

Algebra, Chapter 0

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Chapter I. Preliminaries: Set theory and categories

§1. Naive Set Theory

1.6 Define a relation \sim on the set \mathbb{R} of real numbers, by setting $a \sim b \iff b - a \in \mathbb{Z}$. Prove that this is an equivalence relation, and find a ‘compelling’ description for \mathbb{R}/\sim . Do the same for the relation \approx on the plane $\mathbb{R} \times \mathbb{R}$ defined by declaring $(a_1, a_2) \approx (b_1, b_2) \iff b_1 - a_1 \in \mathbb{Z}$ and $b_2 - a_2 \in \mathbb{Z}$. [§II.8.1, II.8.10]

Imaginatively, \mathbb{R}/\sim can be viewed as a ring of length 1 by bending the real line \mathbb{R} . Then we can rotate a ring around an axis of rotation to get $\mathbb{R} \times \mathbb{R}/\approx$, which makes a torus. ■

§2. Functions between sets

2.1 How many different bijections are there between a set S with n elements and itself? [§II.2.1]

There are $n!$ different bijections $S \rightarrow S$. ■

§3. Categories

3.1 Let \mathbf{C} be a category. Consider a structure \mathbf{C}^{op} with:

- $\text{Obj}(\mathbf{C}^{op}) := \text{Obj}(\mathbf{C})$;
- for A, B objects of \mathbf{C}^{op} (hence, objects of \mathbf{C}), $\text{Hom}_{\mathbf{C}^{op}}(A, B) := \text{Hom}_{\mathbf{C}}(B, A)$

Show how to make this into a category (that is, define composition of morphisms in \mathbf{C}^{op} and verify the properties listed in §3.1). Intuitively, the ‘opposite’ category \mathbf{C}^{op} is simply obtained by ‘reversing all the arrows’ in \mathbf{C} . [5.1, §VIII.1.1, §IX.1.2, IX.1.10]

- For every object A of \mathbf{C} , there exists one identity morphism $1_A \in \text{Hom}_{\mathbf{C}}(A, A)$. Since $\text{Obj}(\mathbf{C}^{op}) := \text{Obj}(\mathbf{C})$ and $\text{Hom}_{\mathbf{C}^{op}}(A, A) := \text{Hom}_{\mathbf{C}}(A, A)$, for every object A of \mathbf{C}^{op} , the identity on A coincides with $1_A \in \mathbf{C}$.
- For A, B, C objects of \mathbf{C}^{op} and $f \in \text{Hom}_{\mathbf{C}^{op}}(A, B) = \text{Hom}_{\mathbf{C}}(B, A)$, $g \in \text{Hom}_{\mathbf{C}^{op}}(B, C) = \text{Hom}_{\mathbf{C}}(C, B)$, the composition laws in \mathbf{C} determines a morphism $f * g$ in $\text{Hom}_{\mathbf{C}}(C, A)$, which deduces the composition defined on \mathbf{C}^{op} :

$$\begin{aligned} \text{Hom}_{\mathbf{C}^{op}}(A, B) \times \text{Hom}_{\mathbf{C}^{op}}(B, C) &\longrightarrow \text{Hom}_{\mathbf{C}^{op}}(A, C) \\ (f, g) &\longmapsto g \circ f := f * g \end{aligned}$$

- Associativity. If $f \in \text{Hom}_{\mathbf{C}^{op}}(A, B)$, $g \in \text{Hom}_{\mathbf{C}^{op}}(B, C)$, $h \in \text{Hom}_{\mathbf{C}^{op}}(C, D)$, then

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

- Identity. For all $f \in \text{Hom}_{\mathcal{C}^{op}}(A, B)$, we have

$$f \circ 1_A = 1_A * f = f, \quad 1_B \circ f = f * 1_B = f.$$

Thus we get the full construction of \mathcal{C}^{op} . ■

3.3 ▷ Formulate precisely what it means to say that 1_a is an identity with respect to composition in Example 3.3, and prove this assertion. [§3.2]

Suppose S is a set, and \sim is a relation on S satisfying the reflexive and transitive property. Then we can encode this data into a category \mathcal{C} :

- Objects: the elements of S ;
- Morphisms: if a, b are objects (that is: if $a, b \in S$) then let $\text{Hom}(a, b)$ be the set consisting of the element $(a, b) \in S \times S$ if $a \sim b$, and $\text{Hom}(a, b) = \emptyset$. otherwise.

Given the composition of two morphisms

$$\begin{aligned} \text{Hom}_{\mathcal{C}}(A, B) \times \text{Hom}_{\mathcal{C}}(B, C) &\longrightarrow \text{Hom}_{\mathcal{C}}(A, C) \\ (a, b) \circ (b, c) &\longmapsto (a, c) \end{aligned}$$

we are asked to check $1_a = (a, a)$ is an identity with respect to this composition. ■

§4. Morphisms

4.2 In Example 3.3 we have seen how to construct a category from a set endowed with a relation, provided this latter is reflexive and transitive. For what types of relations is the corresponding category a groupoid (cf. Example 4.6)? [§4.1]

For a reflexive and transitive relation \sim on a set S , define the category \mathcal{C} as follows:

- Objects: $\text{Obj}(\mathcal{C}) = S$;
- Morphisms: if a, b are objects (that is: if $a, b \in S$) then let

$$\text{Hom}_{\mathcal{C}}(a, b) = \begin{cases} (a, b) \in S \times S & \text{if } a \sim b \\ \emptyset & \text{otherwise} \end{cases}$$

In Example 3.3 we have shown the category. If the relation \sim is endowed with symmetry, we have

$$(a, b) \in \text{Hom}_{\mathcal{C}}(a, b) \implies a \sim b \implies b \sim a \implies (b, a) \in \text{Hom}_{\mathcal{C}}(b, a).$$

Since

$$(a, b)(b, a) = (a, a) = 1_a, \quad (b, a)(a, b) = (b, b) = 1_b,$$

in fact (a, b) is an isomorphism. From the arbitrariness of the choice of (a, b) , we show that \mathbf{C} is a groupoid. Conversely, if \mathbf{C} is a groupoid, we can show the relation \sim is symmetric. To sum up, the category \mathbf{C} is a groupoid if and only if the corresponding relation \sim is an equivalence relation. ■

§5. Universal properties

5.1 Prove that a final object in a category \mathbf{C} is initial in the opposite category \mathbf{C}_{op} (cf. Exercise 3.1).

An object F of \mathbf{C} is final in \mathbf{C} if and only if

$$\forall A \in \text{Obj}(\mathbf{C}) : \text{Hom}_{\mathbf{C}}(A, F) \text{ is a singleton.}$$

That is equivalent to

$$\forall A \in \text{Obj}(\mathbf{C}_{op}) : \text{Hom}_{\mathbf{C}_{op}}(F, A) \text{ is a singleton,}$$

which means F is initial in the opposite category \mathbf{C}_{op} . ■

Chapter II. Groups, first encounter

§1. Definition of group

1.1 Write a careful proof that every group is the group of isomorphisms of a groupoid. In particular, every group is the group of automorphisms of some object in some category.

Assume G is a group. Define a category \mathbf{C} as follows:

- Objects: $\text{Obj}(\mathbf{C}) = \{*\}$;
- Morphisms: $\text{Hom}_{\mathbf{C}}(*, *) = \text{End}_{\mathbf{C}}(*) = G$.

The composition of homomorphism is corresponding to the multiplication between two elements in G . The identity morphism on $*$ is $1_* = e_G$, which satisfies for all $g \in \text{Hom}_{\mathbf{C}}(*, *)$,

$$ge_G = e_Gg = g,$$

and

$$gg^{-1} = e_G, \quad g^{-1}g = e_G.$$

Thus any homomorphism $g \in \text{Hom}_{\mathbf{C}}(*, *)$ is an isomorphism and accordingly \mathbf{C} is a groupoid. Now we see $G = \text{End}_{\mathbf{C}}(*)$ is the group of isomorphisms of a groupoid. Moreover, supposing that $*$ is an object in some category \mathbf{D} , G would be the group of automorphisms of $*$, which is denoted as $\text{Aut}_{\mathbf{D}}(*)$. ■

1.4 Suppose that $g^2 = e$ for all elements g of a group G ; prove that G is commutative.

For all $a, b \in G$,

$$abab = e \implies a(abab)b = ab \implies (aa)ba(bb) = ab \implies ba = ab.$$

■

§2. Examples of groups

2.1 One can associate an $n \times n$ matrix M_σ with a permutation $\sigma \in S_n$, by letting the entry at $(i, \sigma(i))$ be 1, and letting all other entries be 0. For example, the matrix corresponding to the permutation

$$\sigma = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} \in S_3$$

would be

$$M_\sigma = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

Prove that, with this notation,

$$M_{\sigma\tau} = M_\sigma M_\tau$$

for all $\sigma, \tau \in S_n$, where the product on the right is the ordinary product of matrices.

By introducing the Kronecker delta function

$$\delta_{i,j} = \begin{cases} 0 & \text{if } i \neq j, \\ 1 & \text{if } i = j, \end{cases}$$

the entry at (i, j) of the matrix $M_{\sigma\tau}$ can be written as

$$(M_{\sigma\tau})_{i,j} = \delta_{\tau(\sigma(i)),j}$$

and the entry at (i, j) of the matrix $M_\sigma M_\tau$ can be written as

$$(M_\sigma M_\tau)_{i,j} = \sum_{k=1}^n (M_\sigma)_{i,k} (M_\tau)_{k,j} = \sum_{k=1}^n \delta_{\sigma(i),k} \cdot \delta_{\tau(k),j} = \sum_{k=1}^n \delta_{\sigma(i),k} \cdot \delta_{k,\tau^{-1}(j)} = \delta_{\sigma(i),\tau^{-1}(j)},$$

where the last but one equality holds by the fact

$$\tau(k) = j \iff k = \tau^{-1}(j).$$

Noticing that

$$\tau(\sigma(i)) = j \iff \sigma(i) = \tau^{-1}(j),$$

we see $M_{\sigma\tau} = M_\sigma M_\tau$ for all $\sigma, \tau \in S_n$. ■

2.2 Prove that if $d \leq n$, then S_n contains elements of order d .

The cyclic permutation

$$\sigma = (1 \ 2 \ 3 \cdots d)$$

is an element of order d in S_n . ■

2.3 For every positive integer n find an element of order n in $S_{\mathbb{N}}$.

The cyclic permutation

$$\sigma = (1 \ 2 \ 3 \cdots n)$$

is an element of order d in S_n . ■

2.4 Define a homomorphism $D_8 \rightarrow S_4$ by labeling vertices of a square, as we did for a triangle in §2.2. List the 8 permutations in the image of this homomorphism.

The image of n rotations under the homomorphism are

$$\sigma_1 = e_{D_8}, \sigma_2 = (1 \ 2 \ 3 \ 4), \sigma_3 = (1 \ 3)(2 \ 4), \sigma_4 = (1 \ 4 \ 3 \ 2).$$

The image of n reflections under the homomorphism are

$$\sigma_5 = (1 \ 3), \sigma_6 = (2 \ 4), \sigma_7 = (1 \ 2)(3 \ 4), \sigma_8 = (1 \ 4)(3 \ 2).$$

■

2.11 Prove that the square of every odd integer is congruent to 1 modulo 8.

Given an odd integer $2k + 1$, we have

$$(2k + 1)^2 = 4k(k + 1) + 1,$$

where $k(k + 1)$ is an even integer. So $(2k + 1)^2 \equiv 1 \pmod{8}$. ■

2.12 Prove that there are no integers a, b, c such that $a^2 + b^2 = 3c^2$. (Hint: studying the equation $[a]_4^2 + [b]_4^2 = 3[c]_4^2$ in $\mathbb{Z}/4\mathbb{Z}$, show that a, b, c would all have to be even. Letting $a = 2k, b = 2l, c = 2m$, you would have $k^2 + l^2 = 3m^2$. What's wrong with that?)

$$a^2 + b^2 = 3c^2 \implies [a]_4^2 + [b]_4^2 = 3[c]_4^2.$$

Noting that $[0]_4^2 = [0]_4, [1]_4^2 = [1]_4, [2]_4^2 = [0]_4, [3]_4^2 = [1]_4$, we see $[c]_4^2$ must be $[0]_4$ and so do $[a]_4^2$ and $[b]_4^2$. Hence $[a]_4, [b]_4, [c]_4$ can only be $[0]_4$ or $[2]_4$, which justifies letting $a = 2k_1, b =$

$2l_2, c = 2m_1$. After substitution we have $k^2 + l^2 = 3m^2$. Repeating this process n times yields $a = 2^n k_n, b = 2^n l_n, c = 2^n m_n$. For a sufficiently large number N , the absolute value of k_N, l_N, m_N must be less than 1. Thus we conclude that $a = b = c = 0$ is the unique solution to the equation $a^2 + b^2 = 3c^2$. ■

2.13 Prove that if $\gcd(m, n) = 1$, then there exist integers a and b such that $am + bn = 1$. (Use Corollary 2.5.) Conversely, prove that if $am + bn = 1$ for some integers a and b , then $\gcd(m, n) = 1$. [2.15, §V.2.1, V.2.4]

Applying corollary 2.5, we have $\gcd(m, n) = 1$ if and only if $[m]_n$ generates $\mathbb{Z}/n\mathbb{Z}$. Hence

$$\gcd(m, n) = 1 \iff a[m]_n = [1]_n \iff [am]_n = [1]_n \iff am + bn = 1.$$

■

2.15 Let $n > 0$ be an odd integer.

- Prove that if $\gcd(m, n) = 1$, then $\gcd(2m + n, 2n) = 1$. (Use Exercise 2.13.)
- Prove that if $\gcd(r, 2n) = 1$, then $\gcd(\frac{r+n}{2}, n) = 1$. (Ditto.)
- Conclude that the function $[m]_n \rightarrow [2m + n]_{2n}$ is a bijection between $(\mathbb{Z}/n\mathbb{Z})^*$ and $(\mathbb{Z}/2n\mathbb{Z})^*$.

The number $\phi(n)$ of elements of $(\mathbb{Z}/n\mathbb{Z})^*$ is Euler's $\phi(n)$ -function. The reader has just proved that if n is odd, then $\phi(2n) = \phi(n)$. Much more general formulas will be given later on (cf. Exercise V.6.8). [VII.5.11]

- Since $2m + n$ is an odd integer, $\gcd(2m + n, 2n) = 1$ is actually equivalent to $\gcd(2m + n, n) = 1$. According to Exercise 2.13,

$$\gcd(m, n) = 1 \implies am + bn = 1 \implies \frac{a}{2}(2m + n) + \left(b - \frac{a}{2}\right)n = 1.$$

If a is even, we have shown $\gcd(2m + n, n) = 1$. Otherwise we can let $a' = a + n$ be an even integer and $b' = b - m$. Then it holds that

$$\frac{a'}{2}(2m + n) + \left(b' - \frac{a'}{2}\right)n = 1,$$

which also implies $\gcd(2m + n, n) = 1$.

- If $\gcd(r, 2n) = 1$, then r must be an odd integer and accordingly

$$\gcd(2r + 2n, 4n) = 1 \implies a(2r + 2n) + b(4n) = 1 \implies 4a\frac{r+n}{2} + 4bn = 1,$$

which is $\gcd(\frac{r+n}{2}, n) = 1$.

- It is easy to check that the function $f : (\mathbb{Z}/n\mathbb{Z})^* \rightarrow (\mathbb{Z}/2n\mathbb{Z})^*$, $[m]_n \mapsto [2m + n]_{2n}$ is well-defined. The fact

$$\begin{aligned} f([m_1]_n) = f([m_2]_n) &\implies f([2m_1 + n]_{2n}) = f([2m_2 + n]_{2n}) \\ &\implies (2m_1 + n) - (2m_2 + n) = 2kn \\ &\implies m_1 - m_2 = kn \\ &\implies [m_1]_n = [m_2]_n \end{aligned}$$

indicates that f is injective. For any $[r]_{2n} \in (\mathbb{Z}/2n\mathbb{Z})^*$, we have

$$\gcd(r, 2n) = 1 \implies \gcd\left(\frac{r+n}{2}, n\right) = 1 \implies \left[\frac{r+n}{2}\right]_n \in (\mathbb{Z}/n\mathbb{Z})^*,$$

and

$$f\left(\left[\frac{r+n}{2}\right]_n\right) = [r + 2n]_{2n} = [r]_{2n},$$

which indicates that f is surjective. Thus we show f is a bijection. ■

2.16 Find the last digit of $1238237^{18238456}$. (Work in $\mathbb{Z}/10\mathbb{Z}$.)

$$1238237^{18238456} \equiv 7^{18238456} \equiv (7^4)^{4559614} \equiv 2401^{4559614} \equiv 1 \pmod{10},$$

which indicates that the last digit of $1238237^{18238456}$ is 1. ■

2.17 Show that if $m \equiv m' \pmod{n}$, then $\gcd(m, n) = 1$ if and only if $\gcd(m', n) = 1$. [§2.3]

Assume that $m - m' = kn$. If $\gcd(m, n) = 1$, for any common divisor d of m' and n

$$d|m', d|n \implies d|(m' + kn) \implies d|m \implies d = 1,$$

which means $\gcd(m', n) = 1$. Likewise, we can show $\gcd(m', n) = 1 \implies \gcd(m, n) = 1$ ■

§3. The category Grp

3.1 Let $\varphi : G \rightarrow H$ be a morphism in a category \mathbf{C} with products. Explain why there is a unique morphism

$$(\varphi \times \varphi) : G \times G \longrightarrow H \times H.$$

(This morphism is defined explicitly for $\mathbf{C} = \mathbf{Set}$ in §3.1.)

By the universal property of product in \mathbf{C} , there exist a unique morphism $(\varphi \times \varphi) : G \times G \longrightarrow H \times H$ such that the following diagram commutes.

$$\begin{array}{ccc}
 G & \xrightarrow{\varphi} & H \\
 \pi_G \uparrow & & \uparrow \pi_H \\
 G \times G & \xrightarrow{\varphi \times \varphi} & H \times H \\
 \pi_G \downarrow & & \downarrow \pi_H \\
 G & \xrightarrow{\varphi} & H
 \end{array}$$

■

3.2 Let $\varphi : G \rightarrow H, \psi : H \rightarrow K$ be morphisms in a category with products, and consider morphisms between the products $G \times G, H \times H, K \times K$ as in Exercise 3.1. Prove that

$$(\psi\varphi) \times (\psi\varphi) = (\psi \times \psi)(\varphi \times \varphi).$$

(This is part of the commutativity of the diagram displayed in §3.2.)

