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Group theory

Notes

Wednesday 5th July, 2023

Preface

The notes correspond to the bachelor course *Group Theory* of the Vrije Universiteit Brussel, Faculty of Sciences, Department of Mathematics and Data Sciences. The course is divided into twelve two-hours lectures.

The material is somewhat standard. Basic texts on abstract algebra are for example [1], [3] and [4]. Lang's book [5] is also a standard reference, but maybe a little bit more advanced.

We also mention a set of great expository papers by Keith Conrad available at <https://kconrad.math.uconn.edu/blurbs/>. The notes are extremely well-written and are useful at every stage of a mathematical career.

This version was compiled on Wednesday 5th July, 2023 at 18:39. Please send comments and corrections to me at Leandro.Vendramin@vub.be.

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Lecture 1

§1. Groups

Before defining groups, we recall that a binary operation on a set X is simply a map

$$X \times X \rightarrow X, \quad (x, y) \mapsto xy.$$

Note that we have used juxtaposition to denote this generic binary operation. For example, $(x, y) \mapsto x - y$ is a binary operation in \mathbb{Z} but not, for example, in $\mathbb{Z}_{\geq 0}$.

Definition 1.1. A **group** is a non-empty set G with a binary operation $G \times G \rightarrow G$, $(x, y) \mapsto xy$, such that the following properties hold:

- 1) (Associativity) $(xy)z = x(yz)$ for all $x, y, z \in G$.
- 2) (Existence of a neutral element) There exists $e \in G$ such that $xe = ex = x$ for all $x \in G$.
- 3) (Existence of inverses) For every $x \in G$ there exists $y \in G$ such that $xy = yx = e$.

The associativity condition implies that all ordered products that we can form with, say, the elements x_1, x_2, \dots, x_n will be equal. For example,

$$(x_1 x_2)((x_3 x_4)x_5) = x_1(x_2(x_3(x_4 x_5)))$$

and hence we can write, without ambiguity and without using brackets,

$$x_1 x_2 \cdots x_5.$$

This fact can be proved by induction; see for example Lang's book [5]. We will provide an alternative proof as an application of Cayley's theorem 11.28.

Proposition 1.2. *In a group G , every element $x \in G$ admits a unique inverse.*

Proof. Let $y, z \in G$ be inverses of $x \in G$. Then $z = z(xy) = (zx)y = ey = y$. □

Exercise 1.3. Prove that the neutral element of a group is unique.

In general, when the binary operation is written multiplicatively, one writes the neutral element e of a group as 1_G or simply as 1 . The inverse of x will be denoted by x^{-1} .

Example 1.4. Let $n \geq 1$. The set $\mathbf{GL}_n(\mathbb{R})$ of $n \times n$ invertible real matrices forms a group with the usual matrix multiplication.

It is a good idea to keep in mind the *group of invertible matrices*. With this, the following properties look familiar:

- 1) $(x^{-1})^{-1} = x$ for all x .
- 2) $(xy)^{-1} = y^{-1}x^{-1}$ for all x, y .

Exercise 1.5. Prove that in a group, the equation $ax = b$ has a unique solution: $x = a^{-1}b$. Similarly, $x = ba^{-1}$ is the unique solution of the equation $xa = b$.

Definition 1.6. A group G is **abelian** if $xy = yx$ for all $x, y \in G$.

Most of the time, for abelian groups, we will use the *additive notation*. This means that the binary operation of the group will be denoted by $(x, y) \mapsto x + y$, the neutral element by 0 and the inverse of an element x will be $-x$.

Definition 1.7. The **order** $|G|$ of a group G is the cardinality of G . A group G is said to be **finite** if $|G|$ is finite and **infinite** otherwise.

The **trivial group** is the (unique) group containing exactly one element e , the neutral element. Examples include the zero group $\{0\}$ with the addition $0 + 0 = 0$ and the multiplicative group $\{1\}$ with multiplication $1 \cdot 1 = 1$.

