $A$  with injection  $j : A \rightarrow F$ .  
 (1)2. If  $\phi$  is onto then, for every homomorphism  $\alpha : F \rightarrow N$ , there exists a homomorphism  $\beta : F \rightarrow M$  such that  $\phi \circ \beta = \alpha$ .  
 (2)1. ASSUME:  $\phi$  is onto.  
 (2)2. LET:  $\alpha : F \rightarrow N$  be a homomorphism.  
 (2)3. For  $a \in A$ , PICK  $f(a) \in M$  such that  $\phi(f(a)) = \alpha(j(a))$   
 (2)4. LET:  $\beta : F \rightarrow M$  be the unique homomorphism such that  $\beta \circ j = f$   
 (2)5.  $\phi \circ \beta = \alpha$   
 PROOF: Each is the unique homomorphism such that  $\alpha \circ j = \phi \circ f$ .

□

$$\begin{array}{ccccc}
 & & M & \xrightarrow{\phi} & N \\
 & f \nearrow & \uparrow \beta & \nearrow \alpha & \\
 A & \xrightarrow{j} & F & & 
 \end{array}$$

- (1)3. If, for every homomorphism  $\alpha : F \rightarrow N$ , there exists a homomorphism  $\beta : F \rightarrow M$  such that  $\phi \circ \beta = \alpha$ , then  $\phi$  is onto.  
 (2)1. ASSUME: For every homomorphism  $\alpha : F \rightarrow N$  there exists a homomorphism  $\beta : F \rightarrow M$  such that  $\phi \circ \beta = \alpha$ .  
 (2)2. LET:  $n \in N$   
 (2)3. LET:  $\alpha : F \rightarrow N$  be the unique homomorphism such that, for all  $a \in A$ , we have  $\alpha(j(a)) = n$   
 (2)4. PICK a homomorphism  $\beta : F \rightarrow M$  such that  $\phi \circ \beta = \alpha$   
 (2)5. PICK  $a \in A$   
 (2)6.  $\phi(\beta(j(a))) = n$

□

## 26.9 Generators

**Definition 26.43** (Submodule Generated by a Set). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $A$  be a subset of  $M$ . Let  $\phi_A : F^R(A) \rightarrow M$  be the unique left- $R$ -module homomorphism such that the following diagram commutes.

$$\begin{array}{ccc}
 F^R(A) & \xrightarrow{\phi_A} & M \\
 \uparrow & \nearrow & \\
 A & & 
 \end{array}$$

The submodule of  $M$  generated by  $A$ , denoted  $\langle A \rangle$ , is defined to be  $\text{im } \phi_A$ .

**Definition 26.44** (Finitely Generated). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Then  $M$  is *finitely generated* iff there exists a finite set  $A \subseteq M$  such that  $M = \langle A \rangle$ .

**Example 26.45.** A submodule of a finitely generated module is not necessarily finitely generated.

Let  $R = \mathbb{Z}[x_1, x_2, \dots]$ . Then  $R$  is finitely generated as an  $R$ -module, but  $(x_1, x_2, \dots)$  is not.



**Proposition 26.46.** *The homomorphic image of a finitely generated module is finitely generated.*

PROOF: Easy.  $\square$

**Proposition 26.47.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $N$  be a submodule of  $M$ . If  $N$  and  $M/N$  are finitely generated then  $M$  is finitely generated.*

PROOF:

$\langle 1 \rangle 1$ . PICK  $a_1, \dots, a_n$  that generate  $N$ .

$\langle 1 \rangle 2$ . PICK  $b_1, \dots, b_m$  such that  $b_1 + N, \dots, b_m + N$  generate  $M/N$ .

PROVE:  $a_1, \dots, a_n, b_1, \dots, b_m$  generate  $M$ .

$\langle 1 \rangle 3$ . LET:  $m \in M$

$\langle 1 \rangle 4$ . PICK  $r_1, \dots, r_m \in R$  such that  $m + N = r_1 b_1 + \dots + r_m b_m + N$

$\langle 1 \rangle 5$ .  $m - r_1 b_1 - \dots - r_m b_m \in N$

$\langle 1 \rangle 6$ . PICK  $s_1, \dots, s_n \in R$  such that  $m - r_1 b_1 - \dots - r_m b_m = s_1 a_1 + \dots + s_n a_n$

$\langle 1 \rangle 7$ .  $m = r_1 b_1 + \dots + r_m b_m + s_1 a_1 + \dots + s_n a_n$

$\square$

## 26.10 Projections

**Definition 26.48** (Projection). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $p : M \rightarrow M$  be a left- $R$ -module homomorphism. Then  $p$  is a *projection* iff  $p^2 = p$ .

**Proposition 26.49.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Let  $p : M \rightarrow M$  be a projection. Then*

$$M \cong \ker p \oplus \operatorname{im} p .$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $\phi : M \rightarrow \ker p \oplus \operatorname{im} p$  be the map  $\phi(m) = (m - p(m), p(m))$

$\langle 1 \rangle 2$ .  $\phi$  is a left- $R$ -module homomorphism.

$\langle 1 \rangle 3$ .  $\phi$  is injective.

$\langle 1 \rangle 4$ .  $\phi$  is surjective.

$\square$

## 26.11 Pullbacks

**Proposition 26.50.**  *$R - \operatorname{Mod}$  has pullbacks.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\mu : M \rightarrow Z, \nu : N \rightarrow Z$  be left- $R$ -module homomorphisms.

$\langle 1 \rangle 2$ . LET:  $M \times_Z N = \{(m, n) \in M \times N : \mu(m) = \nu(n)\}$  under

$$(m, n) + (m', n') = (m + m', n + n')$$

$$r(m, n) = (rm, rn)$$

$\langle 1 \rangle 3$ .  $M \times_Z N$  is the pullback of  $M$  and  $N$ .

$\square$

## 26.12 Pushouts

**Proposition 26.51.**  $R - \mathbf{Mod}$  has pushouts.

PROOF:

$\langle 1 \rangle$ 1. LET:  $\mu : A \rightarrow M$  and  $\nu : A \rightarrow N$  be left- $R$ -module homomorphisms.

## Chapter 27

# Cyclic Modules

**Definition 27.1** (Cyclic Module). Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Then  $M$  is *cyclic* iff there exists  $m \in M$  such that  $M = \langle m \rangle$ .

**Proposition 27.2.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module. Then  $M$  is cyclic if and only if there exists a left-ideal  $I$  in  $R$  such that  $M \cong R/I$ .*

PROOF:

$\langle 1 \rangle 1$ . If  $M$  is cyclic then there exists a left-ideal  $I$  in  $R$  such that  $M \cong R/I$ .

$\langle 2 \rangle 1$ . ASSUME:  $M$  is cyclic.

$\langle 2 \rangle 2$ . PICK  $m \in M$  such that  $M = \langle m \rangle$

$\langle 2 \rangle 3$ . LET:  $\phi : R \rightarrow M$  be the left- $R$ -module homomorphism  $\phi(r) = rm$ .

$\langle 2 \rangle 4$ .  $\phi$  is surjective.

$\langle 2 \rangle 5$ .  $M \cong R/\ker \phi$

$\langle 1 \rangle 2$ . For every left-ideal  $I$  in  $R$ , we have that  $R/I$  is cyclic.

PROOF:  $R/I$  is generated by  $1 + I$ .

□

**Proposition 27.3.** *A quotient of a cyclic module is cyclic.*

PROOF: If  $M$  is generated by  $m$  then  $M/N$  is generated by  $m + N$ . □

**Proposition 27.4.** *Let  $R$  be a ring. For any left-ideal  $I$  in  $R$  and any left- $R$ -module  $N$ , we have*

$$R - \mathbf{Mod}[R/I, N] \cong \{n \in N : \forall a \in I. an = 0\} .$$

PROOF:

$\langle 1 \rangle 1$ . LET:  $\Phi : R - \mathbf{Mod}[R/I, N] \rightarrow \{n \in N : \forall a \in I. an = 0\}$  be the function

$$\Phi(\alpha) = \alpha(1 + I)$$

PROOF: For all  $a \in I$  we have  $a\alpha(1 + I) = \alpha(a + I) = \alpha(I) = 0$ .

$\langle 1 \rangle 2$ .  $\Phi$  is injective.

PROOF: If  $\alpha(1 + I) = \beta(1 + I)$  then  $\alpha(r + I) = r\alpha(1 + I) = r\beta(1 + I) = \beta(r + I)$  for all  $r \in R$ , hence  $\alpha = \beta$ .

$\langle 1 \rangle 3$ .  $\Phi$  is surjective.

PROOF: Given  $n \in N$  such that  $\forall a \in I. an = 0$ , define  $\alpha : R/I \rightarrow N$  by  $\alpha(r + I) = rn$ .

$\langle 1 \rangle 4$ . If  $R$  is commutative then  $\Phi$  is an  $R$ -module homomorphism.

□

**Corollary 27.4.1.** *For all  $a, b \in \mathbb{Z}$  we have  $\mathbf{Ab}[\mathbb{Z}/a\mathbb{Z}, \mathbb{Z}/b\mathbb{Z}] \cong \mathbb{Z}/\gcd(a, b)\mathbb{Z}$ .*

PROOF:

$$\begin{aligned} \mathbf{Ab}[\mathbb{Z}/a\mathbb{Z}, \mathbb{Z}/b\mathbb{Z}] &\cong \mathbb{Z} - \mathbf{Mod}[\mathbb{Z}/a\mathbb{Z}, \mathbb{Z}/b\mathbb{Z}] \\ &\cong \{n \in \mathbb{Z}/b\mathbb{Z} : \forall x \in a\mathbb{Z}. xn \cong 0(\bmod b)\} \\ &\cong \{n \in \mathbb{Z}/b\mathbb{Z} : \forall x \in \mathbb{Z}. b \mid xan\} \\ &= \{n \in \mathbb{Z}/b\mathbb{Z} : b \mid an\} \end{aligned}$$

## Chapter 28

# Simple Modules

**Definition 28.1** (Simple Module). Let  $R$  be a ring. An  $R$ -module  $M$  is *simple* or *irreducible* iff its only submodules are  $\{0\}$  and  $M$ .

**Proposition 28.2** (Schur's Lemma). Let  $R$  be a ring. Let  $M$  and  $N$  be simple  $R$ -modules. Let  $\phi : M \rightarrow N$  be an  $R$ -module homomorphism. Then either  $\phi = 0$  or  $\phi$  is an isomorphism.

PROOF:

$\langle 1 \rangle 1$ . ASSUME:  $\phi \neq 0$

$\langle 1 \rangle 2$ .  $\ker \phi = 0$

PROOF: Since  $\ker \phi$  is a submodule of  $M$  that is not  $M$ .