By the universal property of product in \mathbf{C} , there exists a unique morphism

$$(\psi\varphi) \times (\psi\varphi) : G \times G \rightarrow K \times K$$

such that the following diagram commutes.

$$\begin{array}{ccc}
 G & \xrightarrow{\psi\varphi} & H \\
 \pi_G \uparrow & & \uparrow \pi_H \\
 G \times G & \xrightarrow{(\psi\varphi) \times (\psi\varphi)} & H \times H \\
 \pi_G \downarrow & & \downarrow \pi_H \\
 G & \xrightarrow{\psi\varphi} & H
 \end{array}$$

As the following commutative diagram tells us the composition

$$(\psi \times \psi)(\varphi \times \varphi) : G \times G \rightarrow K \times K$$

can make the above diagram commute,

$$\begin{array}{ccccc}
 & & \psi\varphi & & \\
 & \curvearrowright & & \curvearrowleft & \\
 G & \xrightarrow{\varphi} & H & \xrightarrow{\psi} & K \\
 \uparrow \pi_G & & \uparrow \pi_H & & \uparrow \pi_K \\
 G \times G & \xrightarrow{\varphi \times \varphi} & H \times H & \xrightarrow{\psi \times \psi} & K \times K \\
 \downarrow \pi_G & & \downarrow \pi_H & & \downarrow \pi_K \\
 G & \xrightarrow{\varphi} & H & \xrightarrow{\psi} & K \\
 & \curvearrowleft & & \curvearrowright & \\
 & \psi\varphi & & \psi\varphi &
 \end{array}$$

there must be $(\psi\varphi) \times (\psi\varphi) = (\psi \times \psi)(\varphi \times \varphi)$. ■

3.3 Show that if G, H are abelian groups, then $G \times H$ satisfies the universal property for coproducts in **Ab**.

Define two monomorphisms:

$$i_G : G \longrightarrow G \times H, a \longmapsto (a, 0_H)$$

$$i_H : H \longrightarrow G \times H, b \longmapsto (0_G, b)$$

We are to show that for any two homomorphisms $g : G \rightarrow M$ and $h : H \rightarrow M$ in **Ab**, the mapping

$$\begin{aligned}
 \varphi : G \times H &\longrightarrow M, \\
 (a, b) &\longmapsto g(a) + h(b)
 \end{aligned}$$

is a homomorphism and makes the following diagram commute.

$$\begin{array}{ccc}
 G & & \\
 i_G \downarrow & \searrow g & \\
 G \times H & \xrightarrow{\varphi} & M \\
 i_H \uparrow & \nearrow h & \\
 H & &
 \end{array}$$

Exploiting the fact that g, h are homomorphisms and M is an abelian group, it is easy to

check that φ preserves the addition operation

$$\begin{aligned}
\varphi((a_1, b_1) + (a_2, b_2)) &= \varphi((a_1 + a_2, b_1 + b_2)) \\
&= g(a_1 + a_2) + h(b_1 + b_2) \\
&= (g(a_1) + g(a_2)) + (h(b_1) + h(b_2)) \\
&= (g(a_1) + h(b_1)) + (g(a_2) + h(b_2)) \\
&= g(a_1 + b_1) + h(a_2 + b_2) \\
&= \varphi((a_1, b_1)) + \varphi((a_2, b_2))
\end{aligned}$$

and the diagram commutes

$$\begin{aligned}
\varphi \circ i_G(a) &= \varphi((a, 0_H)) = g(a) + h(0_H) = g(a) + 0_M = g(a), \\
\varphi \circ i_H(b) &= \varphi((0_G, b)) = g(0_G) + h(b) = 0_M + h(b) = h(b).
\end{aligned}$$

To show the uniqueness of the homomorphism φ we have constructed, suppose a homomorphism φ' can make the diagram commute. Then we have

$$\varphi'((a, b)) = \varphi'((a, 0_H) + (0_G, b)) = \varphi'(i_G(a)) + \varphi'(i_H(b)) = g(a) + h(b) = \varphi((a, b)),$$

that is $\varphi' = \varphi$. Hence we show that there exist a unique homomorphism φ such that the diagram commutes, which amounts to the universal property for coproducts in **Ab**. ■

3.4 Let G, H be groups, and assume that $G \cong H \times G$. Can you conclude that H is trivial? (Hint: No. Can you construct a counterexample?)

Consider the function

$$\begin{aligned}
\varphi : \mathbb{Z} \times \mathbb{Z}[x] &\longrightarrow \mathbb{Z}[x] \\
(n, f(x)) &\longmapsto n + xf(x)
\end{aligned}$$

Firstly, we can show φ is a homomorphism as follows

$$\begin{aligned}
\varphi((n_1, f_1(x)) + (n_2, f_2(x))) &= \varphi((n_1 + n_2, f_1(x) + f_2(x))) \\
&= (n_1 + n_2) + x(f_1(x) + f_2(x)) \\
&= (n_1 + xf_1(x)) + (n_2 + xf_2(x)) \\
&= \varphi(n_1, f_1(x)) + \varphi(n_2, f_2(x)).
\end{aligned}$$

Secondly, we are to show φ is a monomorphism. It follows by

$$\varphi(n, f(x)) = n + xf(x) = 0 \implies n = 0, f(x) = 0 \implies \ker \varphi = \{(0, 0)\}.$$

Lastly, since given any $f(x) = \sum_{n \geq 0} a_n x^n \in \mathbb{Z}[x]$ we have

$$\varphi \left(a_0, \sum_{n \geq 1} a_n x^{n-1} \right) = a_0 + \sum_{n \geq 1} a_n x^n = f(x),$$

we claim φ is surjective and indeed an isomorphism. Therefore, as a counterexample we have $\mathbb{Z}[x] \cong \mathbb{Z} \times \mathbb{Z}[x]$ where \mathbb{Z} is non-trivial. ■

3.5 Prove that \mathbb{Q} is not the direct product of two nontrivial groups.

Consider the additive group of rationals $(\mathbb{Q}, +)$. Assume that φ is a isomorphism between the product $G \times H = \{(a, b) | a \in G, b \in H\}$ and $(\mathbb{Q}, +)$. Note that $\{e_G\} \times H$ and $G \times \{e_H\}$ are subgroups in $G \times H$ and their intersection is the trivial group $\{(e_G, e_H)\}$. It is easy to check that bijection φ satisfies $\varphi(A \cap B) = \varphi(A) \cap \varphi(B)$. So applying the fact we have

$$\varphi(\{(e_G, e_H)\}) = \varphi(\{e_G\} \times H \cap G \times \{e_H\}) = \varphi(\{e_G\} \times H) \cap \varphi(G \times \{e_H\}) = \{0\}.$$

Suppose both $\varphi(\{e_G\} \times H)$ and $\varphi(G \times \{e_H\})$ are nontrivial groups. If $\frac{p}{q} \in \varphi(\{e_G\} \times H) - \{0\}$ and $\frac{r}{s} \in \varphi(G \times \{e_H\}) - \{0\}$, there must be

$$rp = rq \cdot \frac{p}{q} = ps \cdot \frac{r}{s} \in \varphi(\{e_G\} \times H) \cap \varphi(G \times \{e_H\}),$$

which implies $rp = 0$. Since both $\frac{p}{q}$ and $\frac{r}{s}$ are non-zero, it leads to a contradiction. Thus without loss of generality we can assume $\varphi(\{e_G\} \times H)$ is a trivial group $\{0\}$. Since φ is isomorphism, we see that for all $h \in H$,

$$\varphi(e_G, h) = \varphi(e_G, e_H) = 0 \iff h = e_H.$$

That is, H is a trivial group. Therefore, we have shown $(\mathbb{Q}, +)$ will never be isomorphic to the direct product of two nontrivial groups. ■

3.6 Consider the product of the cyclic groups C_2, C_3 (cf. §2.3): $C_2 \times C_3$. By [Exercise 3.3](#), this group is a coproduct of C_2 and C_3 in **Ab**. Show that it is not a coproduct of C_2 and C_3 in **Grp**, as follows:

- find injective homomorphisms $C_2 \rightarrow S_3, C_3 \rightarrow S_3$;
- arguing by contradiction, assume that $C_2 \times C_3$ is a coproduct of C_2, C_3 , and deduce that there would be a group homomorphism $C_2 \times C_3 \rightarrow S_3$ with certain properties;
- show that there is no such homomorphism.

- Monomorphisms $g : C_2 \rightarrow S_3$, $h : C_3 \rightarrow S_3$ can be constructed as follows:

$$g([0]_2) = e, g([1]_2) = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix}.$$

$$h([0]_3) = e, h([1]_3) = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix}, h([2]_3) = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix}.$$

- Supposing that $C_2 \times C_3$ is a coproduct of C_2, C_3 , there would be a unique group homomorphism $\varphi : C_2 \times C_3 \rightarrow S_3$ such that the following diagram commutes

$$\begin{array}{ccc} C_2 & & \\ i_{C_2} \downarrow & \searrow g & \\ C_2 \times C_3 & \xrightarrow{\varphi} & S_3 \\ i_{C_3} \uparrow & \nearrow h & \\ C_3 & & \end{array}$$

In other words, for all $a \in C_2, b \in C_3$,

$$\begin{aligned} \varphi(a, b) &= \varphi([0]_2, b) + \varphi(a, [0]_3) = \varphi([0]_2, b)\varphi(a, [0]_3) = \varphi(i_{C_3}(b))\varphi(i_{C_2}(a)) = h(b)g(a) \\ &= \varphi(a, [0]_3) + \varphi([0]_2, b) = \varphi(a, [0]_3)\varphi([0]_2, b) = \varphi(i_{C_2}(a))\varphi(i_{C_3}(b)) = g(a)h(b). \end{aligned}$$

- Since

$$g([1]_2)h([1]_3) = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix},$$

$$h([1]_3)g([1]_2) = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix},$$

we see $g(a)h(b) \neq h(b)g(a)$ not always holds. The derived contradiction shows that $C_2 \times C_3$ is not a coproduct of C_2, C_3 in \mathbf{Grp} . ■

3.7 Show that there is a surjective homomorphism $Z * Z \rightarrow C_2 * C_3$. (* denotes coproduct in \mathbf{Grp} .)

Consider the mapping

$$\begin{aligned} \varphi : \mathbb{Z} * \mathbb{Z} &\longrightarrow C_2 * C_3 \\ x^{m_1}y^{n_1} \dots x^{m_k}y^{n_k} &\longmapsto x^{[m_1]_2}y^{[n_1]_3} \dots x^{[m_k]_2}y^{[n_k]_3} \end{aligned}$$

Since

$$\begin{aligned} &\varphi(x^{m_1}y^{n_1} \dots x^{m_k}y^{n_k}x^{m'_1}y^{n'_1} \dots x^{m'_{k'}}y^{n'_{k'}}) \\ &= x^{[m_1]_2}y^{[n_1]_3} \dots x^{[m_k]_2}y^{[n_k]_3}x^{[m'_1]_2}y^{[n'_1]_3} \dots x^{[m'_{k'}]_2}y^{[n'_{k'}]_3}, \\ &= \varphi(x^{m_1}y^{n_1} \dots x^{m_k}y^{n_k})\varphi(x^{m'_1}y^{n'_1} \dots x^{m'_{k'}}y^{n'_{k'}}) \end{aligned}$$

φ is a homomorphism. It is clear that φ is surjective. Thus we show there exists a surjective homomorphism $Z * Z \rightarrow C_2 * C_3$. ■

3.8 Define a group G with two generators x, y , subject (only) to the relations $x^2 = e_G, y^3 = e_G$. Prove that G is a coproduct of C_2 and C_3 in **Grp**. (The reader will obtain an even more concrete description for $C_2 * C_3$ in Exercise 9.14; it is called the modular group.) [§3.4, 9.14]

Given the maps $i_1 : C_2 \rightarrow G, [m]_2 \mapsto x^m$ and $i_2 : C_3 \rightarrow G, [n]_3 \mapsto y^n$, we can check that i_1, i_2 are homomorphisms. We are to show that for every group H endowed with two homomorphisms $f_1 : C_2 \rightarrow H, f_2 : C_3 \rightarrow H$, there would be a unique group homomorphism $\varphi : G \rightarrow H$ such that the following diagram commutes

$$\begin{array}{ccc} C_2 & & \\ i_1 \downarrow & \searrow f_1 & \\ G & \xrightarrow{\varphi} & H \\ i_2 \uparrow & \nearrow f_2 & \\ C_3 & & \end{array}$$

or

$$\begin{aligned} \varphi(i_1([m]_2)) &= \varphi(x^m) = \varphi(x)^m = f_1([m]_2), \\ \varphi(i_2([n]_3)) &= \varphi(y^n) = \varphi(y)^n = f_2([n]_3). \end{aligned}$$

Define $\phi : G \rightarrow H$ as $\phi(x^m y^n) = f_1([m]_2) f_2([n]_3)$, $\phi(y^n x^m) = f_2([n]_3) f_1([m]_2)$. It is clear to see ϕ makes the diagram commute. Moreover, if φ makes the diagram commute, it follows that for all $x^m y^n, y^n x^m \in G$,

$$\begin{aligned} \varphi(x^m y^n) &= \varphi(x^m) \varphi(y^n) = f_1([m]_2) f_2([n]_3), \\ \varphi(y^n x^m) &= \varphi(y^n) \varphi(x^m) = f_2([n]_3) f_1([m]_2), \end{aligned}$$

which implies $\varphi = \phi$. Thus we can conclude G is the coproduct of C_2 and C_3 in **Grp**. ■

§4. Group homomorphisms

4.1 Check that the function π_m^n defined in §4.1 is well-defined, and makes the diagram commute. Verify that it is a group homomorphism. Why is the hypothesis $m|n$ necessary? [§4.1]

In §4.1 the function π_m^n is defined as

$$\begin{aligned} \pi_m^n : \mathbb{Z}/n\mathbb{Z} &\longrightarrow \mathbb{Z}/m\mathbb{Z} \\ [a]_n &\longmapsto [a]_m \end{aligned}$$

with the condition $m|n$. We can check that π_m^n is well-defined as

$$[a_1]_n = [a_2]_n \iff a_1 - a_2 = kn = (kl)m \implies [a_1]_m = [a_2]_m \iff \pi_m^n([a_1]_n) = \pi_m^n([a_2]_n).$$

Note $\pi_m^n(\pi_n(a)) = \pi_m^n([a]_n) = [a]_m = \pi_m(a)$. The diagram in §4.1 must commute.

$$\begin{array}{ccc} \mathbb{Z} & & \\ \pi_n \downarrow & \searrow \pi_m & \\ \mathbb{Z}/n\mathbb{Z} & \xrightarrow{\pi_m^n} & \mathbb{Z}/m\mathbb{Z} \end{array}$$

Since

$$\pi_m^n([a]_n + [b]_n) = [a + b]_m = [a]_m + [b]_m = \pi_m^n([a]_n) + \pi_m^n([b]_n),$$

it follows that π_m^n is a group homomorphism. Actually we have shown that without the hypothesis $m|n$, π_m^n may not be well-defined. ■

4.2 Show that the homomorphism $\pi_2^4 \times \pi_2^4 : C_4 \rightarrow C_2 \times C_2$ is not an isomorphism. In fact, is there any nontrivial isomorphism $C_4 \rightarrow C_2 \times C_2$?

Let calculate the order of each non-zero element in both C_4 and $C_2 \times C_2$. For the group C_4 ,

$$|[2]_4| = 2, \quad |[1]_4| = |[3]_4| = 4.$$

For the group $C_2 \times C_2$,

$$|([1]_2, [0]_2)| = |([0]_2, [1]_2)| = |([1]_2, [1]_2)| = 2.$$

Since isomorphism must preserve the order, we can assert that there is no such isomorphism $C_4 \rightarrow C_2 \times C_2$. ■

4.3 Prove that a group of order n is isomorphic to $\mathbb{Z}/n\mathbb{Z}$ if and only if it contains an element of order n . [§4.3]

Assume some group G is isomorphic to $\mathbb{Z}/n\mathbb{Z}$. Since $|[1]_n| = n$ and isomorphism preserves the order, we can affirm that there is an element of order n in G .

Conversely, assume there is a group G of order n in which g is an element of order n . By definition we see $g^0, g^1, g^2 \dots g^{n-1}$ are distinct pairwise. Noticing group G has exactly n elements, G must consist of $g^0, g^1, g^2 \dots g^{n-1}$. We can easily check that the function

$$\begin{aligned} f : G &\longrightarrow \mathbb{Z}/n\mathbb{Z} \\ g^k &\longmapsto [k]_n \end{aligned}$$

is an isomorphism. ■

4.4 Prove that no two of the groups $(\mathbb{Z}, +)$, $(\mathbb{Q}, +)$, $(\mathbb{R}, +)$ are isomorphic to one another. Can you decide whether $(\mathbb{R}, +)$, $(\mathbb{C}, +)$ are isomorphic to one another? (Cf. Exercise VI.1.1.)

Suppose there exists an isomorphism $f : \mathbb{Z} \rightarrow \mathbb{Q}$. Let $f(1) = p/q$ ($p, q \in \mathbb{Z}$). If $p = 1$, for all $n \in \mathbb{Z}$, we have

$$f(n) = \frac{n}{q} \neq \frac{1}{2q}.$$

If $p \neq 1$, for all $n \in \mathbb{Z}$, we have

$$f(n) = \frac{np}{q} \neq \frac{p+1}{q}.$$

In both cases, it implies $f(\mathbb{Z}) \not\subseteq \mathbb{Q}$. Hence we see f is not a surjection, which contradicts the fact that $f : \mathbb{Z} \rightarrow \mathbb{Q}$ is an isomorphism. Compare the cardinality of \mathbb{Z} , \mathbb{Q} , \mathbb{R}

$$|\mathbb{Z}| = |\mathbb{Q}| < |\mathbb{R}|$$

and we show there exists no such isomorphisms like $f : \mathbb{Z} \rightarrow \mathbb{R}$ or $f : \mathbb{Q} \rightarrow \mathbb{R}$.

We can prove $(\mathbb{R}, +)$, $(\mathbb{C}, +)$ are isomorphic, if considering the both as vector spaces over \mathbb{Q} . ■

4.5 Prove that the groups $(\mathbb{R} \setminus \{0\}, \cdot)$ and $(\mathbb{C} \setminus \{0\}, \cdot)$ are not isomorphic.

Suppose $f : \mathbb{R} \rightarrow \mathbb{C}$ is an isomorphism. Then there exists a real number x such that $f(x) = i$.

$$f(x^4) = f(x)^4 = i^4 = 1.$$

Since isomorphism preserves the identity, we have

$$f(1) = 1 = f(x^4).$$

which indicates $x^4 = 1$. Noticing that $x \in \mathbb{R}$, there must be $x^2 = 1$. Now we see

$$f(1) = f(x^2) = f(x)^2 = i^2 = -1,$$

which derives a contradiction. Thus we can conclude that groups $(\mathbb{R} \setminus \{0\}, \cdot)$ and $(\mathbb{C} \setminus \{0\}, \cdot)$ are not isomorphic. ■

4.6 We have seen that $(\mathbb{R}, +)$ and $(\mathbb{R}_{>0}, \cdot)$ are isomorphic (Example 4.4). Are the groups $(\mathbb{Q}, +)$ and $(\mathbb{Q}_{>0}, \cdot)$ isomorphic?