Example 1.8. Let us see some examples abelian groups:

- 1) $\mathbb{Z}, \mathbb{Q}, \mathbb{R}$ and \mathbb{C} with the usual addition.
- 2) Let $n \geq 2$. The set \mathbb{Z}/n of integers modulo n with the usual addition modulo n .
- 3) $\mathbb{Q} \setminus \{0\}, \mathbb{R} \setminus \{0\}$ and $\mathbb{C} \setminus \{0\}$ with the usual multiplication.
- 4) Let p be a prime number. The set $(\mathbb{Z}/p)^\times = (\mathbb{Z}/p) \setminus \{0\}$ of invertible integers modulo p with the usual multiplication modulo p .

The groups of the first two items will be written in additive notation.

The group \mathbb{Z}/n of integers modulo n is a finite group of order n . The group $(\mathbb{Z}/p)^\times$ of units modulo p is a finite group of order $p - 1$. The other groups of Example 1.8 are infinite.

Exercise 1.9. Let G be a group and $g \in G$. Prove that the maps $L_g: G \rightarrow G, x \mapsto gx$, and $R_g: G \rightarrow G, x \mapsto xg$, are bijective.

Let $G = \{g_1, g_2, \dots, g_n\}$ be a finite group. The **table** of G is the matrix that in position (i, j) has the element $g_i g_j$. For example, the table of the (additive) group $\mathbb{Z}/4$ of integers modulo 4 is the following:

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$$\begin{array}{c|cccc} & 0 & 1 & 2 & 3 \\ \hline 0 & 0 & 1 & 2 & 3 \\ 1 & 1 & 2 & 3 & 0 \\ 2 & 2 & 3 & 0 & 1 \\ 3 & 3 & 0 & 1 & 2 \end{array}$$

We know that \mathbb{Z} is a group with the usual addition. We now discuss a multiplicative version of this group, as it will be very important later. We first need a little bit of notation. Let G be a group and $g \in G$. For $k \in \mathbb{Z} \setminus \{0\}$, we write

$$\begin{aligned} g^k &= g \cdots g \quad (k \text{ -- times}) & \text{if } k > 0, \\ g^k &= g^{-1} \cdots g^{-1} \quad (|k| \text{ -- times}) & \text{if } k < 0. \end{aligned}$$

By convention, $g^0 = 1$. The following facts are left as an exercise:

- 1) $(x^k)^l = x^{kl}$ for all $x \in G$ and $k, l \in \mathbb{Z}$.
- 2) If G is abelian, then $(xy)^k = x^k y^k$ for all $x, y \in G$ and $k \in \mathbb{Z}$.

Example 1.10. Fix a symbol g . Consider the set

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

of integers powers of g (with the usual convention $g^0 = 1$). Then $\langle g \rangle$ with the operation $g^i g^j = g^{i+j}$ is an abelian group.

We will see later that \mathbb{Z} and the group of Example 1.10 are “indistinguishable” as groups, even if they appear to be completely different.

Example 1.11. Let n be a positive integer. The set $G_n = \{z \in \mathbb{C} : z^n = 1\}$ is an abelian group with the usual multiplication. Moreover, the set $\cup_{n \geq 1} G_n$ is an abelian group.

Example 1.12. Let X be a non-empty set. The set \mathbb{S}_X of bijective maps $X \rightarrow X$ is a group with the usual composition of maps. If $|X| \geq 3$, the group \mathbb{S}_X is non-abelian. To prove this, let $a, b, c \in X$ be three different elements. Let $f : X \rightarrow X$ be such that $f(a) = b$, $f(b) = c$ and $f(c) = a$ and $g : X \rightarrow X$ be such that $g(a) = b$, $g(b) = a$ and $g(x) = x$ for all $x \in X \setminus \{a, b\}$. Then $fg \neq gf$.