$\langle 1 \rangle 3$ .  $\operatorname{im} \phi = N$

PROOF: Since  $\operatorname{im} \phi$  is a submodule of  $N$  that is not  $\{0\}$ .

□

**Proposition 28.3.** Every simple module is cyclic.

PROOF:

$\langle 1 \rangle 1$ . LET:  $M$  be a simple module.

$\langle 1 \rangle 2$ . ASSUME: w.l.o.g.  $M \neq \{0\}$

PROOF:  $\{0\} = \langle 0 \rangle$  is cyclic.

$\langle 1 \rangle 3$ . PICK  $m \in M$  with  $m \neq 0$

$\langle 1 \rangle 4$ .  $\langle m \rangle = M$

PROOF: Since  $\langle m \rangle$  is a submodule of  $M$  that is not  $\{0\}$ .

□



## Chapter 29

# Noetherian Modules

**Definition 29.1** (Noetherian Module). Let  $R$  be a ring. A left- $R$ -module is *Noetherian* iff every submodule is finitely generated.

**Proposition 29.2.** *Let  $R$  be a ring. Let  $M$  be a left- $R$ -module and  $N$  a submodule of  $M$ . Then  $M$  is Noetherian if and only if  $N$  and  $M/N$  are Noetherian.*

PROOF:

⟨1⟩1. If  $M$  is Noetherian then  $N$  is Noetherian.

PROOF: Every submodule of  $N$  is a submodule of  $M$ , hence finitely generated.

⟨1⟩2. If  $M$  is Noetherian then  $M/N$  is Noetherian.

⟨2⟩1. ASSUME:  $M$  is Noetherian.

⟨2⟩2. LET:  $\pi : M \rightarrow M/N$  be the canonical epimorphism.

⟨2⟩3. LET:  $P$  be a submodule of  $M/N$ .

⟨2⟩4. PICK  $a_1, \dots, a_n \in M$  that generate  $\pi^{-1}(P)$ .

⟨2⟩5.  $a_1 + N, \dots, a_n + N$  generate  $P$ .

⟨1⟩3. If  $N$  and  $M/N$  are Noetherian then  $M$  is Noetherian.

⟨2⟩1. ASSUME:  $N$  and  $M/N$  are Noetherian.

⟨2⟩2. LET:  $P$  be a submodule of  $M$ .

⟨2⟩3. PICK  $a_1, \dots, a_m \in P$  such that  $a_1 + N, \dots, a_m + N$  generate  $\pi(P)$ .

⟨2⟩4. PICK  $b_1, \dots, b_n \in M$  that generated  $P \cap N$ .

PROVE:  $a_1, \dots, a_m, b_1, \dots, b_n$  generate  $P$ .

⟨2⟩5. LET:  $p \in P$

⟨2⟩6. PICK  $r_1, \dots, r_m \in R$  such that  $p + N = r_1 a_1 + \dots + r_m a_m + N$

⟨2⟩7.  $p - r_1 a_1 - \dots - r_m a_m \in P \cap N$

⟨2⟩8. PICK  $s_1, \dots, s_n \in R$  such that  $p - r_1 a_1 - \dots - r_m a_m = s_1 b_1 + \dots + s_n b_n$

⟨2⟩9.  $p = r_1 a_1 + \dots + r_m a_m + s_1 b_1 + \dots + s_n b_n$

□

**Corollary 29.2.1.** *If  $R$  is a Noetherian ring then  $R^{\oplus n}$  is a Noetherian left- $R$ -module.*

PROOF: The proof is by induction on  $n$ . The case  $n = 1$  is immediate.

The induction step holds since  $R^{\oplus(n+1)}/R^{\oplus n} \cong R$ . □

**Corollary 29.2.2.** *If  $R$  is a Noetherian ring and  $M$  is a finitely generated left- $R$ -module then  $M$  is Noetherian.*

PROOF: There is a surjective homomorphism  $R^{\oplus n} \twoheadrightarrow M$  for some  $n$ , so  $M$  is a quotient of  $R^{\oplus n}$ .  $\square$



# Chapter 30

## Algebras

**Definition 30.1** (Algebra). Let  $R$  be a commutative ring. An  $R$ -algebra consists of a ring  $S$  and a ring homomorphism  $\alpha : R \rightarrow S$  such that  $\alpha(R)$  is included in the center of  $S$ . We write  $rs$  for  $\alpha(r)s$ .

**Proposition 30.2.** Let  $R$  be a commutative ring and  $S$  a ring. Let  $\cdot : R \times S \rightarrow S$ . Then there exists  $\alpha : R \rightarrow S$  that makes  $S$  into an  $R$ -algebra such that

$$rs = \alpha(r)s \quad (r \in R, s \in S)$$

iff  $S$  is an  $R$ -module under  $\cdot$  and, for all  $r_1, r_2 \in R$  and  $s_1, s_2 \in S$ ,

$$(r_1 s_1)(r_2 s_2) = (r_1 r_2)(s_1 s_2) .$$

PROOF: Immediate from definitions.  $\square$

**Example 30.3.** Let  $R$  be a commutative ring. Then  $R$  is an  $R$ -algebra under multiplication.

**Example 30.4.** Let  $R$  be a commutative ring and  $I$  an ideal in  $R$ . Then  $R/I$  is an  $R$ -algebra.

**Example 30.5.** Let  $R$  be a commutative ring and  $M$  an  $R$ -module. Then  $\text{End}_{R\text{-Mod}}(M)$  is an  $R$ -algebra under composition.

**Example 30.6.** Let  $R$  be a commutative ring. Then  $\mathfrak{gl}_n(R)$  is an  $R$ -algebra under matrix multiplication.

**Definition 30.7** (Algebra Homomorphism). Let  $R$  be a commutative ring. Let  $S$  and  $T$  be  $R$ -algebras. An  $R$ -algebra homomorphism  $\phi : S \rightarrow T$  is a ring homomorphism such that, for all  $r \in R$  and  $s \in S$ , we have  $\phi(rs) = r\phi(s)$ .

Let  $R\text{-Alg}$  be the category of  $R$ -algebras and  $R$ -algebra homomorphisms.

**Example 30.8.**

$$\mathbb{Z}\text{-Alg} \cong \mathbf{Ring}$$

**Example 30.9.** Let  $R$  be a commutative ring. Then  $R[x_1, \dots, x_n]$ , and any quotient ring of  $R[x_1, \dots, x_n]$ , is a commutative  $R$ -algebra.

**Example 30.10.**  $R$  is the initial object in  $R\text{-Alg}$ .

### 30.1 Rees Algebra

**Definition 30.11** (Rees Algebra). Let  $R$  be a commutative ring. Let  $I$  be an ideal in  $R$ . The *Rees algebra* is the direct sum

$$\text{Rees}_R(I) = \bigoplus_{j \geq 0} I^j$$

under the multiplication

$$\begin{aligned} (r_0, r_1, r_2, r_3, \dots)(s_0, s_1, s_2, \dots) &= (r_0s_0, r_1s_0 + r_0s_1, r_2s_0 + r_1s_1 + r_0s_2, \dots) \\ r(r_0, r_1, r_2, \dots) &= (rr_0, rr_1, rr_2, \dots) \end{aligned}$$

**Proposition 30.12.** *Let  $R$  be a commutative ring. Let  $a \in R$  be a non-zero-divisor. Then  $R[x]$  is the Rees algebra of  $(a)$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\phi : R[x] \rightarrow \text{Rees}_R((a))$  be the function  $\phi(r_0 + r_1x + r_2x^2 + \dots) = (r_0, r_1a, r_2a^2, \dots)$ .

$\langle 1 \rangle 2$ .  $\phi$  is an  $R$ -algebra homomorphism.

$\langle 1 \rangle 3$ .  $\phi$  is injective.

$\langle 2 \rangle 1$ . LET:  $\phi(r_0 + r_1x + r_2x^2 + \dots) = \phi(s_0 + s_1x + s_2x^2 + \dots)$

$\langle 2 \rangle 2$ . For all  $n$  we have  $r_na^n = s_na^n$

$\langle 2 \rangle 3$ .  $(r_n - s_n)a^n = 0$

$\langle 2 \rangle 4$ .  $r_n - s_n = 0$

PROOF: Since  $a$  is not a zero-divisor.

$\langle 2 \rangle 5$ .  $r_n = s_n$

$\langle 1 \rangle 4$ .  $\phi$  is surjective.

□

**Proposition 30.13.** *Let  $R$  be a commutative ring. Let  $a \in R$  be a non-zero-divisor. Let  $I$  be an ideal of  $R$ . Then  $\text{Rees}_R(I) \cong \text{Rees}_R(aI)$ .*

PROOF:

$\langle 1 \rangle 1$ . LET:  $\phi : \text{Rees}_R(I) \rightarrow \text{Rees}_R(aI)$  be the function  $\phi(r_0, r_1, r_2, \dots) = (r_0, ar_1, a^2r_2, \dots)$ .

$\langle 1 \rangle 2$ .  $\phi$  is an  $R$ -algebra homomorphism.

$\langle 1 \rangle 3$ .  $\phi$  is injective.

$\langle 1 \rangle 4$ .  $\phi$  is surjective.

□

### 30.2 Free Algebras

**Proposition 30.14.** *Let  $R$  be a ring. Then  $R[x_1, \dots, x_n]$  is the free commutative  $R$ -algebra on  $\{1, \dots, n\}$ .*

PROOF: Easy. □

**Proposition 30.15.** *Let  $R$  be a ring and  $A$  a set. Let  $A^*$  be the free monoid on  $A$ . Then the monoid ring  $R[A^*]$  is the free  $R$ -algebra on  $A$ .*

PROOF: Easy.  $\square$

**Proposition 30.16.** *Let  $R$  be a commutative ring and  $S$  a commutative  $R$ -algebra. Then  $S$  is finitely generated as an  $R$ -algebra if and only if  $S$  is finitely generated as a commutative  $R$ -algebra.*

PROOF: Since a subalgebra of a commutative subalgebra is commutative, so the smallest algebra that contains  $\{a_1, \dots, a_n\}$  is the smallest commutative subalgebra that contains  $\{a_1, \dots, a_n\}$ .  $\square$



## Chapter 31

# Algebras of Finite Type

**Definition 31.1** (Algebra of Finite Type). Let  $R$  be a ring. Let  $S$  be an  $R$ -algebra. Then  $R$  is of *finite type* iff  $S$  is a finitely generated  $R$ -algebra.

**Proposition 31.2.** *Let  $R$  be a Noetherian ring. Let  $S$  be a finite-type  $R$ -algebra. Then  $S$  is a Noetherian ring.*



## Chapter 32

# Finite Algebras

**Definition 32.1** (Finite Algebra). Let  $R$  be a ring. Let  $S$  be an  $R$ -algebra. Then  $S$  is a *finite*  $R$ -algebra iff it is a finitely generated left- $R$ -module.