Suppose $f : \mathbb{Q} \rightarrow \mathbb{Q}_{>0}$ is an isomorphism. Since isomorphism preserves the multiplication, we have

$$f(1) = f\left(n \cdot \frac{1}{n}\right) = f\left(\frac{1}{n}\right)^n \quad (n \in \mathbb{Z}_{>0}),$$

which implies

$$f\left(\frac{1}{n}\right) = f(1)^{\frac{1}{n}}.$$

Assume

$$f(1) = \frac{p}{q} = \frac{p_1^{r_1} p_2^{r_2} \cdots p_k^{r_k}}{q_1^{s_1} q_2^{s_2} \cdots q_l^{s_l}}$$

where p_i, q_i are pairwise distinct positive prime numbers. Then let

$$M = \max\{p, q\} + 1 > \max\{r_1, \dots, r_k, s_1, \dots, s_l\}.$$

Thus we assert

$$f\left(\frac{1}{M}\right) = \left(\frac{p_1^{r_1} p_2^{r_2} \cdots p_k^{r_k}}{q_1^{s_1} q_2^{s_2} \cdots q_l^{s_l}}\right)^{\frac{1}{M}} \notin \mathbb{Q},$$

which can be proved by contradiction. In fact, Suppose

$$\left(\frac{p}{q}\right)^{\frac{1}{M}} = \frac{a}{b} \in \mathbb{Q}$$

or say

$$pb^M = qa^M,$$

where a, b are coprime. Note that b^M, a^M are also coprime and that the prime factorization of a^M can be written as $a_1^{Mt_1} a_2^{Mt_2} \cdots a_j^{Mt_j}$ where a_i are pairwise distinct positive prime numbers. That forces

$$p = p_1^{r_1} p_2^{r_2} \cdots p_k^{r_k} = N \cdot a_1^{Mt_1} a_2^{Mt_2} \cdots a_j^{Mt_j}.$$

Noticing that a_i must coincide with one number in $\{p_1, p_2, \dots, p_k\}$, we can assume $a_1 = p_1$ without loss of generality. However, since $M > \max\{r_1, \dots, r_k\}$, we see the exponent of p_1 is distinct from that of a_1 , which violates the unique factorization property of \mathbb{Z} . Hence we get a contradiction and verify $f\left(\frac{1}{M}\right) \notin \mathbb{Q}$. Moreover, it contradicts our assumption that $f : \mathbb{Q} \rightarrow \mathbb{Q}_{>0}$ is an isomorphism. Eventually we show that the groups $(\mathbb{Q}, +)$ and $(\mathbb{Q}_{>0}, \cdot)$ are not isomorphic. ■

4.7 Let G be a group. Prove that the function $G \rightarrow G$ defined by $g \mapsto g^{-1}$ is a homomorphism if and only if G is abelian. Prove that $g \mapsto g^2$ is a homomorphism if and only if G is abelian.

Given the function

$$\begin{aligned} f : G &\longrightarrow G \\ g &\longmapsto g^{-1} \end{aligned}$$

we have

$$f(g_1 g_2) = (g_1 g_2)^{-1} = g_2^{-1} g_1^{-1}, \quad f(g_1) f(g_2) = g_1^{-1} g_2^{-1}.$$

If G is abelian, it is clear to see $f(g_1g_2) = f(g_1)f(g_2)$. If f is a homomorphism, $\forall h_1, h_2 \in G$,

$$h_1h_2 = (h_2^{-1}h_1^{-1})^{-1} = f(h_2^{-1}h_1^{-1}) = f(h_2^{-1})f(h_1^{-1}) = h_2h_1.$$

Given the function

$$\begin{aligned} h &: G \longrightarrow G \\ g &\longmapsto g^2 \end{aligned}$$

we have

$$h(g_1g_2) = (g_1g_2)^2 = g_1g_2g_1g_2, \quad h(g_1)h(g_2) = g_1^2g_2^2 = g_1g_1g_2g_2.$$

If G is abelian, it is clear to see $h(g_1g_2) = h(g_1)h(g_2)$. If h is a homomorphism, by cancellation we have

$$h(g_1g_2) = h(g_1)h(g_2) \implies g_2g_1 = g_1g_2.$$

■

4.8 Let G be a group, and $g \in G$. Prove that the function $\gamma_g : G \rightarrow G$ defined by $(\forall a \in G) : \gamma_g(a) = gag^{-1}$ is an automorphism of G . (The automorphisms γ_g are called ‘inner’ automorphisms of G .) Prove that the function $G \rightarrow \text{Aut}(G)$ defined by $g \mapsto \gamma_g$ is a homomorphism. Prove that this homomorphism is trivial if and only if G is abelian.

Since

$$\gamma_g(ab) = gabg^{-1} = gag^{-1}gbg^{-1} = \gamma_g(a)\gamma_g(b),$$

γ_g is an automorphism of G . For all $a \in G$, we have

$$\gamma_{g_1g_2}(a) = g_1g_2ag_2^{-1}g_1^{-1} = \gamma_{g_1}(g_2ag_2^{-1}) = (\gamma_{g_1} \circ \gamma_{g_2})(a),$$

which implies $\gamma_{g_1g_2} = \gamma_{g_1} \circ \gamma_{g_2}$ and $g \mapsto \gamma_g$ is a homomorphism. If G is abelian, for all g the homomorphism

$$\gamma_g(a) = gag^{-1} = gg^{-1}a = a$$

is the identity in $\text{Aut}(G)$. That is, the homomorphism $g \mapsto \gamma_g$ is trivial. If the homomorphism $g \mapsto \gamma_g$ is trivial, we have for all $g, a \in G$,

$$gag^{-1} = a,$$

which implies for all $a, b \in G$,

$$ab = bab^{-1}b = ba.$$

Thus we show the homomorphism $g \mapsto \gamma_g$ is trivial if and only if G is abelian. ■

4.9 Prove that if m, n are positive integers such that $\gcd(m, n) = 1$, then $C_{mn} \cong C_m \times C_n$.

Define a function

$$\begin{aligned} \varphi &: C_m \times C_n \longrightarrow C_{mn} \\ ([a]_m, [b]_n) &\longmapsto [anp + bmq]_{mn} \end{aligned}$$

where $[pn]_m = [1]_m$ and $[qm]_n = [1]_n$, as $\gcd(m, n) = 1$ guarantees the existence of p, q (see textbook p56). First of all, we have to check whether φ is well-defined. Note that

$$[(anp_1 + bmq_1) - (anp_2 + bmp_2)]_m = [a(p_1n - p_2n) + b(q_1m - q_2m)]_m = [0]_m$$

$$[(anp_1 + bmq_1) - (anp_2 + bmp_2)]_n = [a(p_1n - p_2n) + b(q_1m - q_2m)]_n = [0]_n$$

and $\gcd(m, n) = 1$. Thus we have

$$[(anp_1 + bmq_1) - (anp_2 + bmp_2)]_{mn} = [0]_{mn},$$

or

$$[anp_1 + bmq_1]_{mn} = [anp_2 + bmp_2]_{mn}.$$

Then we show φ is a homomorphism.

$$\begin{aligned} \varphi([a_1]_m, [b_1]_n) + ([a_2]_m, [b_2]_n) &= \varphi([a_1 + a_2]_m, [b_1 + b_2]_n) \\ &= [(a_1 + a_2)np + (b_1 + b_2)mq]_{mn} \\ &= [a_1np + b_1mq]_{mn} + [a_2np + b_2mq]_{mn} \\ &= \varphi([a_1]_m, [b_1]_n) + \varphi([a_2]_m, [b_2]_n). \end{aligned}$$

In order to show φ is a monomorphism, we can check

$$\begin{aligned} \varphi([a_1]_m, [b_1]_n) &= \varphi([a_2]_m, [b_2]_n) \\ \implies [a_1np + b_1mq]_{mn} &= [a_2np + b_2mq]_{mn} \\ \implies [(a_1 - a_2)np + (b_1 - b_2)mq]_{mn} &= [0]_{mn} \\ \implies [(a_1 - a_2)np + (b_1 - b_2)mq]_m &= [a_1 - a_2]_m = [0]_m, \\ [(a_1 - a_2)np + (b_1 - b_2)mq]_n &= [b_1 - b_2]_n = [0]_n \\ \implies [a_1]_m &= [a_2]_m, [b_1]_n = [b_2]_n. \end{aligned}$$

Since $|C_m \times C_n| = |C_{mn}| = mn$, we can conclude φ is an isomorphism. Thus we complete proving $C_{mn} \cong C_m \times C_n$. ■

§5. Free groups

5.1 Does the category \mathcal{F}^A defined in §5.2 have final objects? If so, what are they?

Yes, they are functions from A to any trivial group, for example $T = \{t\}$.

$$\begin{array}{ccc} G & \xrightarrow{\exists! \varphi} & \{t\} \\ j \uparrow & \nearrow e & \\ A & & \end{array}$$

For any object (j, G) in \mathcal{F}^A , the trivial homomorphism $\varphi : g \mapsto t$ is the unique homomorphism such that the diagram commutes. That is, $\text{Hom}((j, G), (e, T)) = \{\varphi\}$. ■

5.2 Since trivial groups T are initial in **Grp**, one may be led to think that (e, T) should be initial in \mathcal{F}^A , for every A : e would be defined by sending every element of A to the (only) element in T ; and for any other group G , there is a unique homomorphism $T \rightarrow G$. Explain why (e, T) is not initial in \mathcal{F}^A (unless $A = \emptyset$).

Let $G = C_2 = \{[0]_2, [1]_2\}$. Note that $\varphi \circ e(A)$ must be the trivial subgroup $\{[0]_2\}$. If $x \in A$ and $j(x) = [1]_2$, we see $\varphi \circ e \neq j$ and the following diagram does not commute.

$$\begin{array}{ccc} T & \xrightarrow{\varphi} & G \\ e \uparrow & \nearrow j & \\ A & & \end{array}$$

That implies (e, T) is not initial in \mathcal{F}^A unless $A = \emptyset$. ■

5.3 Use the universal property of free groups to prove that the map $j : A \rightarrow F(A)$ is injective, for all sets A . (Hint: it suffices to show that for every two elements a, b of A there is a group G and a set-function $f : A \rightarrow G$ such that $f(a) \neq f(b)$. Why? and how do you construct f and G ?) [§III.6.3]

Let $G = S_A$ be the symmetric group over A . Define functions $g_a : A \rightarrow A$, $x \mapsto a$ sending every element of A to a . Since $g_a \in S_A$, we can define an injection

$$\begin{aligned} f : A &\longrightarrow S_A \\ a &\longmapsto g_a \end{aligned}$$

In light of the commutative diagram

$$\begin{array}{ccc} F(A) & \xrightarrow{\varphi} & S_A \\ j \uparrow & \nearrow f & \\ A & & \end{array}$$

we have $\forall a, b \in A$,

$$j(a) = j(b) \implies \varphi(j(a)) = \varphi(j(b)) \implies f(a) = f(b) \implies a = b.$$

■

5.4 In the ‘concrete’ construction of free groups, one can try to reduce words by performing cancellations in any order; the ‘elementary reductions’ used in the text (that is, from left to right) is only one possibility. Prove that the result of iterating cancellations on a word is independent of the order in which the cancellations are performed. Deduce the associativity of the product in $F(A)$ from this. [§5.3]

We use induction on the length of w . If w is reduced, there is nothing to show. If not, there must be some pair of symbols that can be cancelled, say the underlined pair

$$w = \dots \underline{xx}^{-1} \dots$$

(Let's allow x to denote any element of A' , with the understanding that if $x = a^{-1}$ then $x^{-1} = a$.) If we show that we can obtain every reduced form of w by cancelling the pair xx^{-1} first, the proposition will follow by induction, because the word $w^* = \dots \cancel{xx}^{-1} \dots$ is shorter.

Let w_0 be a reduced form of w . It is obtained from w by some sequence of cancellations. The first case is that our pair xx^{-1} is cancelled at some step in this sequence. If so, we may as well cancel xx^{-1} first. So this case is settled. On the other hand, since w_0 is reduced, the pair xx^{-1} can not remain in w_0 . At least one of the two symbols must be cancelled at some time. If the pair itself is not cancelled, the first cancellation involving the pair must look like

$$\dots x^{-1} \underline{xx}^{-1} \dots \quad \text{or} \quad \dots \underline{xx}^{-1} x \dots$$

Notice that the word obtained by this cancellation is the same as the one obtained by cancelling the pair xx^{-1} . So at this stage we may cancel the original pair instead. Then we are back in the first case, so the proposition is proved. ■

5.5 Verify explicitly that $H^{\oplus A}$ is a group.

Assume the A is a set and H is an abelian group. $H^{\oplus A}$ are defined as follows

$$H^{\oplus A} := \{\alpha : A \rightarrow H \mid \alpha(a) \neq e_H \text{ for only finitely many elements } a \in A\}.$$

Now that $H^{\oplus A} \subset H^A := \text{Hom}_{\text{Set}}(A, H)$, we can first show $(H^A, +)$ is a group, where for all $\phi, \psi \in H^A$, $\phi + \psi$ is defined by

$$(\forall a \in A) : (\phi + \psi)(a) := \phi(a) + \psi(a).$$

Here is the verification:

- Identity: Define a function $\varepsilon : A \rightarrow H, a \mapsto e_H$ sending all elements in A to e_H . Then for any $\alpha \in H^A$ we have

$$(\forall a \in A) : (\alpha + \varepsilon)(a) = \alpha(a) + \varepsilon(a) = \alpha(a),$$

which is $\alpha + \varepsilon = \alpha$. Because of the commutativity of the operation $+$ defined on H^A , ε is the identity indeed.

- Associativity: This follows by the associativity in H :

$$(\forall a \in A) : ((\alpha + \beta) + \gamma)(a) = (\alpha + \beta)(a) + \gamma(a) = \alpha(a) + (\beta + \gamma)(a) = (\alpha + (\beta + \gamma))(a).$$

- Inverse: Every function $\phi \in H^A$ has inverse $-\phi$ defined by

$$(\forall a \in A) : (-\phi)(a) = -\phi(a).$$

Thus H^A makes a group.

Then it is time to show $H^{\oplus A}$ is a subgroup of H^A . For all $\alpha, \beta \in H^{\oplus A}$, let $N_\alpha = \{a \in A \mid \alpha(a) \neq e_H\}$, $N_\beta = \{a \in A \mid \beta(a) \neq e_H\}$, $N_{\alpha-\beta} = \{a \in A \mid (\alpha - \beta)(a) \neq e_H\}$. Since

$$(\forall a \in A) : (\alpha - \beta)(a) = \alpha(a) - \beta(a),$$

we have

$$(\alpha - \beta)(a) \neq e_H \implies \alpha(a) \neq e_H \text{ or } \beta(a) \neq e_H,$$

which implies $N_{\alpha-\beta} \subset N_\alpha \cup N_\beta$. Note that N_α, N_β are both finite sets, which forces $N_{\alpha-\beta}$ to be finite. So there must be $\alpha - \beta \in H^{\oplus A}$. Now we see $H^{\oplus A}$ is closed under additions and inverses. And $e_{H^A} = \varepsilon \in H^{\oplus A}$ means that $H^{\oplus A}$ is nonempty. Finally we can conclude $H^{\oplus A}$ is a subgroup of H^A . ■

5.6 Prove that the group $F(\{x, y\})$ (visualized in Example 5.3) is a coproduct $\mathbb{Z} * \mathbb{Z}$ of \mathbb{Z} by itself in the category **Grp**. (Hint: with due care, the universal property for one turns into the universal property for the other.) [§3.4, 3.7, 5.7]

Define two homomorphisms

$$\begin{aligned} i_1 : \mathbb{Z} &\longrightarrow F(\{x, y\}), & n &\longmapsto x^n, \\ i_2 : \mathbb{Z} &\longrightarrow F(\{x, y\}), & n &\longmapsto y^n. \end{aligned}$$

We need to show that for any group G with two homomorphisms $f_1, f_2 : \mathbb{Z} \rightarrow G$, there exists a unique homomorphism φ such that the following diagram commutes.

$$\begin{array}{ccc} \mathbb{Z} & & \\ \downarrow i_1 & \searrow f_1 & \\ F(\{x, y\}) & \xrightarrow{\varphi} & G \\ \uparrow i_2 & \nearrow f_2 & \\ \mathbb{Z} & & \end{array}$$

Given the notation of indicator function

$$\mathbf{1}_A(x) := \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A, \end{cases}$$

we can define a function

$$\begin{aligned}\varphi : F(\{x, y\}) &\longrightarrow G, \\ z_1^{n_1} \cdots z_k^{n_k} &\longmapsto f_1(n_1)^{\mathbf{1}_{\{x\}}(z_1)} f_2(n_1)^{\mathbf{1}_{\{y\}}(z_1)} \cdots f_1(n_k)^{\mathbf{1}_{\{x\}}(z_n)} f_2(n_k)^{\mathbf{1}_{\{y\}}(z_n)}, \quad z_i \in \{x, y\}\end{aligned}$$

and check that it is a homomorphism indeed. For all $n \in \mathbb{Z}$, we have

$$\begin{aligned}(\varphi \circ i_1)(n) &= \varphi(x^n) = f_1(n), \\ (\varphi \circ i_2)(n) &= \varphi(y^n) = f_2(n),\end{aligned}$$

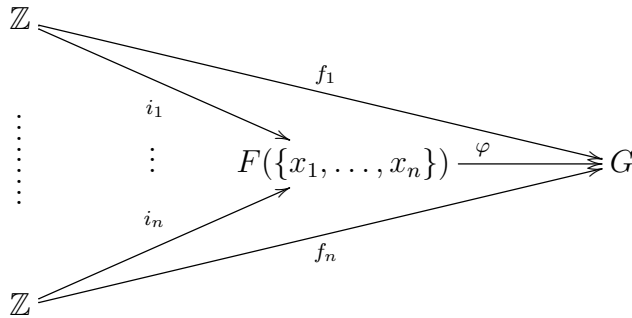
that is, the diagram commutes. Now we see φ exists. For the uniqueness of φ , let φ^* be another homomorphism that makes diagram commute. For all $z_1^{n_1} \cdots z_k^{n_k} \in F(\{x, y\})$, $z_i \in \{x, y\}$, we have

$$\begin{aligned}\varphi^*(z_1^{n_1} \cdots z_k^{n_k}) &= \varphi^*(z^{n_1}) \cdots \varphi^*(z^{n_k}) \\ &= \varphi^*(i_1(n_1))^{\mathbf{1}_{\{x\}}(z_1)} \varphi^*(i_2(n_1))^{\mathbf{1}_{\{y\}}(z_1)} \cdots \varphi^*(i_1(n_k))^{\mathbf{1}_{\{x\}}(z_n)} \varphi^*(i_2(n_k))^{\mathbf{1}_{\{y\}}(z_n)} \\ &= f_1(n_1)^{\mathbf{1}_{\{x\}}(z_1)} f_2(n_1)^{\mathbf{1}_{\{y\}}(z_1)} \cdots f_1(n_k)^{\mathbf{1}_{\{x\}}(z_n)} f_2(n_k)^{\mathbf{1}_{\{y\}}(z_n)} \\ &= \varphi(z_1^{n_1} \cdots z_k^{n_k}).\end{aligned}$$