If $X = \{1, 2, \dots, n\}$, the group \mathbb{S}_X will be written as \mathbb{S}_n . This is the **symmetric group** of degree n . The elements of \mathbb{S}_n are called **permutations** of degree n . Note that $|\mathbb{S}_n| = n!$ and \mathbb{S}_n is abelian if and only if $n \in \{1, 2\}$. Each element of \mathbb{S}_n is a bijective map $f : \{1, \dots, n\} \rightarrow \{1, \dots, n\}$. To denote permutations, we can use the following convention. The symbol

$$\begin{pmatrix} 12345 \\ 32145 \end{pmatrix}$$

denotes the map $f : \{1, 2, 3, 4, 5\} \rightarrow \{1, 2, 3, 4, 5\}$ such that

$$f(1) = 3, \quad f(2) = 2, \quad f(3) = 1, \quad f(4) = 4, \quad f(5) = 5.$$

As we said, the operation of this group is the usual composition of maps. For example,

$$\begin{pmatrix} 12345 \\ 32145 \end{pmatrix} \begin{pmatrix} 12345 \\ 13452 \end{pmatrix} = \begin{pmatrix} 12345 \\ 32145 \end{pmatrix} \circ \begin{pmatrix} 12345 \\ 13452 \end{pmatrix} = \begin{pmatrix} 12345 \\ 31452 \end{pmatrix}.$$

Example 1.13 (Klein group). The set

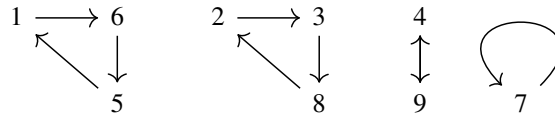
$$K = \left\{ \text{id}, \begin{pmatrix} 1234 \\ 2143 \end{pmatrix}, \begin{pmatrix} 1234 \\ 3412 \end{pmatrix}, \begin{pmatrix} 1234 \\ 4321 \end{pmatrix} \right\}$$

together with the usual composition of maps is an abelian group. Note that K is included in \mathbb{S}_4 . Can you compute the table of this group?

Every permutation can be written as a product of disjoint cycles. The fact is proved by induction but is relatively intuitive. Let us decompose the permutation

$$\sigma = \begin{pmatrix} 123456789 \\ 638915724 \end{pmatrix} \in \mathbb{S}_9$$

as a product of cycles. We need to draw a picture for σ :



We see that σ has two 3-cycles, one 2-cycle and one loop. Therefore

$$\sigma = (165)(238)(49)(7).$$

Generally, one omits loops and orders the cycles according to the length. Thus

$$\sigma = (49)(165)(238).$$

Example 1.14. The set \mathbb{S}_3 of bijective maps $\{1, 2, 3\} \rightarrow \{1, 2, 3\}$ together with the composition of maps is a group of order six. Its elements are the permutations

$$\text{id}, \begin{pmatrix} 123 \\ 213 \end{pmatrix}, \begin{pmatrix} 123 \\ 321 \end{pmatrix}, \begin{pmatrix} 123 \\ 132 \end{pmatrix}, \begin{pmatrix} 123 \\ 231 \end{pmatrix}, \begin{pmatrix} 123 \\ 312 \end{pmatrix}.$$

Writing permutations as a product of disjoint cycles, the elements of \mathbb{S}_3 are

$$\text{id}, (12), (13), (23), (123), (132),$$

where, as we know, the symbol (12) represents the map $\{1, 2, 3\} \rightarrow \{1, 2, 3\}$ such that $1 \mapsto 2$, $2 \mapsto 1$ and $3 \mapsto 3$. Can you construct the table for this group?

Example 1.15. Let $\overline{\mathbb{R}} = \mathbb{R} \cup \{\infty\}$ (here ∞ is just a symbol) and assume that the following rules hold:

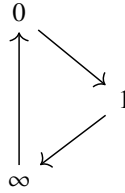
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$$1/\infty = 0, \quad 1/\infty, \quad \infty/\infty = 1, \quad 1 - \infty = \infty - 1 = \infty.$$

We now consider maps $\bar{R} \rightarrow \bar{R}$ such as $x \mapsto x$ and $x \mapsto \frac{1}{x}$. We claim that the set of maps

$$G = \left\{ x, \frac{1}{x}, 1-x, \frac{1}{1-x}, \frac{x}{x-1}, \frac{x-1}{x} \right\} \subseteq \{f: \bar{R} \rightarrow \bar{R} : f \text{ is a map}\}$$

is a non-abelian group with the usual composition of maps. Then G can be identified with the set of bijective maps $\{0, 1, \infty\} \rightarrow \{0, 1, \infty\}$. For example, the map $x \mapsto \frac{1}{x}$ can be identified with the permutation of the set $\{0, 1, \infty\}$ that permutes 0 and ∞ and fixes 1. Similarly, $\frac{1}{1-x}$ permutes the elements $\{0, 1, \infty\}$ cyclically in the following way:



We will see later that the groups of Examples 1.14 and 1.15 are indeed “indistinguishable” as groups.