**Proposition 32.2.** *Let  $R$  be a ring. Every finite  $R$ -algebra is of finite type.*

PROOF: If  $S$  is generated by  $a_1, \dots, a_n$  as an  $R$ -module, then it is generated by  $a_1, \dots, a_n$  as an  $R$ -algebra.  $\square$

**Example 32.3.** The converse does not hold.  $R[x]$  is of finite type but is not finite.





## Chapter 33

# Division Algebras

**Definition 33.1** (Division Algebra). Let  $R$  be a commutative ring. A *division  $R$ -algebra* is an  $R$ -algebra that is a division ring.

**Example 33.2.** Let  $R$  be a commutative ring. Let  $M$  be a simple  $R$ -algebra. Then  $\text{End}_{R\text{-Mod}}(M)$  is a division algebra. For if  $\phi \circ \psi = 0$  then  $\phi$  and  $\psi$  cannot both be isomorphisms, hence  $\phi = 0$  or  $\psi = 0$  by Schur's Lemma.



## Chapter 34

# Chain Complexes

**Definition 34.1** (Chain Complex). Let  $R$  be a ring. A *chain complex of left- $R$ -modules*  $M_\bullet = (M_\bullet, d_\bullet)$  consists of a family of left- $R$ -modules  $\{M_i\}_{i \in \mathbb{Z}}$  and a family of left- $R$ -module homomorphisms  $\{d_i : M_i \rightarrow M_{i-1}\}_{i \in \mathbb{Z}}$  such that, for all  $i$ ,

$$d_i \circ d_{i+1} = 0 \ .$$

We call each  $d_i$  a *differential* and the family  $\{d_i\}_i$  the *boundary* of the chain complex.

**Definition 34.2** (Exact). A chain complex  $M_\bullet$  is *exact* at  $M_i$  iff  $\text{im } d_{i+1} = \ker d_i$ .

It is *exact* or an *exact sequence* iff it is exact at  $M_i$  for all  $i$ .

**Proposition 34.3.** A complex

$$\cdots \rightarrow 0 \rightarrow L \xrightarrow{\alpha} M \rightarrow \cdots$$

is exact at  $L$  iff  $\alpha$  is a monomorphism.

PROOF: Since both are equivalent to  $\ker \alpha = 0$ .  $\square$

**Proposition 34.4.** A complex

$$\cdots \rightarrow M \xrightarrow{\beta} N \rightarrow 0 \rightarrow \cdots$$

is exact at  $N$  iff  $\beta$  is an epimorphism.

PROOF: Since both are equivalent to  $\text{im } \beta = N$ .  $\square$

**Definition 34.5** (Short Exact Sequence). A *short exact sequence* is an exact complex of the form

$$0 \rightarrow L \xrightarrow{\alpha} M \xrightarrow{\beta} N \rightarrow 0 \ .$$

**Proposition 34.6** (Four-Lemma). *If*

$$\begin{array}{ccccccc} A_1 & \xrightarrow{f_1} & B_1 & \xrightarrow{g_1} & C_1 & \xrightarrow{h_1} & D_1 \\ \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma & & \downarrow \delta \\ A_2 & \xrightarrow{f_2} & B_2 & \xrightarrow{g_2} & C_2 & \xrightarrow{h_2} & D_2 \end{array}$$

*is a commutative diagram of left- $R$ -modules with exact rows,  $\alpha$  is an epimorphism, and  $\beta$  and  $\delta$  are monomorphisms, then  $\gamma$  is an monomorphism.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $x, y \in C_1$

$\langle 1 \rangle 2$ . ASSUME:  $\gamma(x) = \gamma(y)$

$\langle 1 \rangle 3$ .  $\delta(h_1(x)) = \delta(h_1(y))$

$\langle 1 \rangle 4$ .  $h_1(x) = h_1(y)$

PROOF:  $\delta$  is injective.

$\langle 1 \rangle 5$ .  $x - y \in \ker h_1$

$\langle 1 \rangle 6$ .  $x - y \in \operatorname{im} g_1$

$\langle 1 \rangle 7$ . PICK  $b \in B_1$  such that  $g_1(b) = x - y$ .

$\langle 1 \rangle 8$ .  $g_2(\beta(b)) = 0$

PROOF:  $g_2(\beta(b)) = \gamma(g_1(b)) = \gamma(x - y) = 0$

$\langle 1 \rangle 9$ .  $\beta(b) \in \ker g_2$

$\langle 1 \rangle 10$ .  $\beta(b) \in \operatorname{im} f_2$

$\langle 1 \rangle 11$ . PICK  $a' \in A_2$  such that  $f_2(a') = \beta(b)$

$\langle 1 \rangle 12$ . PICK  $a \in A_1$  such that  $\alpha(a) = a'$

PROOF:  $\alpha$  is surjective.

$\langle 1 \rangle 13$ .  $\beta(f_1(a)) = \beta(b)$

$\langle 1 \rangle 14$ .  $f_1(a) = b$

PROOF:  $\beta$  is injective.

$\langle 1 \rangle 15$ .  $0 = g_1(b)$

PROOF: Since  $g_1(b) = g_1(f_1(a)) = 0$ .

$\langle 1 \rangle 16$ .  $x = y$

PROOF:  $\langle 1 \rangle 7$

□

**Proposition 34.7** (Four-Lemma). *If*

$$\begin{array}{ccccccc} A_1 & \xrightarrow{f_1} & B_1 & \xrightarrow{g_1} & C_1 & \xrightarrow{h_1} & D_1 \\ \downarrow \beta & & \downarrow \gamma & & \downarrow \delta & & \downarrow \epsilon \\ A_2 & \xrightarrow{f_2} & B_2 & \xrightarrow{g_2} & C_2 & \xrightarrow{h_2} & D_2 \end{array}$$

*is a commutative diagram of left- $R$ -modules with exact rows,  $\beta$  and  $\delta$  are epimorphisms, and  $\epsilon$  is a monomorphism, then  $\gamma$  is an epimorphism.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $b_2 \in B_2$

$\langle 1 \rangle 2$ . PICK  $c_1 \in C_1$  such that  $\delta(c_1) = g_2(b_2)$

PROOF:  $\delta$  is surjective.

$\langle 1 \rangle 3$ .  $\epsilon(h_1(c_1)) = 0$

$\langle 1 \rangle 4$ .  $h_1(c_1) = 0$

PROOF:  $\epsilon$  is injective.

$\langle 1 \rangle 5$ .  $c_1 \in \ker h_1$

$\langle 1 \rangle 6$ .  $c_1 \in \operatorname{im} g_1$

$\langle 1 \rangle 7$ . PICK  $b_1 \in B_1$  such that  $g_1(b_1) = c_1$

$\langle 1 \rangle 8$ .  $g_2(\gamma(b_1)) = g_2(b_2)$

$\langle 1 \rangle 9$ .  $\gamma(b_1) - b_2 \in \ker g_2$

$\langle 1 \rangle 10$ .  $\gamma(b_1) - b_2 \in \operatorname{im} f_2$

$\langle 1 \rangle 11$ . PICK  $a_2 \in A_2$  such that  $f_2(a_2) = \gamma(b_1) - b_2$ .

$\langle 1 \rangle 12$ . PICK  $a_1 \in A_1$  such that  $\beta(a_1) = a_2$ .

PROOF:  $\beta$  is surjective.

$\langle 1 \rangle 13$ .  $\gamma(f_1(a_1)) = \gamma(b_1) - b_2$

$\langle 1 \rangle 14$ .  $b_2 = \gamma(b_1 - f_1(a_1))$

□

**Theorem 34.8** (Snake Lemma). *Suppose we have  $R$ -modules and homomorphisms*

$$\begin{array}{ccccccccc} 0 & \longrightarrow & L_1 & \xrightarrow{\alpha_1} & M_1 & \xrightarrow{\beta_1} & N_1 & \longrightarrow & 0 \\ & & \downarrow \lambda & & \downarrow \mu & & \downarrow \nu & & \\ 0 & \longrightarrow & L_0 & \xrightarrow{\alpha_0} & M_0 & \xrightarrow{\beta_0} & N_0 & \longrightarrow & 0 \end{array}$$

*such that the diagram commutes and the two rows are short exact sequences. Then there exists a homomorphism  $\delta : \ker \nu \rightarrow \operatorname{coker} \lambda$  such that the following is an exact sequence.*

$$0 \rightarrow \ker \lambda \xrightarrow{\alpha_1} \ker \mu \xrightarrow{\beta_1} \ker \nu \xrightarrow{\delta} \operatorname{coker} \lambda \xrightarrow{\alpha_0} \operatorname{coker} \mu \xrightarrow{\beta_0} \operatorname{coker} \nu \rightarrow 0 .$$

PROOF:

$\langle 1 \rangle 1$ . Define  $\delta : \ker \nu \rightarrow \operatorname{coker} \lambda$ .

$\langle 2 \rangle 1$ . LET:  $a \in \ker \nu$

$\langle 2 \rangle 2$ . PICK  $c \in M_1$  such that  $\beta_1(c) = a$ .

PROOF: Since  $\beta_1$  is surjective.

$\langle 2 \rangle 3$ . LET:  $d = \mu(c)$

$\langle 2 \rangle 4$ .  $d \in \ker \beta_0 = \operatorname{im} \alpha_0$

PROOF: Since  $\beta_0(d) = \beta_0(\mu(c)) = \nu(a) = 0$ .

$\langle 2 \rangle 5$ . LET:  $e \in L_0$  be the element such that  $\alpha_0(e) = d$ .

$\langle 2 \rangle 6$ . LET:  $\delta(a) = e + \operatorname{im} \lambda$

$\langle 1 \rangle 2$ .  $\delta$  is a left- $R$ -module homomorphism.

$\langle 2 \rangle 1$ . For  $a, a' \in \ker \nu$  we have  $\delta(a + a') = \delta(a) + \delta(a')$ .

$\langle 3 \rangle 1$ . LET:  $a, a' \in \ker \nu$

$\langle 3 \rangle 2$ . LET:  $c, c', c'' \in M_1$  and  $e, e', e'' \in L_0$  be the elements such that

$$\beta_1(c) = a$$

$$\beta_1(c') = a'$$

$$\beta_1(c'') = a + a'$$

$$\alpha_0(e) = \mu(c)$$

$$\alpha_0(e') = \mu(c')$$

$$\alpha_0(e'') = \mu(c'')$$

$$\delta(a) = e + \text{im } \lambda$$

$$\delta(a') = e' + \text{im } \lambda$$

$$\delta(a + a') = e'' + \text{im } \lambda$$

$\langle 3 \rangle 3$ .  $c'' - c - c' \in \ker \beta_1 = \text{im } \alpha_1$

$\langle 3 \rangle 4$ . PICK  $g \in L_1$  such that  $\alpha_1(g) = c'' - c - c'$ .