To sum up, we have shown that the group $F(\{x, y\})$ is a coproduct $\mathbb{Z} * \mathbb{Z}$ of \mathbb{Z} by itself in the category **Grp**. ■

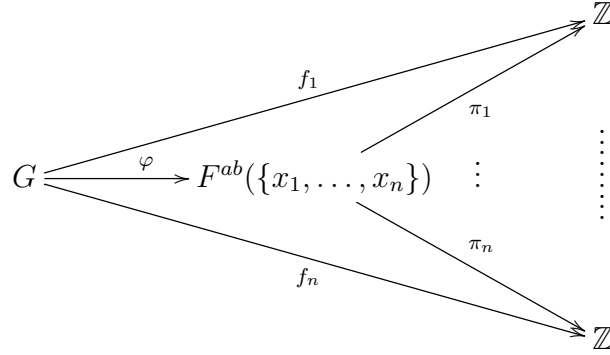
5.7 Extend the result of Exercise 5.6 to free groups $F(\{x_1, \dots, x_n\})$ and to free abelian groups $F^{ab}(\{x_1, \dots, x_n\})$. [§3.4, §5.4]

Let $*$ be coproduct. Then we have $\underbrace{\mathbb{Z} * \mathbb{Z} * \cdots * \mathbb{Z}}_{n \text{ times}} \cong F(\{x_1, \dots, x_n\})$, as the following diagram demonstrates:



Dually, let \times be product. Then we have $\underbrace{\mathbb{Z} \times \mathbb{Z} \times \cdots \times \mathbb{Z}}_{n \text{ times}} \cong F^{ab}(\{x_1, \dots, x_n\})$, as the fol-

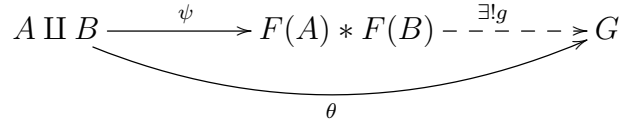
following diagram demonstrates:



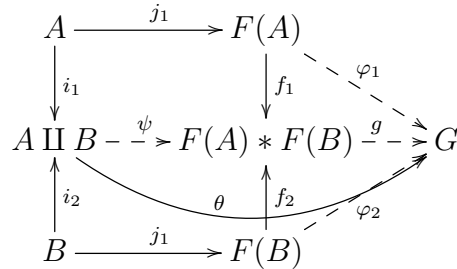
■

5.8 Still more generally, prove that $F(A \amalg B) = F(A) * F(B)$ and that $F^{ab}(A \amalg B) = F^{ab}(A) \oplus F^{ab}(B)$ for all sets A, B . (That is, the constructions F, F^{ab} 'preserve coproducts'.)

In order to show $F(A) * F(B)$ is a free group generated by $A \amalg B$, we should first set an appropriate function $\psi : A \amalg B \rightarrow F(A) * F(B)$ and then prove that given any (θ, G) there exists a unique group homomorphism g such that the following diagram commutes.



The complete proof can be divided into three steps, by decomposing the following diagram into parts.



Step 1. Construct $\psi : A \amalg B \rightarrow F(A) * F(B)$.

Define injective functions

$$\begin{aligned} i_1 : A &\longrightarrow A \amalg B, & a &\longmapsto (a, 1), \\ i_2 : B &\longrightarrow A \amalg B, & b &\longmapsto (b, 2), \\ j_1 : A &\longrightarrow F(A), & a &\longmapsto a, \\ j_2 : B &\longrightarrow F(B), & b &\longmapsto b. \end{aligned}$$

Let f_1, f_2 be the homomorphisms specified by the coproduct in **Grp**. Since $A \amalg B$ is a coproduct in **Set**, the universal property guarantees a unique mapping $\psi : A \amalg B \rightarrow F(A) *$

$F(B)$ such that the following diagram commutes

$$\begin{array}{ccc}
A & \xrightarrow{j_1} & F(A) \\
\downarrow i_1 & & \downarrow f_1 \\
A \amalg B & \xrightarrow{\exists! \psi} & F(A) * F(B) \\
\uparrow i_2 & & \uparrow f_2 \\
B & \xrightarrow{j_1} & F(B)
\end{array}$$

That is,

$$\exists! \psi : A \amalg B \longrightarrow F(A) * F(B) \quad (\psi \circ i_1 = f_1 \circ j_1) \wedge (\psi \circ i_2 = f_2 \circ j_2).$$

Step 2. Prove the existence of g .

$$\begin{array}{ccc}
A & \xrightarrow{j_1} & F(A) \\
\downarrow i_1 & & \searrow \exists! \varphi_1 \\
A \amalg B & \xrightarrow{\theta} & G \\
\uparrow i_2 & & \nearrow \exists! \varphi_2 \\
B & \xrightarrow{j_1} & F(B)
\end{array}$$

Given some (θ, G) , according to the universal property of free groups $F(A)$, $F(B)$, we have

$$\begin{aligned}
\exists! \varphi_1 : F(A) &\longrightarrow G & (\varphi_1 \circ j_1 = \theta \circ i_1), \\
\exists! \varphi_2 : F(B) &\longrightarrow G & (\varphi_2 \circ j_2 = \theta \circ i_2).
\end{aligned}$$

$$\begin{array}{ccc}
F(A) & & \\
\downarrow f_1 & \searrow \varphi_1 & \\
F(A) * F(B) & \xrightarrow{\exists! g} & G \\
\uparrow f_2 & \nearrow \varphi_2 & \\
F(B) & &
\end{array}$$

Then according to the universal property of coproduct $F(A) * F(B)$ in \mathbf{Grp} , we have

$$\exists! g : F(A) * F(B) \longrightarrow G \quad (g \circ f_1 = \varphi_1) \wedge (g \circ f_2 = \varphi_2).$$

The commutative diagram tells us

$$\begin{aligned}
g \circ \psi \circ i_1 &= g \circ f_1 \circ j_1 = \varphi_1 \circ j_1 = \theta \circ i_1, \\
g \circ \psi \circ i_2 &= g \circ f_2 \circ j_2 = \varphi_2 \circ j_2 = \theta \circ i_2.
\end{aligned}$$

Note that $A \amalg B = i_1(A) \cup i_2(B)$. For all $x \in A \amalg B$, x must be either $i_1(a)$ or $i_2(b)$. If $x = i_1(a)$, then

$$g \circ \psi(x) = g \circ \psi \circ i_1(a) = \theta \circ i_1(a) = \theta(x).$$

If $x = i_2(b)$, then

$$g \circ \psi(x) = g \circ \psi \circ i_2(b) = \theta \circ i_2(b) = \theta(x).$$

Hence we show that given some (θ, G) there exists $g : F(A) * F(B) \longrightarrow G$ such that $g \circ \psi = \theta$.

Step 3. Prove the uniqueness of g .

Assume there exists another homomorphism h such that $h \circ \psi = \theta$. We have

$$h \circ f_1 \circ j_1 = h \circ \psi \circ i_1 = \theta \circ i_1,$$

$$h \circ f_2 \circ j_2 = h \circ \psi \circ i_2 = \theta \circ i_2.$$

Since

$$\exists! \varphi_1 : F(A) \longrightarrow G \quad (\varphi_1 \circ j_1 = \theta \circ i_1),$$

$$\exists! \varphi_2 : F(B) \longrightarrow G \quad (\varphi_2 \circ j_2 = \theta \circ i_2),$$

there must be

$$h \circ f_1 = \varphi_1,$$

$$h \circ f_2 = \varphi_2.$$

Again by universal property

$$\exists! g : F(A) * F(B) \longrightarrow G \quad (g \circ f_1 = \varphi_1) \wedge (g \circ f_2 = \varphi_2)$$

we get $h = g$, which implies g is unique.

Conclusion.

To sum up, we prove that there exists a unique group homomorphism g such that the first diagram in this proof commutes. As a result, we have $F(A \amalg B) = F(A) * F(B)$. Note that if **Grp** turns into **Ab**, the method of diagram chasing applied here also works. In the light of the following diagram, we can get $F^{ab}(A \amalg B) = F^{ab}(A) \oplus F^{ab}(B)$ step by step.

$$\begin{array}{ccccc}
 A & \xrightarrow{j_1} & F^{ab}(A) & & \\
 \downarrow i_1 & & \downarrow f_1 & \searrow \varphi_1 & \\
 A \amalg B & \xrightarrow{\psi} & F^{ab}(A) \oplus F^{ab}(B) & \xrightarrow{g} & G \\
 \uparrow i_2 & \searrow \theta & \uparrow f_2 & \swarrow \varphi_2 & \\
 B & \xrightarrow{j_2} & F^{ab}(B) & &
 \end{array}$$

■

5.9 Let $G = \mathbb{Z}^{\oplus \mathbb{N}}$. Prove that $G \times G \cong G$.

Define a function

$$\begin{aligned}\varphi : G \times G &\longrightarrow G \\ ((a_1, a_2, \dots), (b_1, b_2, \dots)) &\longmapsto (a_1, b_1, a_2, b_2, \dots)\end{aligned}$$

It is plain to check that φ is a homomorphism

$$\begin{aligned}&\varphi[((a_1, a_2, \dots), (b_1, b_2, \dots)) + ((a'_1, a'_2, \dots), (b'_1, b'_2, \dots))] \\ &= \varphi[((a_1 + a'_1, a_2 + a'_2, \dots), (b_1 + b'_1, b_2 + b'_2, \dots))] \\ &= (a_1 + a'_1, b_1 + b'_1, a_2 + a'_2, b_2 + b'_2, \dots) \\ &= (a_1, b_1, a_2, b_2, \dots) + (a'_1, b'_1, a'_2, b'_2, \dots) \\ &= \varphi[((a_1, a_2, \dots), (b_1, b_2, \dots))] + \varphi[((a'_1, a'_2, \dots), (b'_1, b'_2, \dots))].\end{aligned}$$

Since $\ker \varphi = \{(0, 0, \dots)\}$ and $\varphi(G \times G) = G$, we can conclude that φ is an isomorphism and accordingly $G \times G \cong G$. ■

5.10 ▮ Let $F = F^{ab}(A)$.

- Define an equivalence relation \sim on F by setting $f \sim f'$ if and only if $f - f' = 2g$ for some $g \in F$. Prove that F/\sim is a finite set if and only if A is finite, and in that case $|F/\sim| = 2^{|A|}$.
- Assume $F^{ab}(B) \cong F^{ab}(A)$. If A is finite, prove that so is B , and $A \cong B$ as sets. (This result holds for free groups as well, and without any finiteness hypothesis. See Exercises 7.13 and VI.1.20.)

[7.4, 7.13]

- If $|A| = \infty$, let $F = F^{ab}(A) = \mathbb{Z}^{\oplus A}$ and accordingly every element of $\mathbb{Z}^{\oplus A}$ can be written uniquely as a finite sum

$$\sum_{a \in A} m_a j(a), \quad m_a \neq 0 \text{ for only finitely many } a.$$

Apparently, the elements in $j(A) = \{j(a) \mid a \in A\}$ are not equivalent pairwise. Note that j is an injection. Hence we see

$$|F/\sim| \geq |j(A)| = A > \infty.$$

In other words, F/\sim is a finite set only if A is finite.

If $|A| = n < \infty$, we can set $F = F^{ab}(A) = \mathbb{Z}^{\oplus n}$. Assume $f = (a_1, a_2, \dots, a_n)$,

$f' = (a'_1, a'_2, \dots, a'_n)$. Then $f \sim f'$ if and only if $a_i - a'_i \in 2\mathbb{Z}$ ($i = 1, 2, \dots, n$). Let $[f]$ denote the equivalence class including f . Thus we get

$$F/\sim = \{[(k_1, k_2, \dots, k_n)] \mid k_i = 0 \text{ or } 1, i = 1, 2, \dots, n\}$$

and accordingly $|F/\sim| = 2^{|A|}$.

- Assume $\varphi : F^{ab}(A) \rightarrow F^{ab}(B)$ is a group isomorphism. Since for all $f, f' \in F^{ab}(A)$,

$$\begin{aligned} f \sim f' &\iff \exists g \in F^{ab}(A), f - f' = 2g \\ &\iff \exists \varphi(g) \in F^{ab}(B), \varphi(f) - \varphi(f') = 2\varphi(g) \\ &\iff \varphi(f) \sim \varphi(f') \end{aligned}$$

in **Set** we have

$$F^{ab}(A)/\sim \simeq F^{ab}(B)/\sim .$$

If A is finite, then $F^{ab}(A)/\sim$ is finite. Furthermore it follows that

$$|F^{ab}(A)/\sim| = |F^{ab}(B)/\sim| \implies 2^{|A|} = 2^{|B|} \implies |A| = |B|.$$

Hence we see B is finite and $A \cong B$ in **Set** .

■

§6. Subgroups

6.1 \neg (If you know about matrices.) The group of invertible $n \times n$ matrices with entries in \mathbb{R} is denoted $\mathrm{GL}_n(\mathbb{R})$ (Example 1.5). Similarly, $\mathrm{GL}_n(\mathbb{C})$ denotes the group of $n \times n$ invertible matrices with complex entries. Consider the following sets of matrices:

- $\mathrm{SL}_n(\mathbb{R}) = \{M \in \mathrm{GL}_n(\mathbb{R}) \mid \det(M) = 1\}$;
- $\mathrm{SL}_n(\mathbb{C}) = \{M \in \mathrm{GL}_n(\mathbb{C}) \mid \det(M) = 1\}$;
- $\mathrm{O}_n(\mathbb{R}) = \{M \in \mathrm{GL}_n(\mathbb{R}) \mid MM^t = M^t M = I_n\}$;
- $\mathrm{SO}_n(\mathbb{R}) = \{M \in \mathrm{O}_n(\mathbb{R}) \mid \det(M) = 1\}$;
- $\mathrm{U}_n(\mathbb{C}) = \{M \in \mathrm{GL}_n(\mathbb{C}) \mid MM^\dagger = M^\dagger M = I_n\}$;
- $\mathrm{SU}_n(\mathbb{C}) = \{M \in \mathrm{U}_n(\mathbb{C}) \mid \det(M) = 1\}$.

Here I_n stands for the $n \times n$ identity matrix, M^t is the transpose of M , M^\dagger is the conjugate transpose of M , and $\det(M)$ denotes the determinant of M . Find all possible inclusions among these sets, and prove that in every case the smaller set is a subgroup of the larger one.

These sets of matrices have compelling geometric interpretations: for example, $\mathrm{SO}^3(\mathbb{R})$ is the group of ‘rotations’ in \mathbb{R}^3 . [8.8, 9.1, III.1.4, VI.6.16]

The following diagram commutes, where all arrows are inclusions.

$$\begin{array}{ccc}
 \mathrm{GL}_n(\mathbb{R}) & \longrightarrow & \mathrm{GL}_n(\mathbb{C}) \\
 \uparrow & & \uparrow \\
 \mathrm{SL}_n(\mathbb{R}) & \longrightarrow & \mathrm{SL}_n(\mathbb{C}) \\
 \uparrow & & \uparrow \\
 \mathrm{O}_n(\mathbb{R}) & \longrightarrow & \mathrm{U}_n(\mathbb{C}) \\
 \uparrow & & \uparrow \\
 \mathrm{SO}_n(\mathbb{R}) & \longrightarrow & \mathrm{SU}_n(\mathbb{C})
 \end{array}$$

■

6.2 \neg Prove that the set of 2×2 matrices

$$\begin{pmatrix} a & b \\ 0 & d \end{pmatrix}$$

with a, b, d in \mathbb{C} and $ad \neq 0$ is a subgroup of $\mathrm{GL}_2(\mathbb{C})$. More generally, prove that the set of $n \times n$ complex matrices $(a_{ij})_{1 \leq i, j \leq n}$ with $a_{ij} = 0$ for $i > j$, and $a_{11} \cdots a_{nn} \neq 0$, is a subgroup of $\mathrm{GL}_n(\mathbb{C})$. (These matrices are called ‘upper triangular’, for evident reasons.) [IV.1.20]

Let A, B are $n \times n$ upper triangular matrices. If $i > j$,

$$(AB)_{ij} = \sum_{k=1}^n a_{ik}b_{kj} = \sum_{k=1}^{i-1} a_{ik}b_{kj} + \sum_{k=i}^n a_{ik}b_{kj} = \sum_{k=1}^{i-1} 0b_{kj} + \sum_{k=i}^n a_{ik}0 = 0,$$

which means the set of upper triangular matrices is closed with respect to the matrix multiplication. Thus it is a subgroup of $\text{GL}_n(\mathbb{C})$. \blacksquare

6.3 \neg Prove that every matrix in $\text{SU}_2(\mathbb{C})$ may be written in the form

$$\begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix}$$

where $a, b, c, d \in \mathbb{R}$ and $a^2 + b^2 + c^2 + d^2 = 1$. (Thus, $\text{SU}_2(\mathbb{C})$ may be realized as a three-dimensional sphere embedded in \mathbb{R}^4 ; in particular, it is simply connected.) [8.9, III.2.5]

Let

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \in \text{SU}_2(\mathbb{C})$$

and we have

$$AA^\dagger = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} \overline{a_{11}} & \overline{a_{21}} \\ \overline{a_{12}} & \overline{a_{22}} \end{pmatrix} = \begin{pmatrix} |a_{11}|^2 + |a_{12}|^2 & a_{11}\overline{a_{21}} + a_{12}\overline{a_{22}} \\ a_{21}\overline{a_{11}} + a_{22}\overline{a_{12}} & |a_{21}|^2 + |a_{22}|^2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

and

$$\det(A) = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21} = 1$$

Note

$$\begin{aligned} \overline{a_{11}a_{12}} &= \overline{a_{11}}\overline{a_{12}} \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = \begin{vmatrix} |a_{11}|^2 & |a_{12}|^2 \\ a_{21}\overline{a_{11}} & a_{22}\overline{a_{12}} \end{vmatrix} = \begin{vmatrix} |a_{11}|^2 & |a_{11}|^2 + |a_{12}|^2 \\ a_{21}\overline{a_{11}} & a_{21}\overline{a_{11}} + a_{22}\overline{a_{12}} \end{vmatrix} = \begin{vmatrix} |a_{11}|^2 & 1 \\ a_{21}\overline{a_{11}} & 0 \end{vmatrix} = -a_{21}\overline{a_{11}} \\ &\implies \overline{a_{11}}(\overline{a_{12}} + a_{21}) = 0, \end{aligned}$$

and

$$\begin{aligned} \overline{a_{21}a_{22}} &= \overline{a_{21}}\overline{a_{22}} \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = \begin{vmatrix} a_{11}\overline{a_{21}} & a_{12}\overline{a_{22}} \\ |a_{21}|^2 & |a_{22}|^2 \end{vmatrix} = \begin{vmatrix} a_{11}\overline{a_{21}} & a_{11}\overline{a_{21}} + a_{12}\overline{a_{22}} \\ |a_{21}|^2 & |a_{21}|^2 + |a_{22}|^2 \end{vmatrix} = \begin{vmatrix} a_{11}\overline{a_{21}} & 0 \\ |a_{21}|^2 & 1 \end{vmatrix} = a_{11}\overline{a_{21}} \\ &\implies \overline{a_{21}}(\overline{a_{11}} - a_{22}) = 0. \end{aligned}$$

If $\overline{a_{11}} \neq 0$, it must be $\overline{a_{12}} + a_{21} = 0$. If $\overline{a_{11}} = 0$, then $|a_{12}|^2 = 1$, $a_{12}\overline{a_{22}} = 0$ and accordingly $a_{22} = 0$. Since $-a_{12}a_{21} = 1 = a_{12}\overline{a_{12}}$, we also have $\overline{a_{12}} + a_{21} = 0$, that is $a_{12} = c + di$, $a_{21} = -c + di$. Likewise, we can show $\overline{a_{11}} - a_{22} = 0$ and $a_{11} = a + bi$, $a_{22} = a - bi$. And we have

$$|a_{11}|^2 + |a_{12}|^2 = a^2 + b^2 + c^2 + d^2 = 1.$$

■

6.4 Let G be a group, and $g \in G$. Verify that the image of the exponential map $\epsilon_g : \mathbb{Z} \rightarrow G$ is a cyclic group (in the sense of Definition 4.7).