Example 1.16. Let $n \geq 2$. The multiplicative units of \mathbb{Z}/n form a group with the usual multiplication modulo n . We will use the following notation:

$$\mathcal{U}(\mathbb{Z}/n) = \{x \in \mathbb{Z}/n : \gcd(x, n) = 1\}.$$

The order of $\mathcal{U}(\mathbb{Z}/n)$ is $\varphi(n)$, where φ is the Euler’s function, that is

$$\varphi(n) = |\{x \in \mathbb{Z} : 1 \leq x \leq n, \gcd(x, n) = 1\}|.$$

Let us discuss a concrete example. The table of $\mathcal{U}(\mathbb{Z}/8) = \{1, 3, 5, 7\}$ is

	1	3	5	7
1	1	3	5	7
3	3	1	7	5
5	5	7	1	3
7	7	5	3	1

Exercise 1.17. Let G and H be groups. Prove that the set $G \times H$ of pairs (g, h) , where $g \in G$ and $h \in H$ is a group with the operation

$$(g, h)(g_1, h_1) = (gg_1, hh_1).$$

This group is called the **direct product** of G and H .

The construction of Example 1.17 can be easily generalized to the product of three or more groups.

Lecture 2

§2. Subgroups

Definition 2.1. Let G be a group. A subset S of G is said to be a **subgroup** of G if the following properties are satisfied:

- 1) $1 \in S$,
- 2) $x \in S \implies x^{-1} \in S$, and
- 3) $x, y \in S \implies xy \in S$.

Notation: S is a subgroup of G if and only if $S \leq G$.

The first condition of the definition can be replaced by the following condition: $S \neq \emptyset$. Why?

Example 2.2. If G is a group, then $\{1\}$ and G are always subgroups of G .

The subgroup $\{1\}$ is known as the **trivial subgroup** of G . A subgroup S of G is said to be **proper** if $S \neq G$.

Example 2.3. Write $2\mathbb{Z} = \{2m : m \in \mathbb{Z}\}$ to denote the set of even integers. Then $2\mathbb{Z} \leq \mathbb{Z} \leq \mathbb{Q} \leq \mathbb{R} \leq \mathbb{C}$ is a chain of subgroups.

Example 2.4. $S^1 = \{z \in \mathbb{C} : |z| = 1\} \leq \mathbb{C}^\times = \mathbb{C} \setminus \{0\}$.

Example 2.5. Let $n \geq 1$. Then $G_n = \{z \in \mathbb{C} : z^n = 1\}$ is a subgroup of \mathbb{C}^\times . Note that

$$G_n = \{1, \exp(2\pi i/n), \exp(4i\pi/n), \dots, \exp(2(n-1)i\pi/n)\}.$$

and

$$G_n \leq \bigcup_{n \geq 1} G_n \leq S^1 \leq \mathbb{C}^\times.$$

Exercise 2.6. Let G be a group. Prove that the **center**

$$Z(G) = \{g \in G : gh = hg \text{ for all } h \in G\}$$

of G is a subgroup of G .

Exercise 2.7. Let G be a group and $g \in G$. Prove that the **centralizer**

$$C_G(g) = \{h \in G : gh = hg\}$$

of g in G is a subgroup of G .

One can prove that, if G is a group, then $Z(G) = \bigcap_{g \in G} C_G(g)$.

Exercise 2.8. Let S be a subgroup of G and $g \in G$. Prove that the **conjugate** gSg^{-1} of S by g is a subgroup of G . Notation: ${}^gS = gSg^{-1}$.

Exercise 2.9. Prove that $Z(\mathbb{S}_3) = \{\text{id}\}$ and compute $C_{\mathbb{S}_3}((12))$.