$\langle 3 \rangle 5$ .  $\alpha_0(\lambda(g)) = \alpha_0(e'' - e - e')$

$\langle 3 \rangle 6$ .  $\lambda(g) = e'' - e - e'$

$\langle 3 \rangle 7$ .  $e'' - e - e' \in \text{im } \lambda$

$\langle 3 \rangle 8$ .  $e'' + \text{im } \lambda = e + e' + \text{im } \lambda$

$\langle 3 \rangle 9$ .  $\delta(a + a') = \delta(a) + \delta(a')$

$\langle 2 \rangle 2$ . For  $r \in R$  and  $a \in \ker \nu$  we have  $\delta(ra) = r\delta(a)$ .

$\langle 3 \rangle 1$ . LET:  $r \in R$  and  $a \in \ker \nu$

$\langle 3 \rangle 2$ . LET:  $c, c' \in M_1$  and  $e, e' \in L_0$  be the elements such that

$$\beta_1(c) = a$$

$$\beta_1(c') = ra$$

$$\alpha_0(e) = \mu(c)$$

$$\alpha_0(e') = \mu(c')$$

$$\delta(a) = e + \text{im } \lambda$$

$$\delta(ra) = e' + \text{im } \lambda$$

$\langle 3 \rangle 3$ .  $rc - c' \in \ker \beta_1 = \text{im } \alpha_1$

$\langle 3 \rangle 4$ . PICK  $g \in L_1$  such that  $\alpha_1(g) = rc - c'$ .

$\langle 3 \rangle 5$ .  $\alpha_0(\lambda(g)) = \alpha_0(re - e')$

$\langle 3 \rangle 6$ .  $\lambda(g) = re - e'$

$\langle 3 \rangle 7$ .  $re - e' \in \text{im } \lambda$

$\langle 3 \rangle 8$ .  $re + \text{im } \lambda = e' + \text{im } \lambda$

$\langle 3 \rangle 9$ .  $r\delta(a) = \delta(ra)$

$\langle 1 \rangle 3$ . The sequence is exact at  $\ker \lambda$ .

PROOF: Since  $\alpha_1$  is injective.

$\langle 1 \rangle 4$ . The sequence is exact at  $\ker \mu$ .

PROOF: Since  $\text{im } \alpha_1 = \ker \beta_1$ .

$\langle 1 \rangle 5$ . The sequence is exact at  $\ker \nu$ , i.e.

$$\beta a_1(\ker \mu) = \ker \delta.$$

$\langle 2 \rangle 1$ . LET:  $a \in \ker \nu$

$\langle 2 \rangle 2$ . LET:  $c \in M_1$  and  $e \in L_0$  be the elements such that  $\beta_1(c) = a$ ,  $\alpha_0(e) = \mu(c)$ , and  $\delta(a) = e + \text{im } \lambda$ .

- (2)3. If  $\delta(a) = \text{im } \lambda$  then  $a \in \beta_1(\ker \mu)$   
 (3)1. ASSUME:  $\delta(a) = \text{im } \lambda$   
 (3)2.  $e \in \text{im } \lambda$   
 (3)3. PICK  $g \in L_1$  such that  $\lambda(g) = e$   
 (3)4.  $\mu(\alpha_1(g)) = \mu(c)$   
 (3)5.  $c - \alpha_1(g) \in \ker \mu$   
 (3)6.  $a = \beta_1(c - \alpha_1(g))$   
 (2)4. If  $a \in \beta_1(\ker \mu)$  then  $\delta(a) = \text{im } \lambda$   
 (3)1. ASSUME:  $c' \in \ker \mu$  and  $a = \beta_1(c')$   
 (3)2.  $c - c' \in \ker \beta_1 = \text{im } \alpha_1$   
 (3)3. PICK  $g \in L_1$  such that  $\alpha_1(g) = c - c'$   
 (3)4.  $\alpha_0(\lambda(g)) = \mu(c) - \mu(c') = \alpha_0(e) - 0 = \alpha_0(e)$   
 (3)5.  $\lambda(g) = e$   
 (3)6.  $e \in \text{im } \lambda$   
 (3)7.  $\delta(a) = \text{im } \lambda$   
 (1)6. The sequence is exact at  $\text{coker } \lambda$ .  
 (2)1. LET:  $e \in L_0$   
 PROVE:  $e + \text{im } \lambda \in \text{im } \delta$  iff  $\alpha_0(e) \in \text{im } \mu$ .  
 (2)2. For all  $a \in \ker \nu$ , if  $\delta(a) = e + \text{im } \lambda$  then  $\alpha_0(e) \in \text{im } \mu$   
 PROOF: From (1)1 and the fact that  $\alpha_0$  is injective hence  $e$  is unique given  $a$ .  
 (2)3. For all  $e \in L_0$ , if  $\alpha_0(e) \in \text{im } \mu$  then  $e + \text{im } \lambda \in \text{im } \delta$ .  
 (3)1. LET:  $e \in L_0$   
 (3)2. ASSUME:  $\alpha_0(e) \in \text{im } \mu$   
 (3)3. PICK  $c \in M_1$  such that  $\mu(c) = \alpha_0(e)$ .  
 PROVE:  $e + \text{im } \lambda = \delta(\beta_1(c))$   
 (3)4. PICK  $c' \in M_1$  and  $e' \in L_0$  such that  $\beta_1(c') = \beta_1(c)$ ,  $\alpha_0(e') = \mu(c')$   
 and  $\delta(\beta_1(c)) = e' + \text{im } \lambda$   
 (3)5.  $c - c' \in \ker \beta_1 = \text{im } \alpha_1$   
 (3)6. PICK  $g \in L_1$  such that  $\alpha_1(g) = c - c'$ .  
 (3)7.  $\alpha_0(\lambda(g)) = \alpha_0(e - e')$   
 (3)8.  $\lambda(g) = e - e'$   
 (3)9.  $e + \text{im } \lambda = e' + \text{im } \lambda = \delta(\beta_1(c))$   
 (1)7. The sequence is exact at  $\text{coker } \mu$ .  
 PROOF: Since  $\text{im } \alpha_0 = \ker \beta_0$ .  
 (1)8. The sequence is exact at  $\text{coker } \nu$ .  
 PROOF: Since  $\beta_0$  is surjective.

□

**Corollary 34.8.1.** *Suppose we have  $R$ -modules and homomorphisms*

$$\begin{array}{ccccccc}
 0 & \longrightarrow & L_1 & \xrightarrow{\alpha_1} & M_1 & \xrightarrow{\beta_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \lambda & & \downarrow \mu & & \downarrow \nu \\
 0 & \longrightarrow & L_0 & \xrightarrow{\alpha_0} & M_0 & \xrightarrow{\beta_0} & N_0 \longrightarrow 0
 \end{array}$$

*such that the diagram commutes and the two rows are short exact sequences.*

Suppose  $\mu$  is surjective and  $\nu$  is injective. Then  $\lambda$  is surjective and  $\nu$  is an isomorphism.

PROOF: We have  $\ker \nu = \operatorname{coker} \mu = 0$  and so  $0 \xrightarrow{\delta} \operatorname{coker} \lambda \xrightarrow{\alpha_0} 0$  is an exact sequence, hence  $\operatorname{coker} \lambda = 0$  and so  $\lambda$  is surjective.

Since  $\operatorname{coker} \mu = 0$  we have  $0 \rightarrow \operatorname{coker} \nu \rightarrow 0$  is an exact sequence and so  $\operatorname{coker} \nu = 0$ , hence  $\nu$  is surjective, hence  $\nu$  is an isomorphism.  $\square$

**Proposition 34.9** (Short Five-Lemma). *Suppose we have  $R$ -modules and homomorphisms*

$$\begin{array}{ccccccccc} 0 & \longrightarrow & L_1 & \xrightarrow{\alpha_1} & M_1 & \xrightarrow{\beta_1} & N_1 & \longrightarrow & 0 \\ & & \downarrow \lambda & & \downarrow \mu & & \downarrow \nu & & \\ 0 & \longrightarrow & L_0 & \xrightarrow{\alpha_0} & M_0 & \xrightarrow{\beta_0} & N_0 & \longrightarrow & 0 \end{array}$$

such that the diagram commutes and the two rows are short exact sequences. If  $\lambda$  and  $\nu$  are isomorphisms then  $\mu$  is an isomorphism.

PROOF:

$\langle 1 \rangle 1$ . There exists a homomorphism  $\delta : 0 \rightarrow L_0$  such that the following is an exact sequence.

$$0 \rightarrow 0 \rightarrow \ker \mu \rightarrow 0 \xrightarrow{\delta} L_0 \xrightarrow{\alpha_0} \operatorname{coker} \mu \xrightarrow{\beta_0} N_0 \rightarrow 0.$$

PROOF: Snake Lemma

$\langle 1 \rangle 2$ .  $\ker \mu = 0$

$\langle 1 \rangle 3$ .  $\operatorname{coker} \mu = M_0$

$\square$

**Proposition 34.10.** *If  $L \xrightarrow{\alpha} M \xrightarrow{\beta} N$  is an exact sequence and  $L$  and  $N$  are Noetherian then  $M$  is Noetherian.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $P$  be a submodule of  $M$ .

$\langle 1 \rangle 2$ . PICK  $a_1, \dots, a_m$  generate  $\alpha^{-1}(P)$ .

$\langle 1 \rangle 3$ . PICK  $c_1, \dots, c_n$  that generate  $\beta(P)$ .

$\langle 1 \rangle 4$ . For  $i = 1, \dots, n$ , PICK  $b_i$  such that  $\beta(b_i) = c_i$ .

PROVE:  $\alpha(a_1), \dots, \alpha(a_m), b_1, \dots, b_n$  generate  $P$ .

$\langle 1 \rangle 5$ . LET:  $p \in P$

$\langle 1 \rangle 6$ . PICK  $r_1, \dots, r_n \in R$  such that  $r_1 c_1 + \dots + r_n c_n = \beta(p)$

$\langle 1 \rangle 7$ .  $r_1 b_1 + \dots + r_n b_n - p \in \ker \beta = \operatorname{im} \alpha$

$\langle 1 \rangle 8$ . PICK  $s_1, \dots, s_m \in R$  such that  $\alpha(s_1 a_1 + \dots + s_m a_m) = r_1 b_1 + \dots + r_n b_n - p$ .