If $|g| = \infty$, then $g^i \neq g^j (i \neq j)$. Define

$$\varphi : \mathbb{Z} \longrightarrow \epsilon_g(\mathbb{Z}), n \longmapsto g^n$$

and we can check it is an isomorphism.

If $|g| = k$, then $e_G, g, g^2, \dots, g^{k-1}$ are distinct. Define

$$\varphi : \mathbb{Z}/k\mathbb{Z} \longrightarrow \epsilon_g(\mathbb{Z}), [n]_k \longmapsto g^n$$

and we can check it is an isomorphism.

Since $\epsilon_g(\mathbb{Z})$ is isomorphic to \mathbb{Z} or $\mathbb{Z}/k\mathbb{Z}$, we show $\epsilon_g(\mathbb{Z})$ is a cyclic group. ■

6.6 Prove that the union of a family of subgroups of a group G is not necessarily a subgroup of G . In fact:

- Let H, H' be subgroups of a group G . Prove that $H \cup H'$ is a subgroup of G only if $H \subseteq H'$ or $H' \subseteq H$.
- On the other hand, let $H_0 \subseteq H_1 \subseteq H_2 \subseteq \dots$ be subgroups of a group G . Prove that $\cup_{i \geq 0} H_i$ is a subgroup of G .

- Let $H \cup H'$ be a subgroup of G . Suppose neither $H \subseteq H'$ nor $H' \subseteq H$ hold. Let $a \in H - H', b \in H' - H, h = ab^{-1} \in H \cup H'$. In the case of $h \in H$, we have $b = h^{-1}a \in H$, contradiction! In the case of $h \in H'$, we have $a = hb \in H'$, contradiction again! Therefore, there must be $H \subseteq H'$ or $H' \subseteq H$.
- For all $a, b \in \cup_{i \geq 0} H_i$, we can suppose $a \in H_j, b \in H_k$ and we have $a, b \in H_{\max\{j,k\}}$. Then $ab \in H_{\max\{j,k\}} \subseteq \cup_{i \geq 0} H_i$, implies that $\cup_{i \geq 0} H_i$ is closed and that $\cup_{i \geq 0} H_i$ is a subgroup of G . ■

6.7 \neg Show that inner automorphisms (cf. [Exercise II.4.8](#)) form a subgroup of $\text{Aut}(G)$; this subgroup is denoted $\text{Inn}(G)$. Prove that $\text{Inn}(G)$ is cyclic if and only if $\text{Inn}(G)$ is trivial if and only if G is abelian. (Hint: Assume that $\text{Inn}(G)$ is cyclic; with notation as in Exercise 4.8, this means that there exists an element $a \in G$ such that $\forall g \in G \exists n \in \mathbb{Z} \gamma_g = \gamma_a^n$. In particular, $gag^{-1} = a^n aa^{-n} = a$. Thus a commutes with every g in G . Therefore...) Deduce that if $\text{Aut}(G)$ is cyclic then G is abelian. [7.10, IV.1.5]

With notation as in Exercise 4.8, we assume $\gamma_g \in \text{Inn}(G)$ is defined by

$$\forall h \in G \quad (\gamma_g(h) = ghg^{-1}).$$

We have

$$\begin{aligned} & \text{Inn}(G) \text{ is cyclic} \\ \iff & \exists \gamma_a \in \text{Inn}(G), \text{Inn}(G) = \langle \gamma_a \rangle \\ \iff & \exists a \in G \forall g \in G \exists n \in \mathbb{Z} (\gamma_g = \gamma_a^n) \\ \implies & \exists a \in G \forall g \in G \exists n \in \mathbb{Z} (\gamma_g(a) = gag^{-1} = \gamma_a^n(a) = a^n aa^{-n} = a) \\ \implies & \exists a \in G \forall g \in G (ga = ag) \\ \implies & \forall h \in G, \gamma_a(h) = aha^{-1} = haa^{-1} = h \\ \implies & \text{Inn}(G) = \langle \text{id} \rangle \\ \implies & \text{Inn}(G) \text{ is trivial} \end{aligned}$$

$$\begin{aligned} & \text{Inn}(G) \text{ is trivial} \\ \implies & \forall g \in G \forall h \in G (\gamma_g(h) = ghg^{-1} = h) \\ \implies & \forall g \in G \forall h \in G (gh = hg) \\ \iff & G \text{ is abelian} \end{aligned}$$

$$\begin{aligned} & G \text{ is abelian} \\ \implies & \forall g \in G \forall h \in G (\gamma_g(h) = ghg^{-1} = h) \\ \implies & \text{Inn}(G) = \{\text{id}\} \\ \implies & \text{Inn}(G) \text{ is cyclic} \end{aligned}$$

If $\text{Aut}(G)$ is cyclic, its subgroup $\text{Inn}(G)$ is also cyclic. As we have shown, that means G is abelian. ■

6.8 Prove that an abelian group G is finitely generated if and only if there is a surjective homomorphism

$$\underbrace{\mathbb{Z} \oplus \cdots \oplus \mathbb{Z}}_{n \text{ times}} \twoheadrightarrow G$$

for some n .

Given any set $H \subseteq G$, there exists a unique homomorphism φ_H such that the following diagram commutes.

$$\begin{array}{ccc} F^{ab}(H) & \xrightarrow{\exists! \varphi} & G \\ j \uparrow & \nearrow i & \\ H & & \end{array}$$

The homomorphism image $\varphi_H(F^{ab}(H)) \leq G$ is called the subgroup generated by H in G , denoted by $\langle H \rangle$.

If G is finitely generated, there is a finite subset $G_n \subseteq G$ with n elements such that $\varphi_H(F^{ab}(G_n)) = \varphi_H(\mathbb{Z}^{\oplus n}) = G$. And φ_H is exactly the surjective homomorphism that we need.

If there is a surjective homomorphism $\psi : \mathbb{Z}^{\oplus n} \twoheadrightarrow G$ for some n . Suppose

$$\psi : \mathbf{1}_i = (0, \dots, 0, \underset{i\text{-th place}}{1}, 0, \dots, 0) \mapsto g_i$$

and $G_n = \{g_1, g_2, \dots, g_n\}$. Then define

$$j : G_n \longrightarrow \mathbb{Z}^{\oplus n}, \quad g_i \longmapsto \mathbf{1}_i.$$

We can check the following diagram commutes

$$\begin{array}{ccc} \mathbb{Z}^{\oplus n} & \xrightarrow{\psi} & G \\ j \uparrow & \nearrow i & \\ G_n & & \end{array}$$

which means $\langle G_n \rangle = \psi(\mathbb{Z}^{\oplus n})$. Since ψ is surjective, we have $\langle G_n \rangle = G$. Hence we show G is finitely generated. ■

6.9 Prove that every finitely generated subgroup of \mathbb{Q} is cyclic. Prove that \mathbb{Q} is not finitely generated.

Given any two rationals

$$\begin{aligned} a_1 &= \frac{p_1}{q_1} \in \mathbb{Q}, (p_1, q_1) = 1, \\ a_2 &= \frac{p_2}{q_2} \in \mathbb{Q}, (p_2, q_2) = 1, \end{aligned}$$

there exists $r = \frac{1}{q_1 q_2} \in \mathbb{Q}$ such that $\langle a_1, a_2 \rangle \leq \langle r_1 \rangle$. Then for some a_3 we have $\langle a_1, a_2, a_3 \rangle \leq \langle r_1, a_3 \rangle \leq \langle r_2 \rangle$. In general, let's set $B_n = \{a_1, a_2, \dots, a_n\}$. If $\langle B_n \rangle \leq \langle r_{n-1} \rangle$. we have $\langle B_{n+1} \rangle = \langle B_n, a_{n+1} \rangle \leq \langle r_{n-1}, a_{n+1} \rangle \leq \langle r_n \rangle$. By induction we can prove $\langle a_1, a_2, \dots, a_n \rangle \leq \langle r_{n-1} \rangle$ for $n \in \mathbb{N}_+$. Since the subgroups of a cyclic group are also cyclic, we see finitely generated subgroup $\langle a_1, a_2, \dots, a_n \rangle \leq \mathbb{Q}$ is cyclic.

Supposing \mathbb{Q} is finitely generated, \mathbb{Q} must be a cyclic group, which contradicts the fact. Thus we show \mathbb{Q} is not finitely generated. ■

6.10 \neg The set of 2×2 matrices with integer entries and determinant 1 is denoted $\text{SL}_2(\mathbb{Z})$:

$$\text{SL}_2(\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \text{ such that } a, b, c, d \in \mathbb{Z}, ad - bc = 1 \right\}.$$

Prove that $\text{SL}_2(\mathbb{Z})$ is generated by the matrices:

$$s = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad t = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}.$$

Let H be the subgroup generated by s and t . We can check that both

$$P = \begin{pmatrix} 1 & -p \\ 0 & 1 \end{pmatrix} = t^{-p} \quad \text{and} \quad Q = \begin{pmatrix} 1 & 0 \\ -q & 1 \end{pmatrix} = s^{-1}t^qs$$

are in H . Given an arbitrary matrix

$$m = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \text{SL}_2(\mathbb{Z}),$$

it suffices to show that we can obtain the identity I_2 by multiplying m by matrices in H . Note that

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & -p \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} a & b - pa \\ c & d - pc \end{pmatrix}, \quad \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -q & 1 \end{pmatrix} = \begin{pmatrix} a - qb & b \\ c - qd & d \end{pmatrix},$$

and c, d cannot be nonzero simultaneously. Without loss of generality, we can assume that $0 < c < d$ and perform Euclidean algorithm. Let $p_1 = \lfloor \frac{d}{c} \rfloor, d_1 = d - p_1c < c$. Multiplying m by $P_1 = \begin{pmatrix} 1 & -p_1 \\ 0 & 1 \end{pmatrix}$ on the right yields

$$m_1 = mP_1 \begin{pmatrix} a & b - p_1a \\ c & d_1 \end{pmatrix}.$$

Then let $q_1 = \lfloor \frac{c}{d_1} \rfloor, c_1 = c - q_1d_1 < d_1$ and right multiplying m by $Q_1 = \begin{pmatrix} 1 & 0 \\ -q_1 & 1 \end{pmatrix}$ yields

$$m_2 = mP_1Q_1 \begin{pmatrix} a - q_1(b - p_1a) & b - p_1a \\ c_1 & d_1 \end{pmatrix}.$$

We can repeat this procedure until some d_i or c_i reduce to 0. The Euclidean algorithm generates a sequence

$$d > c > d_1 > c_1 > d_2 > c_2 > \cdots.$$

If c_i, d_i never reduce to 0, we will get an infinite decreasing positive sequence, which is

impossible. Suppose d_N is the first number reducing to 0. Then

$$m_{2N-1} = mP_1Q_1 \cdots P_N = \begin{pmatrix} a_N & b_N \\ c_{N-1} & 0 \end{pmatrix} \in \text{SL}_2(\mathbb{Z}),$$

which implies

$$m_{2N-1} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

and $m_{2N-1}s^{-1} = I_2$. Suppose c_N is the first number reducing to 0. Then

$$m_{2N} = mP_1Q_1 \cdots P_NQ_N = \begin{pmatrix} a_N & b_N \\ 0 & d_N \end{pmatrix} \in \text{SL}_2(\mathbb{Z}),$$

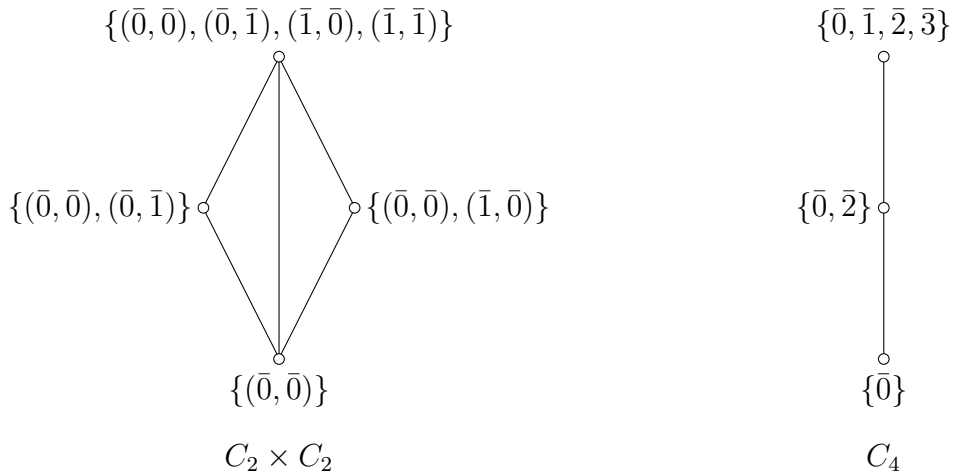
which implies

$$m_{2N} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = I_2.$$

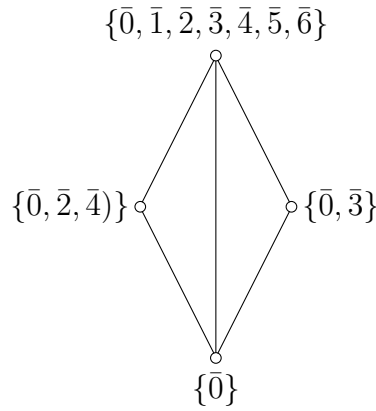
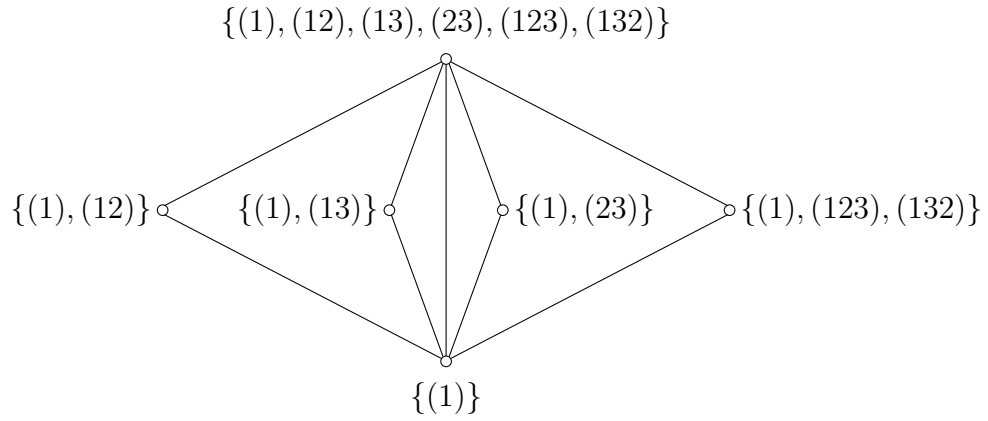
We have shown that we can obtain the identity I_2 by multiplying m by matrices in H , that is, m can be represented as a product of matrices in H . Thus we can conclude $\text{SL}_2(\mathbb{Z})$ is generated by s and t . ■

6.13 ▯ Draw and compare the lattices of subgroups of $C_2 \times C_2$ and C_4 . Draw the lattice of subgroups of S_3 , and compare it with the one for C_6 . [7.1]

Lattices of subgroups $C_2 \times C_2$ and C_4 are drawn as follows:



Lattices of subgroups S_3 and C_6 are drawn as follows:



■

§7. Quotient groups

7.1 ▷ List all subgroups of S_3 (cf. [Exercise II.6.13](#)) and determine which subgroups are normal and which are not normal. [§7.1]

The subgroups of S_3 are $\{(1)\}$, $\{(1), (12)\}$, $\{(1), (13)\}$, $\{(1), (23)\}$, $\{(1), (123), (132)\}$ and S_3 . We can check that $\{(1)\}$, $\{(1), (123), (132)\}$, S_3 are normal subgroups while others are not. ■

7.2 Is the image of a group homomorphism necessarily a normal subgroup of the target?

No. According to exercise 7.1 we have seen not all subgroups are normal. Suppose H is a subgroup of G but not normal. Then H itself is the image of the inclusion homomorphism $i : H \hookrightarrow G$, which makes a counterexample. ■

7.3 ▷ Verify that the equivalent conditions for normality given in §7.1 are indeed equivalent. [§7.1]

That a subgroup N of G is normal has four equivalent conditions:

- (i) $\forall g \in G, gNg^{-1} = N$;
- (ii) $\forall g \in G, gNg^{-1} \subseteq N$;
- (iii) $\forall g \in G, gN \subseteq Ng$;
- (iv) $\forall g \in G, gN = Ng$.

(i) \implies (ii) is straightforward.

(ii) \implies (iii). For any $g \in G$, the element $a \in gN$ can be written as $a = gn_1$ ($n_1 \in N$). Since $gn_1g^{-1} \in gNg^{-1} \subseteq N$, there exists an $n_2 \in N$ such that $gn_1g^{-1} = n_2$, which implies $gn_1 = n_2g \in Ng$. Thus we have $gN \subseteq Ng$.

(iii) \implies (iv). Given any $g \in G$, for all $n_1 \in N$, the element $g^{-1}n_1 \in g^{-1}N$ also belongs to Ng^{-1} , which implies that there exists $n_2 \in N$ such that $g^{-1}n_1 = n_2g^{-1}$, namely $n_1g = gn_2$. Thus we get $Ng \subseteq gN$ and accordingly $gN = Ng$.