The following exercise is useful:

Exercise 2.10. Let G be a group and S be a subset of G . Prove that S is a subgroup of G if and only if $S \neq \emptyset$ and for all $x, y \in S$ one has $xy^{-1} \in S$.

Use the previous exercise and the fact that the determinant is a multiplicative function to solve the following problem:

Exercise 2.11. Prove that $\mathbf{SL}_n(\mathbb{R}) = \{a \in \mathbf{GL}_n(\mathbb{R}) : \det(a) = 1\} \leq \mathbf{GL}_n(\mathbb{R})$.

Exercise 2.12. Prove that the intersection of subgroups is again a subgroup.

The previous exercise is easy but crucial. We need it to construct subgroups generated by a given subset of elements.

Definition 2.13. Let G be a group and X a subset of G . The **subgroup generated** by X is the smallest subgroup of G that contains X , that is

$$\langle X \rangle = \bigcap \{S : S \leq G, X \subseteq S\}.$$

Why this is the smallest subgroup that contains X ? Let $H \leq G$ be such that $X \subseteq H$. Since H is one of the subgroups appearing in the intersection,

$$\langle X \rangle = \bigcap \{S : S \leq G, X \subseteq S\} \subseteq H.$$

We will use the following notation: If $X = \{g_1, \dots, g_k\}$, then

$$\langle X \rangle = \langle \{g_1, \dots, g_k\} \rangle = \langle g_1, \dots, g_k \rangle.$$

Exercise 2.14. Prove that

$$\langle X \rangle = \{x_1^{n_1} \cdots x_k^{n_k} : k \geq 0, x_1, \dots, x_k \in X, -1 \leq n_1, \dots, n_k \leq 1\}.$$

The previous exercise shows that the subgroup generated by, say, the elements x_1, \dots, x_n is nothing but the group formed by (some) words on the letters x_1, \dots, x_n and their inverses $x_1^{-1}, \dots, x_n^{-1}$.

Example 2.15. Let $n \geq 3$. Let

$$r = \begin{pmatrix} \cos(2\pi/n) & -\sin(2\pi/n) \\ \sin(2\pi/n) & \cos(2\pi/n) \end{pmatrix}, \quad s = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

The **dihedral group** \mathbb{D}_n is the subgroup of $\mathbf{GL}_2(\mathbb{C})$ generated by r and s , that is $\mathbb{D}_n = \langle r, s \rangle$. A direct calculation shows that

$$r^n = s^2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad srs = r^{-1}.$$

An element of \mathbb{D}_n is a word of the form

$$r^{i_1} s^{j_1} r^{i_2} s^{j_2} \dots$$

for some $i_1, i_2, \dots \in \{0, 1, \dots, n-1\}$ and $j_1, j_2, \dots \in \{0, 1\}$. Since $rs = sr^{-1}$, we conclude that every element of \mathbb{D}_n can be written as $r^i s^j$ for some $i \in \{0, \dots, n-1\}$ and $j \in \{0, 1\}$. In particular, $|\mathbb{D}_n| = 2n$.

To understand better the previous example, we discuss two concrete particular cases. If $n = 3$,

$$r = \begin{pmatrix} -1/2 & -\sqrt{3}/2 \\ \sqrt{3}/2 & -1/2 \end{pmatrix}, \quad s = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

and we obtain (another representation of) the group of symmetries of a regular triangle. If $n = 4$,

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

and we obtain (another representation of) the group of symmetries of the square.

Exercise 2.16. The union of subgroups is not, in general, a subgroup. Can you give an example?

§3. Subgroups of \mathbb{Z}

It is time for the first theorem. What can we say about the subgroups of \mathbb{Z} ?

Theorem 3.1. If S is a subgroup of \mathbb{Z} , then $S = m\mathbb{Z} = \{mx : x \in \mathbb{Z}\}$ for some $m \geq 0$.

Proof. If $S = \{0\}$, take $m = 0$. Assume now that $S \neq \{0\}$. Let $m = \min\{s \in S : s > 0\}$. Why does this m exist? Since $S \neq \{0\}$, it contains an element $n \in S \setminus \{0\}$. There are then two possible cases: $n > 0$ or $-n > 0$. Since S is a subgroup of \mathbb{Z} , $-n \in S$.