$\langle 1 \rangle 9$ .  $p = s_1 \alpha(a_1) + \dots + s_m \alpha(a_m) + r_1 b_1 + \dots + r_n b_n$

$\square$

**Proposition 34.11.** *Let  $R$  be a ring. Let*

$$0 \rightarrow M \xrightarrow{\alpha} N \xrightarrow{\beta} P \rightarrow 0$$



be a short exact sequence of left- $R$ -modules. Let  $L$  be an  $R$ -module. Then the following is an exact sequence:

$$0 \rightarrow R\text{-}\mathbf{Mod}[P, L] \xrightarrow{R\text{-}\mathbf{Mod}[\beta, \text{id}_L]} R\text{-}\mathbf{Mod}[N, L] \xrightarrow{R\text{-}\mathbf{Mod}[\alpha, \text{id}_L]} R\text{-}\mathbf{Mod}[M, L] .$$

PROOF:

(1)1.  $R\text{-}\mathbf{Mod}[\beta, \text{id}_L]$  is injective.

PROOF: Since  $\beta$  is epi.

(1)2.  $\text{im } R\text{-}\mathbf{Mod}[\beta, \text{id}_L] = \ker R\text{-}\mathbf{Mod}[\alpha, \text{id}_L]$

(2)1.  $\text{im } R\text{-}\mathbf{Mod}[\beta, \text{id}_L] \subseteq \ker R\text{-}\mathbf{Mod}[\alpha, \text{id}_L]$

PROOF: For any  $\gamma \in R\text{-}\mathbf{Mod}[P, L]$  we have  $\gamma \circ \beta \circ \alpha = 0$  because  $\beta \circ \alpha = 0$ .

(2)2.  $\ker R\text{-}\mathbf{Mod}[\alpha, \text{id}_L] \subseteq \text{im } R\text{-}\mathbf{Mod}[\beta, \text{id}_L]$

(3)1. LET:  $\gamma \in \ker R\text{-}\mathbf{Mod}[\alpha, \text{id}_L]$

(3)2.  $\gamma \circ \alpha = 0$

(3)3. PICK  $\delta : P \rightarrow L$  by: for all  $p \in P$ , we have  $\delta(p) = \gamma(n)$  where  $n \in N$  is an element such that  $\beta(n) = p$ .

PROVE:  $\delta \circ \beta = \gamma$

(3)4. LET:  $n \in N$

PROVE:  $\delta(\beta(n)) = \gamma(n)$

(3)5. PICK  $n' \in N$  such that  $\delta(\beta(n)) = \gamma(n')$  and  $\beta(n') = \beta(n)$

(3)6.  $n - n' \in \ker \beta = \text{im } \alpha$

(3)7. PICK  $m \in M$  such that  $\alpha(m) = n - n'$

(3)8.  $0 = \gamma(\alpha(m)) = \gamma(n) - \gamma(n')$

(3)9.  $\gamma(n) = \gamma(n') = \delta(\beta(n))$

□

**Theorem 34.12** (Nine-Lemma). *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_2 & \xrightarrow{f_2} & M_2 & \xrightarrow{g_2} & N_2 \longrightarrow 0 \\
 & & \downarrow \alpha_1 & & \downarrow \beta_1 & & \downarrow \gamma_1 \\
 0 & \longrightarrow & L_1 & \xrightarrow{f_1} & M_1 & \xrightarrow{g_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \alpha_0 & & \downarrow \beta_0 & & \downarrow \gamma_0 \\
 0 & \longrightarrow & L_0 & \xrightarrow{f_0} & M_0 & \xrightarrow{g_0} & N_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

*If the rows are exact and the two rightmost columns are exact then the left column is exact.*

PROOF:

(1)1.  $(L_2, f_2)$  is the kernel of  $g_2$ ,  $(L_1, f_1)$  is the kernel of  $g_1$  and  $(L_0, f_0)$  is the kernel of  $g_0$ .

$\langle 1 \rangle 2$ . 0 is the cokernel of  $g_2, g_1$  and  $g_0$ .

$\langle 1 \rangle 3$ . PICK a homomorphism  $\delta : L_0 \rightarrow 0$  such that the following is an exact sequence:

$$L_2 \xrightarrow{\beta_1 \upharpoonright L_2} L_1 \xrightarrow{\beta_0 \upharpoonright L_1} L_0 \xrightarrow{\delta} 0 \rightarrow 0 \rightarrow 0$$

PROOF: Snake Lemma.

$\langle 1 \rangle 4$ .  $\beta_1 \upharpoonright L_2 = \alpha_1$

$\langle 1 \rangle 5$ .  $\beta_0 \upharpoonright L_1 = \alpha_0$

$\langle 1 \rangle 6$ . The following is an exact sequence:

$$0 \rightarrow L_2 \xrightarrow{\alpha_1} L_1 \xrightarrow{\alpha_0} L_0 \rightarrow 0$$

□

**Theorem 34.13.** *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & \vdots & & \vdots & & \vdots & \\
 & \downarrow & & \downarrow & & \downarrow & \\
 0 & \longrightarrow & L_{i+1} & \longrightarrow & M_{i+1} & \longrightarrow & N_{i+1} \longrightarrow 0 \\
 & & \downarrow \alpha_{i+1} & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_i & \longrightarrow & M_i & \longrightarrow & N_i \longrightarrow 0 \\
 & & \downarrow \alpha_i & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_{i-1} & \xrightarrow{f_{i-1}} & M_{i-1} & \longrightarrow & N_{i-1} \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & \vdots & & \vdots & & \vdots
 \end{array}$$

*Assume the central column is a complex and every row is an exact complex. Then the left and right columns are complexes. Further, if any two of the columns are exact, then so is the third.*

PROOF:

$\langle 1 \rangle 1$ . The left column is a complex.

$\langle 2 \rangle 1$ . LET:  $x \in L_{i+1}$

$\langle 2 \rangle 2$ .  $f_{i-1}(\alpha_i(\alpha_{i+1}(x))) = 0$

$\langle 2 \rangle 3$ .  $\alpha_i(\alpha_{i+1}(x)) = 0$

PROOF:  $f_{i-1}$  is injective.

$\langle 1 \rangle 2$ . The right column is a complex.

$\langle 2 \rangle 1$ . LET:  $x \in N_{i+1}$

$\langle 2 \rangle 2$ . PICK  $y \in N_{i+1}$  such that  $g_{i+1}(y) = x$

$\langle 2 \rangle 3$ .  $\gamma_i(\gamma_{i+1}(x)) = 0$

PROOF:

$$\begin{aligned}
 \gamma_i(\gamma_{i+1}(x)) &= \gamma_i(\gamma_{i+1}(g_{i+1}(y))) \\
 &= g_{i-1}(\beta_i(\beta_{i+1}(y))) \\
 &= g_{i-1}(0) \\
 &= 0
 \end{aligned}$$

(1)3. If the left and center columns are exact then the right column is exact.

- (2)1. LET:  $n_i \in \ker \gamma_{i-1}$   
PROVE:  $n_i \in \operatorname{im} \gamma_i$
- (2)2. PICK  $m_i \in M_i$  such that  $g_i(m_i) = n_i$
- (2)3.  $g_{i-1}(\beta_i(m_i)) = 0$
- (2)4.  $\beta_i(m_i) \in \ker g_{i-1} = \operatorname{im} f_{i-1}$
- (2)5. PICK  $l_{i-1} \in L_{i-1}$  such that  $f_{i-1}(l_{i-1}) = \beta_i(m_i)$
- (2)6.  $\beta_{i-1}(f_{i-1}(l_{i-1})) = 0$
- (2)7.  $f_{i-2}(\alpha_{i-1}(l_{i-1})) = 0$
- (2)8.  $\alpha_{i-1}(l_{i-1}) = 0$
- (2)9.  $l_{i-1} \in \ker \alpha_{i-1} = \operatorname{im} \alpha_i$
- (2)10. PICK  $l_i \in L_i$  such that  $\alpha_i(l_i) = l_{i-1}$
- (2)11.  $\beta_i(f_i(l_i)) = \beta_i(m_i)$
- (2)12.  $f_i(l_i) - m_i \in \ker \beta_i = \operatorname{im} \beta_{i+1}$
- (2)13. PICK  $m_{i+1} \in M_{i+1}$  such that  $\beta_{i+1}(m_{i+1}) = f_i(l_i) - m_i$
- (2)14.  $\gamma_{i+1}(-g_{i+1}(m_{i+1})) = n_i$

(1)4. If the left and right columns are exact then the center column is exact.

- (2)1. LET:  $x \in \ker \beta_i$   
PROVE:  $x \in \operatorname{im} \beta_{i+1}$
- (2)2.  $g_{i-1}(\beta_i(x)) = 0$
- (2)3.  $\gamma_i(g_i(x)) = 0$
- (2)4.  $g_i(x) \in \ker \gamma_i = \operatorname{im} \gamma_{i+1}$
- (2)5. PICK  $n_{i+1} \in N_{i+1}$  such that  $\gamma_{i+1}(n_{i+1}) = g_i(x)$
- (2)6. PICK  $m_{i+1} \in M_{i+1}$  such that  $g_{i+1}(m_{i+1}) = n_{i+1}$
- (2)7.  $g_i(\beta_{i+1}(m_{i+1})) = g_i(x)$
- (2)8.  $\beta_{i+1}(m_{i+1}) - x \in \ker g_i = \operatorname{im} f_i$
- (2)9. PICK  $l_i \in L_i$  such that  $f_i(l_i) = \beta_{i+1}(m_{i+1}) - x$
- (2)10.  $\beta_i(f_i(l_i)) = 0$
- (2)11.  $f_{i-1}(\alpha_i(l_i)) = 0$
- (2)12.  $\alpha_i(l_i) = 0$
- (2)13.  $l_i \in \ker \alpha_i = \operatorname{im} \alpha_{i+1}$
- (2)14. PICK  $l_{i+1} \in L_{i+1}$  such that  $\alpha_{i+1}(l_{i+1}) = l_i$
- (2)15.  $\beta_{i+1}(f_{i+1}(l_{i+1})) = \beta_{i+1}(m_{i+1}) - x$
- (2)16.  $x = \beta_{i+1}(m_{i+1} - f_{i+1}(l_{i+1}))$

(1)5. If the center and right columns are exact then the left column is exact.