(iv) \implies (i). For any $g \in G$, the element $b \in gNg^{-1}$ can be written as $a = gn_1g^{-1}$ ($n_1 \in N$). Since $gn_1 \in gN = Ng$, there exists an $n_2 \in N$ such that $gn_1 = n_2g$, which implies $gn_1g^{-1} = n_2 \in N$. Thus we have

$$\begin{aligned} & \forall g \in G, \quad gNg^{-1} \subseteq N \\ \implies & \forall g^{-1} \in G, \quad g^{-1}(gNg^{-1})g \subseteq gNg^{-1} \\ \implies & \forall g \in G, \quad N \subseteq gNg^{-1}. \end{aligned}$$

Hence we have $\forall g \in G, gNg^{-1} = N$. ■

7.4 Prove that the relation defined in [Exercise II.5.10](#) on a free abelian group $F = F^{ab}(A)$ is compatible with the group structure. Determine the quotient F/\sim as a better known group.

For all $f, f', h \in F$,

$$f \sim f' \iff f - f' = 2g, (g \in F) \implies (h + f) - (h + f') = 2g, (g \in F) \iff h + f \sim h + f'.$$

Since F is abelian, we see the relation \sim defined on a free abelian group $F = F^{ab}(A)$ is compatible with the group structure. By the notation of quotient group, we have

$$F/\sim = F/2F,$$

where $2F = \{2g \in F \mid g \in F\}$. ■

7.5 \neg Define an equivalence relation \sim on $\mathrm{SL}_2(\mathbb{Z})$ by letting $A \sim A' \iff A' = \pm A$. Prove that \sim is compatible with the group structure. The quotient $\mathrm{SL}_2(\mathbb{Z})/\sim$ is denoted $\mathrm{PSL}_2(\mathbb{Z})$, and is called the *modular group*; it would be a serious contender in a context for ‘the most important group in mathematics’, due to its role in algebraic geometry and number theory. Prove that $\mathrm{PSL}_2(\mathbb{Z})$ is generated by the (cosets of the) matrices

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}.$$

(You will not need to work very hard, if you use the result of [Exercise 6.10](#).) Note that the first has order 2 in $\mathrm{PSL}_2(\mathbb{Z})$, the second has order 3, and their product has infinite order. [9.14]

For all $A_1, A_2, B \in \mathrm{SL}_2(\mathbb{Z})$,

$$A_1 \sim A_2 \iff A_2 = \pm A_1 \iff BA_2 = \pm BA_1 \iff BA_1 \sim BA_2.$$

Hence \sim is compatible with the group structure and $\mathrm{PSL}_2(\mathbb{Z}) = \mathrm{SL}_2(\mathbb{Z})/\{I_2, -I_2\}$. In [Exercise 6.10](#) we have shown $\mathrm{SL}_2(\mathbb{Z})$ is generated by the matrices

$$s = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad t = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}.$$

It is clear that $\mathrm{SL}_2(\mathbb{Z})$ can also be generated by the matrices

$$s = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad \text{and} \quad ts = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix},$$

which implies $\mathrm{PSL}_2(\mathbb{Z})$ is generated by the cosets of the matrices s and ts . ■

7.6 Let G be a group, and let n be a positive integer. Consider the relation

$$a \sim b \iff (\exists g \in G) ab^{-1} = g^n.$$

- Show that in general \sim is not an equivalence relation.
- Prove that \sim is an equivalence relation if G is commutative, and determine the corresponding subgroup of G .

- Let G be the symmetric group S_4 and let $n = 2$. We can check that

$$\begin{aligned} (3\ 4)(2\ 3)^{-1} &= (2\ 4\ 3) = (2\ 3\ 4)^2 \implies (3\ 4) \sim (2\ 3) \\ (2\ 3)(1\ 2)^{-1} &= (1\ 3\ 2) = (1\ 2\ 3)^2 \implies (2\ 3) \sim (1\ 2) \end{aligned}$$

but $(3\ 4)(1\ 2)^{-1} = (1\ 2)(3\ 4)$ is not the square of any element in S_4 .

- Suppose that G is commutative. $aa^{-1} = e^n$ implies \sim is reflexive. Since

$$a \sim b \implies ab^{-1} = g^n \ (g \in G) \implies b^{-1}a = g^{-n} \ (g^{-1} \in G) \implies b \sim a,$$

\sim is symmetric. Since G is commutative, we have

$$\begin{aligned} a \sim b, b \sim c &\implies ab^{-1} = g_1^n, bc^{-1} = g_2^n \ (g_1, g_2 \in G) \\ &\implies ac^{-1} = ab^{-1}bc^{-1} = g_1^n g_2^n = (g_1 g_2)^n \ (g_1 g_2 \in G) \implies a \sim c, \end{aligned}$$

which means \sim is transitive. Thus we show that \sim is an equivalence relation. Since

$$a \sim b \implies ab^{-1} = g^n \implies ga(gb)^{-1} = (ag)(bg)^{-1} = g^n \implies ga \sim gb, ag \sim bg,$$

we see \sim is compatible with the group G and the equivalence class of the identity $H = \{g^n | g \in G\}$ is a subgroup of G . ■

7.7 Let G be a group, n a positive integer, and let $H \subseteq G$ be the subgroup generated by all elements of order n in G . Prove that H is normal.

For all $h \in H, g \in G$, we have

$$(ghg^{-1})^n = gh^n g^{-1} = gg^{-1} = e_G \implies ghg^{-1} \in H,$$

which means $gHg^{-1} \subseteq H$ for all $g \in G$. Thus we show that H is normal. ■

7.10 \neg Let G be a group, and $H \subseteq G$ a subgroup. With notation as in [Exercise II.6.7](#), show that H is normal in G if and only if $\forall \gamma \in \text{Inn}(G), \gamma(H) \subseteq H$. Conclude that if H is normal in G then there is an interesting homomorphism $\text{Inn}(G) \rightarrow \text{Aut}(H)$. [8.25]

Consistent with the notation as in [Exercise II.6.7](#), suppose

$$\gamma_g : G \longrightarrow G, \ h \longmapsto ghg^{-1}.$$

Then we have

$$\forall \gamma_g \in \text{Inn}(G), \gamma_g(H) \subseteq H \iff \forall g \in G, gHg^{-1} \subseteq H \iff H \text{ is normal in } G.$$

Thus we see that if H is normal in G , γ can be restricted to H so that $\gamma|_H : H \rightarrow H$ is an automorphism on H . Let

$$i : \text{Inn}(G) \longrightarrow \text{Aut}(H), \ \gamma \longmapsto \gamma|_H$$

and with the property of γ we have shown in [Exercise II.4.8](#), it is straightforward to check that

$$i(\gamma_{g_1} \gamma_{g_2}) = i(\gamma_{g_1 g_2}) = \gamma_{g_1 g_2}|_H = (\gamma_{g_1} \gamma_{g_2})|_H = \gamma_{g_1}|_H \gamma_{g_2}|_H = i(\gamma_{g_1}) i(\gamma_{g_2}).$$

That is, i is the interest homomorphism $\text{Inn}(G) \rightarrow \text{Aut}(H)$ that we expect. ■

7.11 ▷ Let G be a group, and let $[G, G]$ be the subgroup of G generated by all elements of the form $aba^{-1}b^{-1}$. (This is the commutator subgroup of G ; we will return to it in §IV.3.3.) Prove that $[G, G]$ is normal in G . (Hint: with notations in [Exercise II.4.8](#), $gaba^{-1}b^{-1}g^{-1} = \gamma_g(aba^{-1}b^{-1})$.) Prove that $[G, G]$ is normal in G . [7.12, §IV.3.3]

Since for all $g \in G$, $aba^{-1}b^{-1} \in [G, G]$, we have

$$gaba^{-1}b^{-1}g^{-1} = gag^{-1}gbg^{-1}ga^{-1}g^{-1}gb^{-1}g^{-1} = (gag^{-1})(gbg^{-1})(gag^{-1})^{-1}(gbg^{-1})^{-1} \in [G, G],$$

it follows that that $[G, G]$ is normal in G . Then we can show $[G, G]$ is normal in G by

$$[g_1][g_2] = [g_1g_2] = [g_1g_2(g_2^{-1}g_1^{-1}g_2g_1)] = [g_2g_1] = [g_2][g_1], \quad \forall [g_1], [g_2] \in [G, G].$$

■

7.12 ▷ Let $F = F(A)$ be a free group, and let $f : A \rightarrow G$ be a set-function from the set A to a commutative group G . Prove that f induces a unique homomorphism $F/[F, F] \rightarrow G$, where $[F, F]$ is the commutator subgroup of F defined in [Exercise II.7.11](#). (Use Theorem 7.12.) Conclude that $F/[F, F] \simeq F^{ab}(A)$. (Use Proposition I.5.4.) [§6.4, 7.13, VI.1.20]

By the universal property of free group, there exists a unique homomorphism $\varphi : F \rightarrow G$ such that $\forall a \in A$, $\varphi(j(a)) = f(a)$ where $j : A \rightarrow F(A)$ is a inclusion. Note that G is commutative, we have

$$\varphi(aba^{-1}b^{-1}) = \varphi(a)\varphi(b)\varphi(a)^{-1}\varphi(b)^{-1} = e_G,$$

which implies $[F, F] \subseteq \ker \varphi$. Theorem 7.12 indicates that there exists a unique group homomorphism $\tilde{\varphi} : F/[F, F] \rightarrow G$ so that $\tilde{\varphi} \circ \pi = \varphi$. Now we deduce that the diagram

$$\begin{array}{ccc} A & & \\ \downarrow j & \searrow f & \\ F & \xrightarrow{\exists! \varphi} & G \\ \downarrow \pi & \nearrow \exists! \tilde{\varphi} & \\ F/[F, F] & & \end{array}$$

commutes. For the diagram we see $\tilde{\varphi} \circ \pi \circ j = f$. Suppose there exists ψ such that $\psi \circ \pi \circ j = f$, which amounts to $(\psi \circ \pi) \circ j = \varphi \circ j$. By the uniqueness of φ we have $\psi \circ \pi = \varphi$. Then by the uniqueness of $\tilde{\varphi}$ we have $\psi = \tilde{\varphi}$. Thus we show that there exists unique $\tilde{\varphi}$ such that $\tilde{\varphi} \circ \pi \circ j = f$. According to the property of free abelian group, we can conclude that $F/[F, F] \simeq F^{ab}(A)$. ■

7.13 \neg Let A, B be sets, and $F(A), F(B)$ the corresponding free groups. Assume $F(A) \simeq F(B)$. If A is finite, prove that so is B , and $A \simeq B$. (Use [Exercise II.7.12](#) to upgrade [Exercise II.5.10](#).) [5.10, VI.1.20]

[Exercise II.7.12](#) tells us that the free abelian group generated by a set is merely determined by its free group, which means

$$F(A) \simeq F(B) \implies F(A)/[F(A), F(A)] \simeq F(B)/[F(B), F(B)] \implies F^{ab}(B) \cong F^{ab}(A).$$

Then under the auspices of the conclusion in [Exercise II.5.10](#) we complete the proof. ■

§8. Canonical decomposition and Lagrange's theorem

8.1 If a group H may be realized as a subgroup of two groups G_1 and G_2 , and

$$\frac{G_1}{H} \cong \frac{G_2}{H},$$

does it follow that $G_1 \cong G_2$. Give a proof or a counterexample.

A counterexample is given as follows. Take $H = C_3$, the cyclic group of order 3. Take $G_1 = D_6$ and $G_2 = C_6$, then one sees both G_1/H and G_2/H are C_2 . But obviously G_1 and G_2 are not isomorphic, one being abelian while the other is not. ■

8.2 \neg Extend Example 8.6 as follows. Suppose G is a group, and $H \subseteq G$ is a subgroup of index 2: that is, such that there are precisely two (say, left) cosets of H in G . Prove that H is normal in G . [9.11, IV.1.16]

Since $[G/H] = 2$, there must be $G/H = \{H, G - H\}$. For any $g \in G$:

- if $g \in H$, then $gH = Hg = H$;
- if $g \in G - H$, then $gH \neq H$ and $Hg \neq H$. Thus we have $gH = Hg = G - H$.

In either case $gH = Hg$ holds for all $g \in G$, which implies H is normal in G . ■

8.7 Let $(A|\mathcal{R})$, resp. $(A'|\mathcal{R}')$ be presentations for two groups G , resp. G' (cf. §8.2); we may assume that A, A' are disjoint. Prove that the group $G * G'$ presented by

$$(A \cup A' | \mathcal{R} \cup \mathcal{R}')$$

satisfies the universal property for the *coproduct* of G and G' in **Grp**. (Use the universal properties of both free groups and quotients to construct natural homomorphisms $G \rightarrow G * G'$, $G' \rightarrow G * G'$.) [§3.4, §8.2, 9.14].

Assume that $F(A)/R = (A|\mathcal{R})$, $F(A')/R' = (A'|\mathcal{R}')$, and $F(A \amalg A')/R'' = (A \cup A'|\mathcal{R} \cup \mathcal{R}')$.

$$\begin{array}{ccccc}
 & & G & & \\
 & \nearrow f & \uparrow \delta & \nwarrow f' & \\
 F(A)/R & \xrightarrow{\psi} & F(A \amalg A')/R'' & \xleftarrow{\psi'} & F(A')/R' \\
 \uparrow k & & \uparrow \pi & & \uparrow k' \\
 A & & F(A \amalg A') & & A' \\
 & \searrow i & \uparrow j & \swarrow i' & \\
 & & A \amalg A' & &
 \end{array}$$

According to [Lemma II.1](#), there exist unique ψ and ψ' such that

$$\psi \circ k = \pi \circ j \circ i, \quad \psi' \circ k' = \pi \circ j \circ i'.$$

Define

$$\begin{aligned}
 \delta : F(A \amalg A')/R'' &\longrightarrow G \\
 [\{a_1\} * \{a'_1\} * \cdots * \{a_n\} * \{a'_n\}] &\longmapsto f([\{a_1\}])f'([\{a'_1\}]) \cdots f([\{a_n\}])f'([\{a'_n\}]).
 \end{aligned}$$

where $*$ means the junction of words and $\{a_i\} = a_{i1} * a_{i2} * \cdots * a_{im_i}$, $a_{ij} \in A$ ($1 \leq i \leq n, 1 \leq j \leq m_i$) and $\{a'_i\} = a'_{i1} * a'_{i2} * \cdots * a'_{im'_i}$, $a'_{ij'} \in A$ ($1 \leq i \leq n, 1 \leq j' \leq m'_i$). It is routine to check that δ is a well-defined homomorphism such that

$$\delta \circ \psi = f, \quad \delta \circ \psi' = f'.$$

Then verify that if $\hat{\delta}$ is a homomorphism such that

$$\delta \circ \psi = f, \quad \delta \circ \psi' = f',$$

there must be $\hat{\delta} = \delta$. After these tasks are done, we can conclude that $F(A \amalg A')/R''$ satisfies the universal property of coproduct. ■

§9. Group actions

§10. Group objects in categories

Chapter III Chapter Rings and modules

§1. Definition of ring

1.1 ▷ Prove that if $0 = 1$ in a ring R , then R is a zero-ring. [§1.2]

For any x in the ring R , we have

$$1 \cdot x = x, \quad 0 \cdot x = 0.$$

Since $0 = 1$ we see that $x = 0$, which implies R is a ring with only one element 0. ■

1.2 \neg Let S be a set, and define operations on the power set $\mathcal{P}(S)$ of S by setting $\forall A, B \in \mathcal{P}(S)$

$$A + B := (A \cup B) \setminus (A \cap B) \quad , \quad A \cdot B = A \cap B$$

Prove that $(\mathcal{P}(S), +, \cdot)$ is a commutative ring. [2.3, 3.15]

First, we need to check that $(\mathcal{P}(S), +)$ is an abelian group:

- associativity:

$$\begin{aligned} & (A + B) + C \\ &= ((A \cup B) \setminus (A \cap B)) + C \\ &= ((A \cup B) \cap (A^C \cup B^C)) + C \\ &= (A \cap (A^C \cup B^C)) \cup (B \cap (A^C \cup B^C)) + C \\ &= (A \cap B^C) \cup (A^C \cap B) + C \\ &= (((A \cap B^C) \cup (A^C \cap B)) \cap C^C) \cup (((A \cap B^C) \cup (A^C \cap B))^C \cap C) \\ &= ((A \cap B^C \cap C^C) \cup (A^C \cap B \cap C^C)) \cup ((A^C \cup B) \cap (A \cup B^C) \cap C) \\ &= ((A \cap B^C \cap C^C) \cup (A^C \cap B \cap C^C)) \cup ((A^C \cap B^C) \cup (A \cap B) \cap C) \\ &= (A \cap B^C \cap C^C) \cup (A^C \cap B \cap C^C) \cup (A^C \cap B^C \cap C) \cup (A \cap B \cap C) \\ &= (A \cap (B \cap C) \cup (B^C \cap C^C)) \cup ((A^C \cap B \cap C^C) \cup (A^C \cap B^C \cap C)) \\ &= (A \cap (B^C \cup C) \cap (B \cup C^C)) \cup ((A^C \cap B \cap C^C) \cup (A^C \cap B^C \cap C)) \\ &= (A \cap ((B \cap C^C) \cup (B^C \cap C))^C) \cup (A^C \cap ((B \cap C^C) \cup (B^C \cap C))) \\ &= A + ((B \cap C^C) \cup (B^C \cap C)) \\ &= A + (B + C); \end{aligned}$$

- commutativity:

$$A + B = (A \cup B) \setminus (A \cap B) = (B \cup A) \setminus (B \cap A) = B + A;$$

- additive identity: the additive identity is \emptyset since

$$A + \emptyset = (A \cup \emptyset) \setminus (A \cap \emptyset) = A; \quad \emptyset + A = \emptyset \cup A = A$$

- inverse: the inverse of some set A is just itself since

$$A + A = (A \cup A) \setminus (A \cap A) = A \setminus A = \emptyset.$$

Then we have to show that $(\mathcal{P}(S), \cdot)$ is a commutative monoid, which clearly holds with the multiplicative identity S . What is left to show is the distributive properties and the check is straightforward.

$$\begin{aligned}
& (A + B) \cdot C \\
&= ((A \cap B^C) \cup (A^C \cap B)) \cap C \\
&= (A \cap B^C \cap C) \cup (A^C \cap B \cap C) \\
&= (A \cap C \cap (B^C \cup C^C)) \cup ((A^C \cup C^C) \cap (B \cap C)) \\
&= (A \cap C \cap (B \cap C)^C) \cup ((A \cap C)^C \cap (B \cap C)) \\
&= A \cdot C + B \cdot C.
\end{aligned}$$

■

1.3 \neg Let R be a ring, and let S be any set. Explain how to endow the set R^S of set-functions $S \rightarrow R$ of two operations $+$, \cdot so as to make R^S into a ring, such that R^S is just a copy of R if S is a singleton. [2.3]