We claim that $S = n\mathbb{Z}$. If $x \in S$, then $x = my + r$ for $y, r \in \mathbb{Z}$ with $0 \leq r < m$. Suppose that $r \neq 0$. Since $x, m \in S$, it follows that $r \in S$, a contradiction to the minimality of n . Thus $r = 0$ and hence $x = my \in m\mathbb{Z}$. Conversely, since $n \in S$, it follows that $nk \in S$ for all $k \in \mathbb{Z}$. In fact, if $k = 0$, then $nk = 0 \in S$. If $k > 0$, then

$$\underbrace{n + \cdots + n}_{k\text{-times}} \in S.$$

Finally, if $k < 0$, then

$$nk = \underbrace{-n + (-n) + \cdots + (-n)}_{|k| \text{-times}} \in S. \quad \square$$

The previous theorem has nice applications. If $a, b \in \mathbb{Z}$, we say that a **divides** b (or b is divisible by a) if $b = ac$ for some $c \in \mathbb{Z}$. Notation:

$$a \mid b \iff b = ac \text{ for some } c \in \mathbb{Z}.$$

If $a, b \in \mathbb{Z}$ are such that $ab \neq 0$, then

$$S = a\mathbb{Z} + b\mathbb{Z} = \{m \in \mathbb{Z} : m = ar + bs \text{ for } r, s \in \mathbb{Z}\}$$

is a subgroup of \mathbb{Z} (this is an exercise). By Theorem 3.1, $S = d\mathbb{Z}$ for some $d > 0$. This positive integer d is the **greatest common divisor** of a and b , that is $d = \gcd(a, b)$.

Exercise 3.2. Let $a, b \in \mathbb{Z}$ be such that $ab \neq 0$ and $d = \gcd(a, b)$. Prove the following statements:

- 1) d divides a and b .
- 2) If $e \in \mathbb{Z}$ divides a and b , then e divides d .
- 3) There are $r, s \in \mathbb{Z}$ such that $d = ar + bs$.

Two integers a and b are said to be **coprime** if and only if the only positive integer dividing a and b is one, that is

$$\begin{aligned} a \text{ and } b \text{ are coprime} &\iff \gcd(a, b) = 1 \\ &\iff \mathbb{Z} = a\mathbb{Z} + b\mathbb{Z} \\ &\iff \text{there exist } r, s \in \mathbb{Z} \text{ such that } ar + bs = 1. \end{aligned}$$

Exercise 3.3. Let p be a prime and $a, b \in \mathbb{Z}$. Prove that if $p \mid ab$, then $p \mid a$ or $p \mid b$.

If S and T are subgroups of \mathbb{Z} , then $S \cap T$ is a subgroup of \mathbb{Z} . Let $a, b \in \mathbb{Z}$ be such that $ab \neq 0$. Since $a\mathbb{Z} \cap b\mathbb{Z}$ is a non-zero subgroup of \mathbb{Z} (note that it contains $ab \neq 0$), we can write $a\mathbb{Z} \cap b\mathbb{Z} = m\mathbb{Z}$ for some $m \geq 1$. The integer m is the **least common multiple** of a and b and will be written as $m = \text{lcm}(a, b)$.

Exercise 3.4. Let $a, b \in \mathbb{Z} \setminus \{0\}$ and $m = \text{lcm}(a, b)$. Prove the following statements:

- 1) m is divisible by both a and b .
- 2) If n is divisible by both a and b , then n is divisible by m .

Exercise 3.5. Let $a, b \in \mathbb{Z}_{\geq 1}$. Prove that if $d = \gcd(a, b)$ and $m = \text{lcm}(a, b)$, then $ab = dm$.

§4. Commutators

Definition 4.1. The **commutator subgroup** $[G, G]$ of G is the subgroup generated by the commutators of G , that is

$$[G, G] = \langle [x, y] \mid x, y \in G \rangle,$$

where $[x, y] = xyx^{-1}y^{-1}$ is the commutator of x and y .

In the literature, the commutator subgroup of a group G is also called the **derived subgroup** of G .