- (2)1. LET:  $l_i \in \ker \alpha_i$   
PROVE:  $l_i \in \operatorname{im} \alpha_{i+1}$
- (2)2.  $\beta_i(f_i(l_i)) = 0$
- (2)3.  $f_i(l_i) \in \ker \beta_i = \operatorname{im} \beta_{i+1}$
- (2)4. PICK  $m_{i+1} \in M_{i+1}$  such that  $\beta_{i+1}(m_{i+1}) = f_i(l_i)$
- (2)5.  $\gamma_{i+1}(g_{i+1}(m_{i+1})) = 0$
- (2)6.  $g_{i+1}(m_{i+1}) \in \ker \gamma_{i+1} = \operatorname{im} \gamma_{i+2}$
- (2)7. PICK  $n_{i+2} \in N_{i+2}$  such that  $\gamma_{i+2}(n_{i+2}) = g_{i+1}(m_{i+1})$
- (2)8. PICK  $m_{i+2} \in M_{i+2}$  such that  $g_{i+2}(m_{i+2}) = n_{i+2}$
- (2)9.  $g_{i+1}(\beta_{i+2}(n_{i+2})) = g_{i+1}(m_{i+1})$
- (2)10.  $\beta_{i+2}(n_{i+2}) - m_{i+1} \in \ker g_{i+1} = \operatorname{im} f_{i+1}$

- (2)11. PICK  $l_{i+1} \in L_{i+1}$  such that  $f_{i+1}(l_{i+1}) = \beta_{i+2}(n_{i+2}) - m_{i+1}$   
 (2)12.  $f_i(\alpha_{i+1}(l_{i+1})) = -f_i(l_i)$   
 (2)13.  $l_i = \alpha_{i+1}(-l_{i+1})$

□

**Corollary 34.13.1** (Nine-Lemma). *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_2 & \xrightarrow{f_2} & M_2 & \xrightarrow{g_2} & N_2 \longrightarrow 0 \\
 & & \downarrow \alpha_1 & & \downarrow \beta_1 & & \downarrow \gamma_1 \\
 0 & \longrightarrow & L_1 & \xrightarrow{f_1} & M_1 & \xrightarrow{g_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \alpha_0 & & \downarrow \beta_0 & & \downarrow \gamma_0 \\
 0 & \longrightarrow & L_0 & \xrightarrow{f_0} & M_0 & \xrightarrow{g_0} & N_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

*If the rows are exact and the two leftmost columns are exact then the right column is exact.*

**Proposition 34.14.** *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_2 & \xrightarrow{f_2} & M_2 & \xrightarrow{g_2} & N_2 \longrightarrow 0 \\
 & & \downarrow \alpha_1 & & \downarrow \beta_1 & & \downarrow \gamma_1 \\
 0 & \longrightarrow & L_1 & \xrightarrow{f_1} & M_1 & \xrightarrow{g_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \alpha_0 & & \downarrow \beta_0 & & \downarrow \gamma_0 \\
 0 & \longrightarrow & L_0 & \xrightarrow{f_0} & M_0 & \xrightarrow{g_0} & N_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

*If the rows are exact and the left and right columns are exact then  $\beta_1$  is monic.*

PROOF: By the Snake Lemma, the following is an exact sequence

$$0 \rightarrow \ker \alpha_1 \rightarrow \ker \beta_1 \rightarrow \ker \gamma_1$$

But  $\ker \alpha_1 = \ker \gamma_1 = 0$  so  $\ker \beta_1 = 0$ . □

**Proposition 34.15.** *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_2 & \xrightarrow{f_2} & M_2 & \xrightarrow{g_2} & N_2 \longrightarrow 0 \\
 & & \downarrow \alpha_1 & & \downarrow \beta_1 & & \downarrow \gamma_1 \\
 0 & \longrightarrow & L_1 & \xrightarrow{f_1} & M_1 & \xrightarrow{g_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \alpha_0 & & \downarrow \beta_0 & & \downarrow \gamma_0 \\
 0 & \longrightarrow & L_0 & \xrightarrow{f_0} & M_0 & \xrightarrow{g_0} & N_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

*If the rows are exact and the left and right columns are exact then  $\beta_0$  is epi.*

PROOF: Similar.  $\square$

**Proposition 34.16.** *Let the following be a commuting diagram of left- $R$ -modules.*

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & L_2 & \xrightarrow{f_2} & M_2 & \xrightarrow{g_2} & N_2 \longrightarrow 0 \\
 & & \downarrow \alpha_1 & & \downarrow \beta_1 & & \downarrow \gamma_1 \\
 0 & \longrightarrow & L_1 & \xrightarrow{f_1} & M_1 & \xrightarrow{g_1} & N_1 \longrightarrow 0 \\
 & & \downarrow \alpha_0 & & \downarrow \beta_0 & & \downarrow \gamma_0 \\
 0 & \longrightarrow & L_0 & \xrightarrow{f_0} & M_0 & \xrightarrow{g_0} & N_0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

*If the rows are exact, the left and right columns are exact, and the central column is a complex, then the central column is exact.*

PROOF:

$\langle 1 \rangle 1.$  LET:  $x \in \ker \beta_0$

PROVE:  $x \in \operatorname{im} \beta_1$

$\langle 1 \rangle 2.$   $\gamma_0(g_1(x)) = 0$

$\langle 1 \rangle 3.$   $g_1(x) \in \ker \gamma_0 = \operatorname{im} \gamma_1$

$\langle 1 \rangle 4.$  PICK  $n_2 \in N_2$  such that  $\gamma_1(n_2) = g_1(x)$

$\langle 1 \rangle 5.$  PICK  $m_2 \in M_2$  such that  $g_2(m_2) = n_2$

$\langle 1 \rangle 6.$   $g_1(\beta_1(m_2)) = g_1(x)$

$\langle 1 \rangle 7.$   $\beta_1(m_2) - x \in \ker g_1 = \operatorname{im} f_1$

$\langle 1 \rangle 8.$  PICK  $l_1 \in L_1$  such that  $f_1(l_1) = \beta_1(m_2) - x$ .

- ⟨1⟩9.  $f_0(\alpha_0(l_1)) = 0$   
 ⟨1⟩10.  $\alpha_0(l_1) = 0$   
 ⟨1⟩11.  $l_1 \in \ker \alpha_0 = \operatorname{im} \alpha_1$   
 ⟨1⟩12. PICK  $l_2 \in L_2$  such that  $\alpha_1(l_2) = l_1$ .  
 ⟨1⟩13.  $\beta_1(f_2(l_2)) = \beta_1(m_2) - x$   
 ⟨1⟩14.  $x = \beta_1(m_2 - f_2(l_2))$   
 $\square$

**Example 34.17.** We cannot remove the hypothesis that the central column is a complex. Consider the situation

$$\begin{array}{ccccccc}
 & & 0 & & 0 & & 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 0 & \longrightarrow & 0 & \longrightarrow & \mathbb{Z} & \xlongequal{\quad} & \mathbb{Z} \longrightarrow 0 \\
 & & \downarrow & & \downarrow \Delta & & \parallel \\
 0 & \longrightarrow & \mathbb{Z} & \xrightarrow{\kappa_1} & \mathbb{Z} \oplus \mathbb{Z} & \xrightarrow{\pi_2} & \mathbb{Z} \longrightarrow 0 \\
 & & \parallel & & \downarrow \pi_1 & & \downarrow \\
 0 & \longrightarrow & \mathbb{Z} & \xlongequal{\quad} & \mathbb{Z} & \longrightarrow & 0 \longrightarrow 0 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 & & 0 & & 0 & & 0
 \end{array}$$

This diagram commutes, the rows are exact, the left and right columns are exact, but the central column is not a complex and  $\operatorname{im} \Delta \neq \ker \pi_1$ .

### 34.1 Split Exact Sequences

**Definition 34.18** (Split Sequence). Let  $0 \rightarrow M_1 \xrightarrow{\alpha} N \xrightarrow{\beta} M_2 \rightarrow 0$  be a short exact sequence. Then this sequence *splits* iff there exists an isomorphism

$$\phi : N \cong M_1 \oplus M_2$$

such that  $\phi \circ \alpha = \kappa_1 : M_1 \rightarrow M_1 \oplus M_2$  and  $\beta \circ \phi^{-1} = \pi_2 : M_1 \oplus M_2 \rightarrow M_2$ .

**Proposition 34.19.** Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then  $\phi$  has a left-inverse if and only if the sequence

$$0 \rightarrow M \xrightarrow{\phi} N \rightarrow \operatorname{coker} \phi \rightarrow 0$$

*splits*.

PROOF:

- ⟨1⟩1. If  $\phi$  has a left-inverse then the sequence splits.  
 ⟨2⟩1. ASSUME:  $\phi$  has a left-inverse  $\psi : N \rightarrow M$ .  
 ⟨2⟩2. Define  $i : N \rightarrow M \oplus \operatorname{coker} \phi$  by  $i(n) = (\psi(n), n + \operatorname{im} \phi)$ .

$\langle 2 \rangle 3$ . Define  $i^{-1} : M \oplus \text{coker } \phi$  by  $i^{-1}(m, x + \text{im } \phi) = \phi(m) + x - \phi(\psi(x))$ .

$\langle 2 \rangle 4$ .  $i \circ i^{-1} = \text{id}_{M \oplus \text{coker } \phi}$

PROOF:

$$\begin{aligned} \psi(\phi(m) + x - \phi(\psi(x))) &= m + \psi(x) - \psi(x) \\ &= m \end{aligned}$$

$\langle 2 \rangle 5$ .  $i^{-1} \circ i = \text{id}_N$

PROOF:

$$\begin{aligned} i^{-1}(\psi(n), n + \text{im } \phi) &= \phi(\psi(n)) + n - \phi(\psi(n)) \\ &= n \end{aligned}$$

$\langle 2 \rangle 6$ .  $i \circ \phi = \kappa_1 : M \rightarrow M \oplus \text{coker } \phi$

PROOF:

$$\begin{aligned} i(\phi(m)) &= (\psi(\phi(m)), \phi(m) + \text{im } \phi) \\ &= (m, \text{im } \phi) \end{aligned}$$

$\langle 2 \rangle 7$ .  $\pi \circ i^{-1} = \pi_2 : M \oplus \text{coker } \phi \rightarrow \text{coker } \phi$

PROOF:

$$\begin{aligned} i^{-1}(\psi(n), n + \text{im } \phi) + \text{im } \phi &= \phi(\psi(n)) + n - \phi(\psi(n)) + \text{im } \phi \\ &= n + \text{im } \phi \end{aligned}$$

$\langle 1 \rangle 2$ . If the sequence splits then  $\phi$  has a left-inverse.

PROOF: Since  $\kappa_1 : M \rightarrow M \oplus \text{coker } \phi$  has left inverse  $\pi_1$ .

□

**Proposition 34.20.** *Let  $\phi : M \rightarrow N$  be a left- $R$ -module homomorphism. Then  $\phi$  has a right-inverse if and only if the sequence*

$$0 \rightarrow \ker \phi \rightarrow M \xrightarrow{\phi} N \rightarrow 0$$

*splits.*

PROOF:

$\langle 1 \rangle 1$ . If  $\phi$  has a right-inverse then the sequence splits.

$\langle 2 \rangle 1$ . LET:  $\psi : N \rightarrow M$  be a right inverse to  $\phi$ .