To make $(R^S, +, \cdot)$ a ring, for all $f, g \in R^S$ we define addition and multiplication as

$$\begin{aligned}
f + g : S &\longrightarrow R, & x &\longmapsto f(x) + g(x) \\
f \cdot g : S &\longrightarrow R, & x &\longmapsto f(x) \cdot g(x).
\end{aligned}$$

■

1.4 \triangleright The set of $n \times n$ matrices with entries in a ring R is denoted $\mathcal{M}_n(R)$. Prove that componentwise addition and matrix multiplication makes $\mathcal{M}_n(R)$ into a ring, for any ring R . The notation $\mathfrak{gl}_n(R)$ is also commonly used, especially $R = \mathbb{R}$ or \mathbb{C} (although this indicates one is considering them as *Lie algebras*) in parallel with the analogous notation for the corresponding groups of units, cf. [Exercise II.6.1](#). In fact, the parallel continues with the definition of the following sets of matrices:

- $\mathfrak{sl}_n(\mathbb{R}) = \{M \in \mathfrak{gl}_n(\mathbb{R}) \mid \text{tr}(M) = 0\};$
- $\mathfrak{sl}_n(\mathbb{C}) = \{M \in \mathfrak{gl}_n(\mathbb{C}) \mid \text{tr}(M) = 0\};$
- $\mathfrak{so}_n(\mathbb{R}) = \{M \in \mathfrak{sl}_n(\mathbb{R}) \mid M + M^t = 0\};$
- $\mathfrak{su}_n(\mathbb{C}) = \{M \in \mathfrak{sl}_n(\mathbb{C}) \mid M + M^\dagger = 0\}.$

Here $\text{tr}(M)$ is the trace of M , that is, the sum of its diagonal entries. The other notation matches the notation used in [Exercise II.6.1](#). Can we make rings of these sets, by endowing them of ordinary addition and multiplication of matrices? (These sets are all Lie algebras, cf. [Exercise VI.1.4](#).) [§1.2, 2.4, 5.9, VI.1.2, VI.1.4]

It is plain to show $\mathcal{M}_n(R)$ is a ring according to the definition. For multiplicative associativity, it follows that for all $A, B, C \in \mathcal{M}_n(R)$,

$$\begin{aligned}
& ((AB)C)_{\alpha,\delta} \\
&= \sum_{i=1}^n (AB)_{\alpha,i} c_{i,\delta} \\
&= \sum_{i=1}^n \left(\sum_{j=1}^n a_{\alpha,j} b_{j,i} \right) c_{i,\delta} \\
&= \sum_{i=1}^n \sum_{j=1}^n (a_{\alpha,j} b_{j,i}) c_{i,\delta} \\
&= \sum_{j=1}^n \sum_{i=1}^n a_{\alpha,j} (b_{j,i} c_{i,\delta}) \\
&= \sum_{j=1}^n a_{\alpha,j} \left(\sum_{i=1}^n b_{j,i} c_{i,\delta} \right) \\
&= \sum_{j=1}^n a_{\alpha,j} (BC)_{j,\delta} \\
&= (A(BC))_{\alpha,\delta}.
\end{aligned}$$

Under the ordinary addition and multiplication of matrices, $\mathfrak{sl}_n(\mathbb{R})$, $\mathfrak{sl}_n(\mathbb{C})$, $\mathfrak{so}_n(\mathbb{R})$, $\mathfrak{su}_n(\mathbb{C})$ are not rings. In fact, they are not closed under the multiplication. ■

1.5 Let R be a ring. If a, b are zero-divisors in R , is $a + b$ necessarily a zero-divisor?

That is not true. Let's take $\mathbb{Z}/6\mathbb{Z}$ as an counterexample. Though both $[2]_6$ and $[3]_6$ are zero-divisors, their sum $[5]_6$ is not a zero-divisor. ■

1.6 \neg An element a of a ring R is *nilpotent* if $a^n = 0$ for some n .

1. Prove that if a and b are nilpotent in R and $ab = ba$, then $a + b$ is also nilpotent.
2. Is the hypothesis $ab = ba$ in the previous statement necessary for its conclusion to hold?

[3.12]

1. Assume that $a^n = b^m = 0$ and let $k = 2 \max\{n, m\}$. If $ab = ba$, we can get

$$(a+b)^k = \sum_{p=0}^{\frac{k}{2}} \binom{k}{p} a^k b^{k-p} + \sum_{p=\frac{k}{2}+1}^k \binom{k}{p} a^k b^{k-p} = \sum_{p=0}^{\frac{k}{2}} \binom{k}{p} a^k \cdot 0 + \sum_{p=\frac{k}{2}+1}^k \binom{k}{p} 0 \cdot b^{k-p} = 0,$$

which means $a + b$ is also nilpotent.

2. The hypothesis $ab = ba$ is necessary. A counterexample can be found in the ring $\mathfrak{gl}_2(\mathbb{R})$. Let

$$a = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad b = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

and then we have $a^2 = b^2 = 0$. In other words, a and b are nilpotent. However, by diagonalization we see that

$$(a + b)^n = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}^n = \begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}^n \begin{pmatrix} -1 & 1 \\ 1 & 1 \end{pmatrix}^{-1} \neq \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

Thus in such case, $a + b$ is no longer nilpotent. ■

1.8 Prove that $x = \pm 1$ are the only solutions to the equation $x^2 = 1$ in an integral domain. Find a ring in which the equation $x^2 = 1$ has more than 2 solutions.

It clearly holds that $1 \cdot 1 = 1$ and $(-1) \cdot (-1) = ((-1) \times (-1))1 \cdot 1 = 1$. That is to say, $x = \pm 1$ are the solutions to the equation $x^2 = 1$. Note that if there exists x in an integral domain such that $x^2 = 1$, then we have

$$(x - 1) \cdot (x + 1) = x^2 - 1 = 0,$$

which implies $x - 1 = 0$ or $x + 1 = 0$. Therefore, we can assert $x = \pm 1$ are the solutions. In the ring $\mathbb{Z}/8\mathbb{Z}$, $[3]_8$ and $[5]_8$ are also the solutions to the equation $x^2 = 1$. ■

1.10 Let R be a ring. Prove that if $a \in R$ is a right unit, and has two or more left-inverses, then a is not a left-zero-divisor, and is a right-zero-divisor.

Since $a \in R$ is a right unit, it cannot be a left-zero-divisor. Assume there exist two distinct elements $x, y \in R$ such that $xa = ya = 1$ and it deduces $(y - x)a = 0$. Thus we show that a is a right-zero-divisor. ■

1.11 Construct a field with 4 elements: as mentioned in the text, the underlying abelian group will have to be $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$; $(0, 0)$ will be the zero element, and $(1, 1)$ will be the multiplicative identity. The question is what $(0, 1) \cdot (0, 1)$, $(0, 1) \cdot (1, 0)$, $(1, 0) \cdot (1, 0)$ must be, in order to get a field. [§1.2, §V.5.1]

Define

$$(0, 1) \cdot (0, 1) = (0, 1), \quad (0, 1) \cdot (1, 0) = (0, 0), \quad (1, 0) \cdot (1, 0) = (1, 0),$$

and the the rest definition of multiplication will be determined uniquely according to field properties. For example, we have no alternatives but to define

$$(0, 1) \cdot (1, 1) = (0, 1) \cdot ((0, 1) + (1, 0)) = (0, 1) \cdot (0, 1) + (0, 1) \cdot (1, 0) = (0, 1) + (0, 0) = (0, 1).$$

Then we can check $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ forms a field by definition. ■

1.12 Just as complex numbers may be viewed as combinations $a + bi$, where $a, b \in \mathbb{R}$, and i satisfies the relation $i^2 = -1$ (and commutes with \mathbb{R}), we may construct a ring \mathbb{H} by considering linear combinations $a + bi + cj + dk$ where $a, b, c, d \in \mathbb{R}$, and i, j, k commute with \mathbb{R} and satisfy the following relations:

$$i^2 = j^2 = k^2 = -1 \quad , \quad ij = -ji = k \quad , \quad jk = -kj = i \quad , \quad ki = -ik = j.$$

Addition in \mathbb{H} is defined componentwise, while multiplication is defined by imposing distributivity and applying the relations. For example,

$$(1 + i + j) \cdot (2 + k) = 1 \cdot 2 + i \cdot 2 + j \cdot 2 + 1 \cdot k + i \cdot k + j \cdot k = 2 + 2i + 2j + k - j + i = 2 + 3i + j + k.$$

- (i) Verify that this prescription does indeed define a ring.
- (ii) Compute $(a + bi + cj + dk)(a - bi - cj - dk)$, where $a, b, c, d \in \mathbb{R}$.
- (iii) Prove that \mathbb{H} is a division ring. Elements of \mathbb{H} are called quaternions. Note that $Q_8 := \{\pm 1, \pm i, \pm j, \pm k\}$ forms a subgroup of the group of units of \mathbb{H} ; it is a noncommutative group of order 8, called the quaternionic group.
- (iv) List all subgroups of Q_8 , and prove that they are all normal.
- (v) Prove that Q_8, D_8 are not isomorphic.
- (vi) Prove that Q_8 admits the presentation $(x, y | x^2y^{-2}, y^4, xyx^{-1}y)$.

[§II.7.1, 2.4, IV.1.12, IV.5.16, IV.5.17, V.6.19]

- (i) Verifying the $(\mathbb{H}, +)$ is an abelian group is immediate and we just omitted it. It is easy to see the multiplicative identity is 1 and the distributive properties are guaranteed by definition. The check of the associativity of multiplication looks straightforward but tedious.

$$\begin{aligned} & ((a_1 + b_1i + c_1j + d_1k) \cdot (a_2 + b_2i + c_2j + d_2k)) \cdot (a_3 + b_3i + c_3j + d_3k) \\ &= [-c_3(a_2c_1 + a_1c_2 + b_2d_1 - b_1d_2) - b_3(a_2b_1 + a_1b_2 - c_2d_1 + c_1d_2) \\ &\quad + a_3(a_1a_2 - b_1b_2 - c_1c_2 - d_1d_2) - d_3(-b_2c_1 + b_1c_2 + a_2d_1 + a_1d_2)] \\ &\quad + [-c_3(-b_2c_1 + b_1c_2 + a_2d_1 + a_1d_2) + a_3(a_2b_1 + a_1b_2 - c_2d_1 + c_1d_2) \\ &\quad + b_3(a_1a_2 - b_1b_2 - c_1c_2 - d_1d_2) + d_3(a_2c_1 + a_1c_2 + b_2d_1 - b_1d_2)]i \\ &\quad + [b_3(-b_2c_1 + b_1c_2 + a_2d_1 + a_1d_2) + a_3(a_2c_1 + a_1c_2 + b_2d_1 - b_1d_2) \\ &\quad + c_3(a_1a_2 - b_1b_2 - c_1c_2 - d_1d_2) - d_3(a_2b_1 + a_1b_2 - c_2d_1 + c_1d_2)]j \\ &\quad + [a_3(-b_2c_1 + b_1c_2 + a_2d_1 + a_1d_2) - b_3(a_2c_1 + a_1c_2 + b_2d_1 - b_1d_2) \\ &\quad + c_3(a_2b_1 + a_1b_2 - c_2d_1 + c_1d_2) + d_3(a_1a_2 - b_1b_2 - c_1c_2 - d_1d_2)]k \end{aligned}$$

$$\begin{aligned}
& (a_1 + b_1i + c_1j + d_1k) \cdot ((a_2 + b_2i + c_2j + d_2k) \cdot (a_3 + b_3i + c_3j + d_3k)) \\
&= [-d_1(a_3d_2 + a_2d_3 - b_3c_2 + b_2c_3) - c_1(a_3c_2 + a_2c_3 + b_3d_2 - b_2d_3) \\
&\quad - b_1(a_3b_2 + a_2b_3 - c_3d_2 + c_2d_3) + a_1(a_2a_3 - b_2b_3 - c_2c_3 - d_2d_3)] \\
&\quad + [c_1(a_3d_2 + a_2d_3 - b_3c_2 + b_2c_3) - d_1(a_3c_2 + a_2c_3 + b_3d_2 - b_2d_3) \\
&\quad + a_1(a_3b_2 + a_2b_3 - c_3d_2 + c_2d_3) + b_1(a_2a_3 - b_2b_3 - c_2c_3 - d_2d_3)]i \\
&\quad + [-b_1(a_3d_2 + a_2d_3 - b_3c_2 + b_2c_3) + a_1(a_3c_2 + a_2c_3 + b_3d_2 - b_2d_3) \\
&\quad + d_1(a_3b_2 + a_2b_3 - c_3d_2 + c_2d_3) + c_1(a_2a_3 - b_2b_3 - c_2c_3 - d_2d_3)]j \\
&\quad + [a_1(a_3d_2 + a_2d_3 - b_3c_2 + b_2c_3) + b_1(a_3c_2 + a_2c_3 + b_3d_2 - b_2d_3) \\
&\quad - c_1(a_3b_2 + a_2b_3 - c_3d_2 + c_2d_3) + d_1(a_2a_3 - b_2b_3 - c_2c_3 - d_2d_3)]k
\end{aligned}$$

(ii) Expand it by distributive properties and we get

$$\begin{aligned}
& (a + bi + cj + dk)(a - bi - cj - dk) \\
&= a^2 - abi - acj - adk + abi + b^2 - bck + bdj + acj + bck + c^2 - cdi + adk - bdj + cdi + d^2 \\
&= a^2 + b^2 + c^2 + d^2.
\end{aligned}$$

(iii) Applying the results in (ii) we see that for any non-zero element $a + bi + cj + dk \in \mathbb{H}$,

$$(a + bi + cj + dk) \cdot \frac{a - bi - cj - dk}{a^2 + b^2 + c^2 + d^2} = \frac{a - bi - cj - dk}{a^2 + b^2 + c^2 + d^2} \cdot (a + bi + cj + dk) = 1,$$

which implies $a + bi + cj + dk$ is a two-sided unit. Thus we show that \mathbb{H} is a division ring.

- (iv) Q_8 has 6 subgroups: $\{1\}$, $\{1, -1\}$, $\{1, -1, i, -i\}$, $\{1, -1, j, -j\}$, $\{1, -1, k, -k\}$, Q_8 . We can just prove that they are all normal by the definition of normal subgroups.
- (v) Note that $D_8 = \{e, r, r^2, r^3, s_1, s_2, s_3, s_4\}$ has 7 subgroups: $\{e\}$, $\{e, r, r^2, r^3\}$, $\{e, s_1\}$, $\{e, s_2\}$, $\{e, s_3\}$, $\{e, s_4\}$, D_8 , while Q_8 has 6 subgroups. Thus Q_8, D_8 are not isomorphic.
- (vi) Let $P = (x, y | x^2y^{-2}, y^4, xyx^{-1}y)$. The relation $x^2y^{-2} = e$ implies $x^2 = y^2$ and the relation $xyx^{-1}y = e$ implies $yx = yx^{-1}x^2 = x^{-1}y^{-1}x^2 = x^3y^3x^2 = x^3y^5 = x^3y$. First, we can always replace yx by x^3y until we obtain a word of the form $x^i y^j$. Then applying $x^4 = y^4 = e$ and replace y^2 by x^2 , we can transform it into the form $x^i y^j$ with $0 \leq i \leq 3$ and $0 \leq j \leq 1$. Thus we see P has at most 8 elements.

Next we will complete our proof by means of the [Lemma II.1](#) in the appendix. Define a mapping

$$\begin{aligned}
f : \{x, y\} &\longrightarrow Q_8, & x &\longmapsto i, \\
& & y &\longmapsto j.
\end{aligned}$$

Let $\varphi : F(\{x, y\}) \rightarrow Q_8$ be the unique homomorphism induced by the universal property of free group. Since

$$\begin{aligned}\varphi(x^2y^{-2}) &= i^2j^{-2} = 1, \\ \varphi(y^4) &= j^4 = 1, \\ \varphi(xyx^{-1}y) &= iji^{-1}j = 1,\end{aligned}$$

we see $\mathcal{R} = \{x^2y^{-2}, y^4, xyx^{-1}y\} \subset \ker \varphi$. And it is immediate to show that Q_8 can be generated by $\{i, j\}$. Thus according to the lemma, there exists a unique homomorphism $\psi : P \rightarrow Q_8$ such that $f = \psi \circ \pi \circ i$ and actually ψ is surjective.

$$\begin{array}{ccc} & P & \\ \pi \uparrow & \searrow \exists! \psi & \\ F(\{x, y\}) & \xrightarrow{\varphi} & Q_8 \\ i \uparrow & \nearrow f & \\ \{x, y\} & & \end{array}$$

Hence we get the inequality of cardinality $|P| \geq |Q_8|$. Since we have shown $|P| \leq 8 = |Q_8|$, there must be $|P| = |Q_8| = 8$, which implies ψ is indeed an isomorphism. Finally we conclude that $Q_8 \cong (x, y | x^2y^{-2}, y^4, xyx^{-1}y)$ and complete our proof. ■

1.14 ▷ Let R be a ring, and let $f(x), g(x) \in R[x]$ be nonzero polynomials. Prove that

$$\deg(f(x) + g(x)) \leq \max(\deg(f(x)), \deg(g(x))).$$

Assuming that R is an integral domain, prove that

$$\deg(f(x) \cdot g(x)) = \deg(f(x)) + \deg(g(x)).$$

[§1.3]

Assume

$$f(x) = \sum_{i \geq 0} a_i x^i, \quad g(x) = \sum_{i \geq 0} b_i x^i, \quad a_i, b_i \in R$$

and n, m are respectively the largest integers p, q for which a_p, b_q are non-zero. In others words, we have $a_n \neq 0, a_i = 0$ for $i > n$ and $b_m \neq 0, b_i = 0$ for $i > m$. Since

$$f(x) + g(x) = \sum_{i \geq 0} (a_i + b_i) x^i = \sum_{i=0}^{\max\{n, m\}} (a_i + b_i) x^i,$$

we see that

$$\deg(f(x) + g(x)) \leq \max\{n, m\} = \max(\deg(f(x)), \deg(g(x))).$$

Now Suppose that R is an integral domain. Noticing $a_n \neq 0$ and $b_m \neq 0$ implies $a_n b_m \neq 0$, we can see

$$f(x) \cdot g(x) = \sum_{k \geq 0} \sum_{i+j=k} a_i b_j x^{i+j} = \sum_{k=0}^{n+m} \sum_{i+j=k} a_i b_j x^{i+j}$$

has a degree of $n + m$. That is,

$$\deg(f(x) \cdot g(x)) = \deg(f(x)) + \deg(g(x)).$$

■

1.15 ▷ Prove that $R[x]$ is an integral domain if and only if R is an integral domain. [§1.3]

Assume R is an integral domain. [Exercise III.1.14](#) tells us if $f(x), g(x) \in R[x]$ are nonzero polynomials, we have

$$\deg(f(x) \cdot g(x)) = \deg(f(x)) + \deg(g(x)),$$

which implies $f(x) \cdot g(x)$ is also nonzero polynomial. Thus we show $R[x]$ is a integral domain.