Example 4.2. In \mathbb{Z} , the commutator of $x, y \in \mathbb{Z}$ is the integer

$$[x, y] = x + y - x - y = 0.$$

This example uses additive notation! Thus $[\mathbb{Z}, \mathbb{Z}] = \{0\}$.

Exercise 4.3. Prove that $[\mathbb{S}_3, \mathbb{S}_3] = \{\text{id}, (123), (132)\}$.

Why do we need to consider the subgroup generated by commutators? Because the set of commutators is not always a subgroup. With the help of computers, one can verify the following examples. The first one is taken from Carmichael's book [2].

Example 4.4. Let G be the subgroup of \mathbb{S}_{16} generated by the permutations

$$\begin{aligned} a &= (13)(24), & b &= (57)(68), \\ c &= (911)(1012), & d &= (1315)(1416), \\ e &= (13)(57)(911), & f &= (12)(34)(1315), \\ g &= (56)(78)(1314)(1516), & h &= (910)(1112). \end{aligned}$$

Then $[G, G]$ has order 16, but the set of commutators of G has 15 elements.

The following example goes back to Guralnick [?]. It was found by hand when computers were not as popular in group theory as now.

Example 4.5. The group

$$G = \langle (135)(246)(7119)(81210), (39410)(58)(67)(1112) \rangle.$$

has order 96. The set of commutators is different from the commutator subgroup. Moreover, G is the smallest group with the property that the set of commutators is not a subgroup.

§5. Cyclic groups

Definition 5.1. A group G is said to be **cyclic** if $G = \langle g \rangle$ for some $g \in G$.

If G is a cyclic group generated by g , then $G = \langle g \rangle = \{g^k : k \in \mathbb{Z}\}$. Every cyclic group is, in particular, an abelian group.

Examples 5.2.

- 1) $\mathbb{Z} = \langle 1 \rangle = \langle -1 \rangle$.
- 2) $\mathbb{Z}/n = \langle 1 \rangle$.
- 3) $G_n = \langle \exp(2i\pi/n) \rangle$.

Example 5.3. $\mathcal{U}(\mathbb{Z}/8) \neq \langle 3 \rangle$. In fact, $\langle 3 \rangle = \{1, 3\} \subsetneq \{1, 3, 5, 7\} = \mathcal{U}(\mathbb{Z}/8)$.

Exercise 5.4. Prove that subgroups of a cyclic group are cyclic.

Definition 5.5. Let G be a group and $g \in G$. The **order** of g is the order of the subgroup generated by g . Notation: $|g| = |\langle g \rangle|$.

Theorem 5.6. Let G be a group and $g \in G$ and $n \geq 1$. The following statements are equivalent:

- 1) $|g| = n$.
- 2) $n = \min\{k \in \mathbb{Z}_{\geq 1} : g^k = 1\}$.
- 3) For every $k \in \mathbb{Z}$, $g^k = 1 \iff n \mid k$.
- 4) $\langle g \rangle = \{1, g, \dots, g^{n-1}\}$ and the elements $1, g, \dots, g^{n-1}$ are all different.

Proof. We first prove that (1) \implies (2). If $g = 1$, then $n = 1$. Assume that $g \neq 1$. Since $\langle g \rangle = \{g^k : k \in \mathbb{Z}\}$, there exist integers i and j with $i > j$ such that $g^i = g^j$, that is $g^{i-j} = 1$. In particular, the set $\{k \in \mathbb{Z}_{\geq 1} : g^k = 1\}$ is non-empty and hence has a minimal element, say

$$d = \min\{k \in \mathbb{Z}_{\geq 1} : g^k = 1\}.$$

Thus $\langle g \rangle \subseteq \{1, g, \dots, g^{d-1}\} \subseteq \langle g \rangle$. If $g^k \in \langle g \rangle$, then $k = dq + r$ for some $q, r \in \mathbb{Z}$ with $0 \leq r < d$. Since $g^d = 1$,

$$g^k = g^{dq+r} = (g^d)^q g^r = g^r \in \{1 = g^0, g, g^2, \dots, g^{d-1}\}$$

Moreover, $\{1, g, \dots, g^{d-1}\} \subseteq \langle g \rangle$ and $\{1, g, \dots, g^{d-1}\}$ has d elements.