$\langle 2 \rangle 2$ . LET:  $i : M \rightarrow \ker \phi \oplus N$  be the function  $i(m) = (m - \psi(\phi(m)), \phi(m))$ .

PROOF:  $m - \psi(\phi(m)) \in \ker \phi$  since  $\phi(m - \psi(\phi(m))) = \phi(m) - \phi(m) = 0$ .

$\langle 2 \rangle 3$ . LET:  $i^{-1} : \ker \phi \oplus N \rightarrow M$  be the function  $i^{-1}(x, n) = x + \psi(n)$ .

$\langle 2 \rangle 4$ .  $i \circ i^{-1} = \text{id}_{\ker \phi \oplus N}$

PROOF:

$$\begin{aligned} i(i^{-1}(x, n)) &= i(x + \psi(n)) \\ &= (x + \psi(n) - \psi(\phi(x)) - \psi(\phi(\psi(n))), \phi(x) + \phi(\psi(n))) \\ &= (x + \psi(n) - \psi(n), n) \\ &= (x, n) \end{aligned}$$

$\langle 2 \rangle 5$ .  $i^{-1} \circ i = \text{id}_M$

PROOF:

$$\begin{aligned} i^{-1}(i(m)) &= m - \psi(\phi(m)) + \psi(\phi(m)) \\ &= m \end{aligned}$$

$\langle 2 \rangle 6$ .  $i \circ \iota = \kappa_1$

PROOF: For  $m \in \ker \phi$  we have  $i(m) = (m - \psi(\phi(m)), \phi(m)) = (m, 0)$ .

$\langle 2 \rangle 7$ .  $\phi \circ i^{-1} = \pi_2$

PROOF:

$$\begin{aligned}\phi(i^{-1}(x, n)) &= \phi(x) + \phi(\psi(n)) \\ &= 0 + n \\ &= n\end{aligned}$$

$\langle 1 \rangle 2$ . If the sequence splits then  $\phi$  has a right-inverse.

PROOF: Since  $\kappa_2 : N \rightarrow M \oplus N$  is a right-inverse to  $\pi_2$ .

□

**Proposition 34.21.** *Let*

$$0 \rightarrow M \xrightarrow{\alpha} N \xrightarrow{\beta} F \rightarrow 0$$

*be a short exact sequence where  $F$  is free. Then the sequence splits.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $F = R^{\oplus A}$

$\langle 1 \rangle 2$ . PICK  $\gamma : F \rightarrow N$  such that  $\text{id}_F = \beta \circ \gamma$

$\langle 1 \rangle 3$ . LET:  $i : M \oplus F \rightarrow N$  be the homomorphism  $i(m, f) = \alpha(m) + \gamma(f)$

$\langle 1 \rangle 4$ .  $i$  is injective.

$\langle 2 \rangle 1$ . ASSUME:  $i(m, f) = i(m', f')$

$\langle 2 \rangle 2$ .  $\alpha(m) + \gamma(f) = \alpha(m') + \gamma(f')$

$\langle 2 \rangle 3$ .  $\alpha(m - m') = \gamma(f - f')$

$\langle 2 \rangle 4$ .  $f - f' = 0$

PROOF: Applying  $\beta$  to both sides of  $\langle 2 \rangle 3$ .

$\langle 2 \rangle 5$ .  $f = f'$

$\langle 2 \rangle 6$ .  $\alpha(m - m') = 0$

$\langle 2 \rangle 7$ .  $m = m'$

PROOF: Since  $\alpha$  is injective.

$\langle 1 \rangle 5$ .  $i$  is surjective.

$\langle 2 \rangle 1$ . LET:  $n \in N$

$\langle 2 \rangle 2$ .  $n - \gamma(\beta(n)) \in \ker \beta = \text{im } \alpha$

$\langle 2 \rangle 3$ . PICK  $m \in M$  such that  $\alpha(m) = n - \gamma(\beta(n))$

$\langle 2 \rangle 4$ .  $n = i(m, \beta(n))$

$\langle 1 \rangle 6$ .  $\alpha = i \circ \kappa_1$

$\langle 1 \rangle 7$ .  $\beta \circ i = \pi_2$

□



## Chapter 35

# Homology

**Definition 35.1** (Homology). Let  $(M_\bullet, d_\bullet)$  be a chain complex. The *i*th homology of the complex is the  $R$ -module

$$H_i(M_\bullet) := \frac{\ker d_i}{\operatorname{im} d_{i+1}} .$$

**Proposition 35.2.** *Consider the complex*

$$0 \rightarrow M_1 \xrightarrow{\phi} M_0 \rightarrow 0 .$$

*The 1st homology is  $\ker \phi$ , and the 0th homology is  $\operatorname{coker} \phi$ .*



**Part IV**

**Field Theory**



# Chapter 36

## Fields

**Definition 36.1** (Field). A *field* is a non-trivial commutative division ring.

**Example 36.2.**  $\mathbb{Q}$ ,  $\mathbb{R}$  and  $\mathbb{C}$  are fields.

**Proposition 36.3.** *Every field is an integral domain.*

PROOF: By Propositions 12.8 and 12.9.  $\square$

**Example 36.4.** The converse does not hold:  $\mathbb{Z}$  is an integral domain but not a field.

**Proposition 36.5.** *Every finite integral domain is a field.*

PROOF: In a finite integral domain, multiplication by any non-zero element is injective, hence surjective.  $\square$

**Corollary 36.5.1.** *For any positive integer  $n$ , the following are equivalent:*

- $n$  is prime.
- $\mathbb{Z}/n\mathbb{Z}$  is an integral domain.
- $\mathbb{Z}/n\mathbb{Z}$  is a field.

**Theorem 36.6** (Wedderburn's Little Theorem). *Every finite division ring is a field.*

**Proposition 36.7.** *Every subring of a field is an integral domain.*

PROOF: Easy.  $\square$

**Proposition 36.8.** *The center of a division ring is a field.*

PROOF:

$\langle 1 \rangle$ 1. LET:  $R$  be a division ring.

$\langle 1 \rangle$ 2. LET:  $Z$  be the center of  $R$ .

$\langle 1 \rangle$ 3.  $Z$  is non-trivial.

PROOF: Since  $1 \in Z$ .

$\langle 1 \rangle 4$ .  $Z$  is commutative.

$\langle 1 \rangle 5$ .  $Z$  is a division ring.

$\langle 2 \rangle 1$ . LET:  $a \in Z$

$\langle 2 \rangle 2$ .  $a^{-1} \in Z$

$\langle 3 \rangle 1$ . LET:  $x \in R$

$\langle 3 \rangle 2$ .  $ax = xa$

$\langle 3 \rangle 3$ .  $xa^{-1} = a^{-1}x$

□

**Definition 36.9.** For any prime  $p$  and positive integer  $r$ , define a multiplication on  $(\mathbb{Z}/p\mathbb{Z})^r$  that makes this group into a field by:

**Proposition 36.10.** *A commutative ring is a field if and only if it is simple.*

PROOF: Proposition 22.5. □

**Corollary 36.10.1.** *Every field has Krull dimension 0.*

**Proposition 36.11.** *Let  $K$  be a field. Then  $K[x]$  is a PID, and every non-zero ideal in  $K[x]$  is generated by a unique monic polynomial.*

PROOF:

$\langle 1 \rangle 1$ . LET:  $I$  be a non-zero ideal in  $K[x]$

$\langle 1 \rangle 2$ . PICK a monic polynomial  $f \in K[x]$  of minimal degree.

PROVE:  $I = (f)$

$\langle 1 \rangle 3$ . LET:  $g \in I$

$\langle 1 \rangle 4$ . PICK polynomials  $q, r$  with  $\deg r < \deg f$  such that  $g = qf + r$

$\langle 1 \rangle 5$ .  $r \in I$

$\langle 1 \rangle 6$ .  $r = 0$

$\langle 1 \rangle 7$ .  $g \in (f)$

□

**Proposition 36.12.** *Let  $R$  be a commutative ring and  $I$  an ideal in  $R$ . Then  $I$  is maximal iff  $R/I$  is a field.*

PROOF: From Proposition 23.3. □

**Example 36.13.** Let  $R$  be a commutative ring and  $a \in R$ . Then  $(x - a)$  is a maximal ideal in  $R[x]$  iff  $R$  is a field, since  $R[x]/(x - a) \cong R$ .

**Example 36.14.** The ideal  $(2, x)$  is a maximal ideal in  $\mathbb{Z}[x]$ , since  $\mathbb{Z}[x]/(2, x) \cong \mathbb{Z}/2\mathbb{Z}$ .

**Proposition 36.15.** *Every maximal ideal in a commutative ring is a prime ideal.*

PROOF: Since every field is an integral domain. □

**Proposition 36.16.** *Let  $R$  be a commutative ring and  $I$  an ideal in  $R$ . If  $I$  is a prime ideal and  $R/I$  is finite then  $I$  is a maximal ideal.*

PROOF: Since every finite integral domain is a field.  $\square$

**Proposition 36.17.** *Let  $R$  be a commutative ring and  $I$  a proper ideal in  $R$ . Then  $I$  is maximal iff, whenever  $J$  is an ideal and  $I \subseteq J$ , then  $I = J$  or  $J = R$ .*

**Example 36.18.** The inverse image of a maximal ideal under a homomorphism is not necessarily maximal.

Let  $i : \mathbb{Z}[x] \rightarrow \mathbb{Q}[x]$  be the inclusion. Then  $(x)$  is maximal in  $\mathbb{Q}[x]$  but its inverse image  $(x)$  is not maximal in  $\mathbb{Z}[x]$ .

**Definition 36.19** (Maximal Spectrum). Let  $R$  be a commutative ring. The *maximal spectrum* of  $R$  is the set of all maximal ideals in  $R$ .

**Proposition 36.20.** *Let  $K$  be a field. The Krull dimension of  $K[x_1, \dots, x_n]$  is  $n$ .*

**Theorem 36.21** (Hilbert's Nullstellensatz). *Let  $K$  be a field and  $L$  a subfield of  $K$ . If  $K$  is an  $L$ -algebra of finite type, then  $K$  is a finite  $L$ -algebra.*

**Proposition 36.22.** *Let  $K$  be a subfield of  $L$ . Then  $L$  is a  $K$ -algebra under multiplication.*

PROOF: Easy.  $\square$





## Chapter 37

# Algebraically Closed Fields

**Definition 37.1** (Algebraically Closed). A field  $K$  is *algebraically closed* iff, for every  $f \in K[x]$  that is not constant, there exists  $r \in K$  such that  $f(r) = 0$ .