Conversely, assume $R[x]$ is an integral domain. Note that given any $a, b \in R$, they also belong to $R[x]$. Hence we obtain

$$a \neq 0, b \neq 0 \implies ab \neq 0,$$

which means R is an integral domain.

■

1.16 Let R be a ring, and consider the ring of power series $R[[x]]$ (cf. §1.3).

1. Prove that a power series $a_0 + a_1x + a_2x^2 + \cdots$ is a unit in $R[[x]]$ if and only if a_0 is a unit in R . What is the inverse of $1 - x$ in $R[[x]]$?
2. Prove that $R[[x]]$ is an integral domain if and only if R is.

1. If a_0 is a unit in R then we can assume there exists $b_0 \in R$ such that $a_0 b_0 = 1$. Let

$$f(x) = \sum_{n \geq 0} a_n x^n, \quad g(x) = \sum_{n \geq 0} b_n x^n,$$

where

$$b_n = -b_0 \sum_{i=1}^n a_i b_{n-i}, \quad n \geq 1.$$

Noticing that

$$a_0 b_n = -a_0 b_0 \sum_{i=1}^n a_i b_{n-i} = - \sum_{i=1}^n a_i b_{n-i}, \quad n \geq 1,$$

we have

$$\begin{aligned} f(x)g(x) &= \sum_{n \geq 0} \sum_{i=0}^n a_{n-i} b_i x^n \\ &= 1 + \sum_{n \geq 1} \sum_{i=0}^n a_i b_{n-i} x^n \\ &= 1 + \sum_{n \geq 1} \left(a_0 b_n + \sum_{i=1}^n a_i b_{n-i} \right) x^n \\ &= 1 + \sum_{n \geq 1} (a_0 b_n - a_0 b_n) x^n \\ &= 1. \end{aligned}$$

Hence we show $f(x) = a_0 + a_1 x + a_2 x^2 + \cdots$ is a unit.

For the other direction, supposing $f(x) = a_0 + a_1 x + a_2 x^2 + \cdots$ is a unit, then there exists $g(x) = b_0 + b_1 x + b_2 x^2 + \cdots$ such that

$$f(x)g(x) = a_0 b_0 + \sum_{n \geq 1} \sum_{i=0}^n a_i b_{n-i} x^n = 1.$$

By comparing the both sides of the equality we can find $a_0 b_0 = 1$, which implies a_0 is a unit in R .

We can check that the inverse of $1 - x$ in $R[[x]]$ is $1 + x + x^2 + \cdots$ since

$$(1 - x) \sum_{i \geq 0} x^i = \sum_{i \geq 0} x^i - \sum_{i \geq 0} x^{i+1} = 1.$$

2. Suppose R is an integral domain. If $f(x), g(x) \in R[x]$ are nonzero polynomials, we can assume that

$$f(x) = \sum_{i \geq 0} a_i x^i, \quad g(x) = \sum_{i \geq 0} b_i x^i, \quad a_i, b_i \in R$$

and that n, m are respectively the smallest integers p, q for which a_p, b_q are non-zero. In others words, we have $a_n \neq 0$, $a_i = 0$ for $i < n$ and $b_m \neq 0$, $b_i = 0$ for $i < m$. Noticing $a_n \neq 0$ and $b_m \neq 0$ implies $a_n b_m \neq 0$, we can see

$$f(x) \cdot g(x) = \sum_{k \geq 0} \sum_{i+j=k} a_i b_j x^{i+j} = a_n b_m x^{n+m} + \sum_{k \geq n+m+1} \sum_{i+j=k} a_i b_j x^{i+j} \neq 0.$$

Thus we show $R[[x]]$ is an integral domain.

Conversely, assume that $R[[x]]$ is an integral domain. Note that given any $a, b \in R$, they also belong to $R[[x]]$. Hence we obtain

$$a \neq 0, b \neq 0 \implies ab \neq 0,$$

which means that R is also an integral domain. ■

§2. The category Ring

2.1 Prove that if there is a homomorphism from a zero-ring to a ring R , then R is a zero-ring [§2.1]

Suppose that φ is a homomorphism from a zero-ring O to a ring R . Since $\varphi(0_O) = 0_R$, $\varphi(1_O) = 1_R$, $0_O = 1_O$, we have $0_R = 1_R$, which implies that R is a zero-ring. ■

2.4 Define functions $\mathbb{H} \rightarrow \mathfrak{gl}_4(\mathbb{R})$ and $\mathbb{H} \rightarrow \mathfrak{gl}_4(\mathbb{C})$ (cf. [Exercise III.1.4](#) and [1.12](#)) by

$$\begin{aligned} a + bi + cj + dk &\longmapsto \begin{pmatrix} a & b & c & d \\ -b & a & -d & c \\ -c & d & a & -b \\ -d & -c & b & a \end{pmatrix} \\ a + bi + cj + dk &\longmapsto \begin{pmatrix} a + bi & c + di \\ -c + di & a - bi \end{pmatrix} \end{aligned}$$

for all $a, b, c, d \in \mathbb{R}$. Prove that both functions are injective ring homomorphisms. Thus, quaternions may be viewed as real or complex matrices.

Let f be the function $\mathbb{H} \rightarrow \mathfrak{gl}_4(\mathbb{R})$ described above. For simplicity, we omit trivial check and only verify f preserves multiplication

$$\begin{aligned} &f((a_1 + b_1i + c_1j + d_1k) \cdot (a_2 + b_2i + c_2j + d_2k)) \\ &= f((a_1a_2 - b_1b_2 - c_1c_2 - d_1d_2) + (a_2b_1 + a_1b_2 - c_2d_1 + c_1d_2)i \\ &\quad + (a_2c_1 + a_1c_2 + b_2d_1 - b_1d_2)j + (a_2d_1 + a_1d_2 - b_2c_1 + b_1c_2)k) \\ &= \begin{pmatrix} a_1 & b_1 & c_1 & d_1 \\ -b_1 & a_1 & -d_1 & c_1 \\ -c_1 & d_1 & a_1 & -b_1 \\ -d_1 & -c_1 & b_1 & a_1 \end{pmatrix} \begin{pmatrix} a_2 & b_2 & c_2 & d_2 \\ -b_2 & a_2 & -d_2 & c_2 \\ -c_2 & d_2 & a_2 & -b_2 \\ -d_2 & -c_2 & b_2 & a_2 \end{pmatrix} \\ &= f(a_1 + b_1i + c_1j + d_1k)f(a_2 + b_2i + c_2j + d_2k) \end{aligned}$$
■

2.6 Verify the ‘extension property’ of polynomial rings, stated in Example 2.3. [§2.2]

Define the following ring homomorphisms

$$\begin{aligned}\alpha : R &\longrightarrow S, & r &\longmapsto \alpha(r) \\ \epsilon : R &\longrightarrow R[x], & r &\longmapsto r,\end{aligned}$$

and functions

$$\begin{aligned}j : \{s\} &\longrightarrow R[x], & s &\longmapsto x, \\ i : \{s\} &\longrightarrow S, & s &\longmapsto s.\end{aligned}$$

Assume that $s \in S$ is an element commuting with $\alpha(r)$ for all $r \in R$, we are to show that there exists a unique ring homomorphism $\bar{\alpha} : R[x] \rightarrow S$ such that the following diagram commutes.

$$\begin{array}{ccc} R & & \\ \epsilon \downarrow & \searrow \alpha & \\ R[x] & \xrightarrow{\exists! \bar{\alpha}} & S \\ j \uparrow & \nearrow i & \\ \{s\} & & \end{array}$$

Uniqueness. If $\bar{\alpha}$ exists, then the postulated commutativity of the diagram means that for all $f(x) = \sum_{n \geq 0} a_n x^n \in R[x]$, there must be

$$\bar{\alpha}(f(x)) = \bar{\alpha}\left(\sum_{n \geq 0} a_n x^n\right) = \sum_{n \geq 0} \bar{\alpha}(a_n) \bar{\alpha}(x)^n = \sum_{n \geq 0} \alpha(a_n) s^n.$$

That is, $\bar{\alpha}$ is unique.

Existence. The only choice is to define

$$\bar{\alpha} : R[x] \longrightarrow S, \quad \sum_{n \geq 0} a_n x^n \longmapsto \sum_{n \geq 0} \alpha(a_n) s^n$$

and to check whether it is a ring homomorphism.

1. Preserving addition:

$$\begin{aligned}
\bar{\alpha} \left(\sum_{n \geq 0} a_n x^n + \sum_{n \geq 0} b_n x^n \right) &= \bar{\alpha} \left(\sum_{n \geq 0} (a_n + b_n) x^n \right) \\
&= \sum_{n \geq 0} \alpha(a_n + b_n) s^n \\
&= \sum_{n \geq 0} \alpha(a_n) s^n + \sum_{n \geq 0} \alpha(b_n) s^n \\
&= \bar{\alpha} \left(\sum_{n \geq 0} a_n x^n \right) + \bar{\alpha} \left(\sum_{n \geq 0} b_n x^n \right).
\end{aligned}$$

2. Preserving multiplication:

$$\begin{aligned}
\bar{\alpha} \left(\sum_{n \geq 0} a_n x^n \sum_{n \geq 0} b_n x^n \right) &= \bar{\alpha} \left(\sum_{n \geq 0} \sum_{i+j=n} a_i b_j x^n \right) \\
&= \sum_{n \geq 0} \alpha \left(\sum_{i+j=n} a_i b_j \right) s^n \\
&= \sum_{n \geq 0} \sum_{i+j=n} \alpha(a_i) s^i \alpha(b_j) s^j \\
&= \left(\sum_{n \geq 0} \alpha(a_n) s^n \right) \left(\sum_{n \geq 0} \alpha(b_n) s^n \right) \\
&= \bar{\alpha} \left(\sum_{n \geq 0} a_n x^n \right) \bar{\alpha} \left(\sum_{n \geq 0} b_n x^n \right).
\end{aligned}$$

3. Preserving identity element:

$$\bar{\alpha}(1_R) = \alpha(1_R) = 1_S.$$

Integrating the two parts we finally conclude there exists a unique ring homomorphism $\bar{\alpha}$ such that the diagram commutes. ■

2.7 Let $R = \mathbb{Z}/2\mathbb{Z}$, and let $f(x) = x^2 - x$; note $f(x) \neq 0$. What is the polynomial function $R \rightarrow R$ determined by $f(x)$? [§2.2, §V.4.2, §V.5.1]

It determines a function $f : \mathbb{Z}/2\mathbb{Z} \rightarrow \mathbb{Z}/2\mathbb{Z}$ sends all elements to identity, that is, $f([0]_2) = [0]_2$, $f([1]_2) = [0]_2$. ■

2.8 Prove that every subring of a field is an integral domain

Suppose $\varphi : R \hookrightarrow K$ is a inclusion homomorphism. If $a \neq 0$, we have

$$ab = ac \implies \varphi(a)\varphi(b) = \varphi(a)\varphi(c) \implies \varphi(b) = \varphi(c) \implies b = c.$$

Due to the commutativity of field it also holds that $ba = ca$. Thus we show R is an integral domain. ■

2.9 \neg The *center* of a ring R consists of the elements a such that $ar = ra$ for all $r \in R$. Prove that the center is a subring of R . Prove that the center of a division ring is a field. [2.11, IV.2.17, VII.5.14, VII.5.16]

Denote the center of R by $Z(R)$. We can check that

1. for all $x, y \in Z(R)$, for all $r \in R$,

$$(x - y)r = xr - yr = rx - ry = r(x - y) \implies x - y \in Z(R);$$

2. for all $r \in R$,

$$1r = r1 \implies 1 \in Z(R);$$

3. for all $x, y \in Z(R)$, for all $r \in R$,

$$(xy)r = xry = r(xy) \implies xy \in Z(R).$$

Thus we show that $Z(R)$ is a subring of R . If R is a division ring, then $Z(R)$ is also a division ring. Note that for all $x, y \in Z(R)$, $xy = yx$, we see that $Z(R)$ is a commutative division ring, namely field. ■

2.10 \neg The *centralizer* of an element a of a ring R consists of the elements $r \in R$ such that $ar = ra$. Prove that the centralizer of a is a subring of R , for every $a \in R$. Prove that the center of R is the intersection of all its centralizers. Prove that every centralizer in a division ring is a division ring. [2.11, IV.2.17, VII.5.16]

Denote the centralizer of an element a of R by $Z_a(R)$. We can check that

1. for all $x, y \in Z_a(R)$,

$$(x - y)a = xa - ya = ax - ay = a(x - y) \implies x - y \in Z_a(R);$$

- 2.

$$1a = a1 \implies 1 \in Z_a(R);$$

3. for all $x, y \in Z_a(R)$,

$$(xy)a = xay = a(xy) \implies xy \in Z_a(R).$$

Thus we show that $Z_a(R)$ is a subring of R . By definition we have $Z(R) \subseteq Z_a(R)$ for all $a \in R$, which implies $Z(R) \subseteq \bigcap_{a \in R} Z_a(R)$. Assume $s \in \bigcap_{a \in R} Z_a(R)$, then we see $sa = as$ for all $a \in R$, which means $s \in Z(R)$ and accordingly $\bigcap_{a \in R} Z_a(R) \subseteq Z(R)$. Thus we deduce that $Z(R) = \bigcap_{a \in R} Z_a(R)$. If R is a division ring, then $Z_a(R)$ is also a division ring because $Z_a(R)$ is a subring. ■

§3. Ideals and quotient rings

3.1 Prove that the image of a ring homomorphism $\varphi : R \rightarrow S$ is a subring of S . What can you say about φ , if its image is an ideal of S ? What can you say about φ , if its kernel is a subring of R ?

We can see that $\text{im } \varphi$ is a subring of S from the canonical decomposition

$$R \twoheadrightarrow R / \ker \varphi \xrightarrow[\tilde{\varphi}]{\varphi} \text{im } \varphi \hookrightarrow S$$

If $\text{im } \varphi$ is an ideal, then $s \in S, 1 \in \text{im } \varphi \implies s \in \text{im } \varphi$. So $\text{im } \varphi = S$ and φ is an epimorphism. Since $\ker \varphi$ is a ideal, if it is also a subring, we have $\ker \varphi = R$. ■

3.2 Let $\varphi : R \rightarrow S$ be a ring homomorphism, and let J be an ideal of S . Prove that $I = \varphi^{-1}(J)$ is an ideal of R . [§3.1]

In **Ab** we see $\varphi^{-1}(J)$ is a subgroup of R . For all $r \in R, a \in \varphi^{-1}(J)$, we have

$$\varphi(ra) = \varphi(r)\varphi(a) \in J \implies ra \in \varphi^{-1}(J).$$

Similarly we can obtain $ar \in \varphi^{-1}(J)$. Therefore, we conclude that $I = \varphi^{-1}(J)$ is an ideal of R . ■

3.3 ▮ Let $\varphi : R \rightarrow S$ be a ring homomorphism, and let J be an ideal of R .

- Show that $\varphi(J)$ need not be an ideal of S .
- Assume that φ is surjective; then prove that $\varphi(J)$ is an ideal of S .
- Assume that φ is surjective, and let $I = \ker \varphi$; thus we may identify S with R/I . Let $\bar{J} = \varphi(J)$, an ideal of R/I by the previous point. Prove that

$$\frac{R/I}{\bar{J}} \cong \frac{R}{I + J}$$

(Of course this is just a rehash of Proposition 3.11.) [4.11]

- Let $\varphi : \mathbb{Z} \hookrightarrow \mathbb{Q}$ and $J = \mathbb{Z}$. It is clear that $\varphi(J) = \mathbb{Z}$ is not an ideal of \mathbb{Q} .
- Assume that φ is surjective. In **Ab** we see $\varphi(J)$ is a subgroup of S . For all $a' = \varphi(a) \in \varphi(J)$, $r' = \varphi(r) \in S$,

$$ra \in J \implies r'a' = \varphi(r)\varphi(a) = \varphi(ra) \in \varphi(J).$$

Similarly we can obtain $a'r' \in \varphi(J)$. Therefore, we conclude that $\varphi(J)$ is an ideal of S .

- Assume that φ is surjective, and let $I = \ker \varphi$; thus we may identify S with R/I . Let $J = \varphi(J)$, an ideal of R/I by the previous point. Prove that

$$\frac{R/I}{J} \cong \frac{R}{I+J}$$

■

Appendix

Lemma II.1 (von Dyck) Given a presentation $(A|\mathcal{R}) = F(A)/R$, where A is the set of generators, $\mathcal{R} \in F(A)$ is the set of relators and R is the smallest normal subgroup of $F(A)$ containing \mathcal{R} . Define inclusion mapping $i : A \rightarrow F(A)$ and projection $\pi : F(A) \rightarrow F(A)/R$. If f is a mapping from A to a group G , and every relations in \mathcal{R} holds in G via f , that is, $\mathcal{R} \subset \ker \varphi$ where φ is the unique homomorphism induced by the universal property of free group, then there exists a unique homomorphism $\psi : F(A)/R \rightarrow G$ such that $f = \psi \circ \pi \circ i$. If G is generated by $f(A)$, then ψ is surjective.

$$\begin{array}{ccc}
 & F(A)/R & \\
 \pi \uparrow & \searrow \exists! \psi & \\
 F(A) & \xrightarrow{\varphi} & G \\
 i \uparrow & \nearrow f & \\
 A & &
 \end{array}$$

Proof of the lemma. Since R is the smallest normal subgroup of $F(A)$ containing \mathcal{R} and the normal subgroup $\ker \varphi$ contains \mathcal{R} , we must have $R \subset \ker \varphi$. Then according to Theorem 7.12, there exists a unique homomorphism $\psi : F(A)/R \rightarrow G$ such that $\varphi = \psi \circ \pi$, which means the whole diagram commutes. If there exists a homomorphism $\zeta : F(A)/R \rightarrow G$ such that $f = \zeta \circ \pi \circ i$, then we have $\varphi \circ i = \zeta \circ \pi \circ i$, which implies $\varphi(t) = \zeta(\pi(t))$ for all $t \in A$. Note that a homomorphism defined on $F(A)$ can be specified only by its valuation on the set of generators A , we can assert that $\varphi = \zeta \circ \pi$. Since there exists a unique homomorphism $\psi : F(A)/R \rightarrow G$ such that $\varphi = \psi \circ \pi$, we have $\zeta = \psi$. Thus we show that there exists a unique homomorphism $\psi : F(A)/R \rightarrow G$ such that $f = \psi \circ \pi \circ i$.

Moreover, if G is generated by $f(A)$, then $\text{im} \psi = G$, since $f(A) = \psi(\pi(i(A))) \subset \text{im} \psi$ implies $G \subset \text{im} \psi$. \lrcorner

References