**Theorem 37.2.**  $\mathbb{C}$  is algebraically closed.

**Proposition 37.3.** Let  $K$  be an algebraically closed field. Let  $I$  be an ideal in  $K[x]$ . Then  $I$  is maximal if and only if  $I = (x - c)$  for some  $c \in K$ .

PROOF:

$\langle 1 \rangle 1$ . If  $I$  is maximal then there exists  $c \in K$  such that  $I = (x - c)$ .

$\langle 2 \rangle 1$ . ASSUME:  $I$  is maximal.

$\langle 2 \rangle 2$ . PICK  $f$  monic of minimal degree such that  $f \in I$ .

$\langle 2 \rangle 3$ .  $f$  is not constant.

PROOF: Otherwise  $f = 1$  and  $I = K[x]$ .

$\langle 2 \rangle 4$ . PICK  $c \in K$  such that  $f(c) = 0$

$\langle 2 \rangle 5$ .  $x - c \mid f$

$\langle 2 \rangle 6$ .  $I \subseteq (x - c)$

$\langle 2 \rangle 7$ .  $I = (x - c)$

$\langle 1 \rangle 2$ . For all  $c \in K$  we have  $(x - c)$  is maximal.

PROOF: Example 36.13.

□



**Part V**

**Linear Algebra**



## Chapter 38

# Vector Spaces

**Definition 38.1** (Vector Space). Let  $K$  be a field. A  $K$ -vector space is a  $K$ -module. A *linear map* is a homomorphism of  $K$ -modules. We write  $K - \mathbf{Vect}$  for  $K - \mathbf{Mod}$ .

**Definition 38.2.** Let  $\mathrm{GL}_n(\mathbb{R})$  be the group of invertible  $n \times n$  real matrices.  $\mathrm{GL}_n(\mathbb{R})$  acts on  $\mathbb{R}^n$  by matrix multiplication.

**Definition 38.3.** Let  $\mathrm{GL}_n(\mathbb{C})$  be the group of invertible  $n \times n$  complex matrices.  $\mathrm{GL}_n(\mathbb{C})$  acts on  $\mathbb{C}^n$  by matrix multiplication.

**Definition 38.4.** Let  $\mathrm{SL}_n(\mathbb{R}) = \{M \in \mathrm{GL}_n(\mathbb{R}) : \det M = 1\}$ .

**Proposition 38.5.**  $\mathrm{SL}_n(\mathbb{R})$  is a normal subgroup of  $\mathrm{GL}_n(\mathbb{R})$ .

PROOF: If  $\det M = 1$  then  $\det(AMA^{-1}) = (\det A)(\det M)(\det A)^{-1} = 1$ .  $\square$

**Proposition 38.6.**

$$\mathrm{GL}_n(\mathbb{R})/\mathrm{SL}_n(\mathbb{R}) \cong \mathbb{R}^*$$

**Definition 38.7.** Let  $\mathrm{SL}_n(\mathbb{C}) = \{M \in \mathrm{GL}_n(\mathbb{C}) : \det M = 1\}$ .

**Definition 38.8.** Let  $\mathrm{O}_n(\mathbb{R}) = \{M \in \mathrm{GL}_n(\mathbb{R}) : MM^T = M^T M = I_n\}$ .

**Proposition 38.9.** The action of  $\mathrm{O}_n(\mathbb{R})$  on  $\mathbb{R}^n$  preserves lengths and angles.

**Definition 38.10.** Let  $\mathrm{SO}_n(\mathbb{R}) = \{M \in \mathrm{O}_n(\mathbb{R}) : \det M = 1\}$ .

**Definition 38.11.** Let  $\mathrm{U}_n(\mathbb{C}) = \{M \in \mathrm{GL}_n(\mathbb{C}) : MM^\dagger = M^\dagger M = I_n\}$ .

**Definition 38.12.** Let  $\mathrm{SU}_n(\mathbb{C}) = \{M \in \mathrm{U}_n(\mathbb{C}) : \det M = 1\}$ .

**Proposition 38.13.** Every matrix in  $\mathrm{SU}_2(\mathbb{C})$  can be written in the form

$$\begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix}$$

for some  $a, b, c, d \in \mathbb{R}$  with  $a^2 + b^2 + c^2 + d^2 = 1$ .

PROOF:

$$\langle 1 \rangle 1. \text{ LET: } M = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \in \text{SU}_2(\mathbb{C})$$

$$\langle 1 \rangle 2. M^{-1} = M^\dagger$$

$$\langle 1 \rangle 3. \begin{pmatrix} \delta & -\beta \\ -\gamma & \alpha \end{pmatrix} = \begin{pmatrix} \bar{\alpha} & \bar{\gamma} \\ \bar{\beta} & \bar{\delta} \end{pmatrix}$$

$$\langle 1 \rangle 4. \text{ LET: } \alpha = a + bi \text{ and } \beta = c + di.$$

$$\langle 1 \rangle 5. \delta = \bar{\alpha} = a - bi$$

$$\langle 1 \rangle 6. \gamma = -\bar{\beta} = -c + di$$

$$\langle 1 \rangle 7. \det M = a^2 + b^2 + c^2 + d^2 = 1$$

□

**Corollary 38.13.1.**  $\text{SU}_2(\mathbb{C})$  is simply connected.

**Corollary 38.13.2.**

$$\text{SO}_3(\mathbb{R}) \cong \text{SU}_2(\mathbb{C}) / \{I, -I\}$$

PROOF: The function that maps  $\begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix}$  to  $\begin{pmatrix} a^2 + b^2 - c^2 - d^2 & 2(bc - ad) & 2(ad + bc) \\ 2(ad + bc) & a^2 - b^2 + c^2 - d^2 & 2(bd - ac) \\ 2(bd - ac) & 2(ab + cd) & a^2 - b^2 - c^2 - d^2 \end{pmatrix}$

is a surjective homomorphism with kernel  $\{I, -I\}$ . □

**Corollary 38.13.3.** The fundamental group of  $\text{SO}_3(\mathbb{R})$  is  $C_2$ .

**Part VI**

**Linear Algebra**





## Chapter 39

# Vector Spaces

**Definition 39.1** (Vector Space). Let  $K$  be a field. A *vector space* over  $K$  is a module over  $K$ . A *linear transformation* is a  $K$ -module homomorphism.

**Definition 39.2** (Bilinear Map). Let  $K$  be a field. Let  $U, V$  and  $W$  be vector spaces over  $K$ . A function  $f : U \times V \rightarrow W$  is *bilinear* iff, for all  $u_1, u_2 \in U$  and  $v_1, v_2 \in V$  and  $\alpha \in K$ ,

$$\begin{aligned} f(u_1 + \alpha u_2, v_1) &= f(u_1, v_1) + \alpha f(u_2, v_1) \\ f(u_1, v_1 + \alpha v_2) &= f(u_1, v_1) + \alpha f(u_1, v_2) \end{aligned}$$

**Theorem 39.3.** Let  $K$  be a field. Let  $U$  and  $V$  be vector spaces. There exists a vector space  $U \otimes V$  over  $K$  and bilinear map  $-\otimes- : U \times V \rightarrow U \otimes V$ , unique up to isomorphism, such that, for every vector space  $W$  over  $K$  and bilinear map  $f : U \times V \rightarrow W$ , there exists a unique linear map  $\bar{f} : U \otimes V \rightarrow W$  such that the following diagram commutes.

$$\begin{array}{ccc} U \otimes V & \xrightarrow{\bar{f}} & W \\ -\otimes- \uparrow & \nearrow f & \\ U \times V & & \end{array}$$

Further,  $-\otimes-$  is injective and its image spans  $U \otimes V$ .

PROOF: We can construct  $U \otimes V$  as follows. Let  $L$  be the free vector space generated by  $U \times V$ . Let  $R$  be the subspace generated by all vectors of the form

$$(u_1 + \alpha u_2, v) - (u_1, v) - \alpha(u_2, v) \quad (u, v_1 + \alpha v_2) - (u, v_1) - \alpha(u, v_2)$$

Take  $U \otimes V := L/R$ .  $\square$

**Proposition 39.4.** If  $\sum_{i=1}^n u_i \otimes v_i = 0$  and  $v_1, \dots, v_n$  are linearly independent in  $V$  then  $u_1 = \dots = u_n = 0$ .

PROOF:

$\langle 1 \rangle$ 1. LET:  $f : U \times V \rightarrow V^{U*}$  be the function  $f(u, v)(\Phi) = \Phi(u)v$

- ⟨1⟩2.  $f$  is bilinear.  
 ⟨1⟩3. LET:  $\bar{f} : U \otimes V \rightarrow V^{U*}$  be the induced linear transformation.  
 ⟨1⟩4.  $\bar{f}(\sum_{i=1}^n u_i \otimes v_i) = 0$   
 ⟨1⟩5.  $\sum_{i=1}^n \bar{f}(u_i, v_i) = 0$   
 ⟨1⟩6. For all  $\Phi \in U^*$  we have  $\sum_{i=1}^n \Phi(u_i)v_i = 0$   
 ⟨1⟩7. For all  $\Phi \in U^*$  we have  $\Phi(u_1) = \cdots = \Phi(u_n) = 0$   
 ⟨1⟩8.  $u_1 = \cdots = u_n = 0$   
 $\square$

**Proposition 39.5.** *Let  $U$  and  $V$  be vector spaces over  $K$  with bases  $\mathcal{B}_1$  and  $\mathcal{B}_2$ . Then  $\mathcal{B} = \{b_1 \otimes b_2 : b_1 \in \mathcal{B}_1, b_2 \in \mathcal{B}_2\}$  is a basis for  $U \otimes V$ .*

PROOF:

- ⟨1⟩1.  $\mathcal{B}$  is linearly independent.  
 ⟨2⟩1. ASSUME:  $\sum_{i=1}^m \sum_{j=1}^n \alpha_{ij} b_i \otimes b'_j = 0$   
 ⟨2⟩2. For all  $j$  we have  $\sum_{i=1}^m \alpha_{ij} b_i = 0$   
 PROOF: Proposition 39.4.  
 ⟨2⟩3. Each  $\alpha_{ij}$  is 0.  
 ⟨1⟩2.  $\mathcal{B}$  spans  $U \otimes V$ .

PROOF: If  $u = \alpha_1 b_1 + \cdots + \alpha_m b_m$  and  $v = \beta_1 b'_1 + \cdots + \beta_n b'_n$  then

$$u \otimes v = \sum_{i=1}^m \sum_{j=1}^n \alpha_i \beta_j (b_i \otimes b'_j)$$

The result follows since the vectors of the form  $u \otimes v$  span  $U \otimes V$ .

$\square$

**Corollary 39.5.1.** *If  $U$  and  $V$  are finite dimensional vector spaces over  $K$  then*

$$\dim(U \otimes V) = (\dim U)(\dim V) .$$