We now prove that (2) \implies (3). Assume that $g^k = 1$. If we write $k = nt + r$ with $0 \leq r < n$, then $g^k = g^{nt+r} = g^r$. The minimality of n implies that $r = 0$. Hence n divides k . Conversely, if $k = nt$ for some $t \in \mathbb{Z}$, then $g^k = (g^n)^t = 1$.

Let us prove that (3) \implies (4). Clearly, $\{1, g, \dots, g^{n-1}\} \subseteq \langle g \rangle$. To prove the other inclusion, we write $k = nt + r$ with $0 \leq r \leq n-1$. Then

$$g^k = g^{nt+r} = (g^n)^t g^r = g^r,$$

as, by assumption, $g^n = 1$. To see that the elements $1, g, \dots, g^{n-1}$ are all different, it is enough to show that if $g^k = g^l$ with $0 \leq k < l \leq n-1$, then, since $g^{l-k} = 1$ and $0 < l-k \leq n-1$, it follows that $n \leq l-k$ (because by assumption n divides $l-k$, a contradiction).

Finally, the implication (4) \implies (1) is trivial. \square

Corollary 5.7. *If G is a group and $g \in G$ has order n , then*

$$|g^m| = \frac{n}{\gcd(n, m)}.$$

Proof. Let k be such that $(g^m)^k = 1 = g^{mk}$. This means that n divides km , as g has order n . This is also equivalent to the fact that n/d divides mk/d , where $d = \gcd(n, m)$. Therefore, since n/d and m/d are coprime, $(g^m)^k = 1$ is equivalent to n/d divides k , which implies that g^m has order n/d . \square

Exercise 5.8. Let G be a group and $g \in G$. Prove that the following statements are equivalent:

- 1) g has infinite order.
- 2) The set $\{k \in \mathbb{Z}_{\geq 1} : g^k = 1\}$ is empty.
- 3) If $g^k = 1$, then $k = 0$.
- 4) If $k \neq l$, then $g^k \neq g^l$.

Exercise 5.9. Let G be an abelian group. Prove that $T(G) = \{g \in G : |g| < \infty\}$ is a subgroup of G . Compute $T(\mathbb{C}^\times)$.

Exercise 5.10. Let $G = \langle g \rangle$ be a cyclic group.

- 1) If G is infinite, only g and g^{-1} generate G .
- 2) If G is finite of order n , then $G = \langle g^k \rangle$ if and only if k and n are coprime.

The following exercise is a particular case of Cauchy's theorem.

Exercise 5.11. Prove that every group of odd order contains an element of order two.

Let us see some concrete examples:

Example 5.12. In \mathbb{S}_3 we have the following order pattern:

$$|\text{id}| = 1, \quad |(12)| = |(13)| = |(23)| = 2, \quad |(123)| = |(132)| = 3.$$

Example 5.13. In \mathbb{Z} , every non-zero element has infinite order.

Example 5.14. In $\mathbb{Z} \times \mathbb{Z}/6$ there are elements of (in)finite order. For example, $(1, 0)$ has infinite order and $(0, 1)$ has order six.

Example 5.15. The matrix $\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \in \mathbf{GL}_2(\mathbb{R})$ has infinite order.

Example 5.16. The group $G_\infty = \bigcup_{n \geq 1} G_n$ is abelian and infinite. Note that every element of G_∞ has finite order.

We conclude the topic with some exercises.

Exercise 5.17. Compute the orders of the elements of $\mathbb{Z}/6$.

Exercise 5.18. Prove that $a = \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix}$ has order four, $b = \begin{pmatrix} 0 & 1 \\ -1 & -1 \end{pmatrix}$ has order three and compute the order of ab .

Exercise 5.19. Compute the order of $\begin{pmatrix} 1 & 1 \\ -1 & 0 \end{pmatrix} \in \mathbf{GL}_2(\mathbb{R})$.

Exercise 5.20. Prove that in \mathbb{D}_n one has $|r^j s| = 2$ and $|r^j| = n/\gcd(n, j)$.

Exercise 5.21. Prove that a group with finitely many subgroups is finite.

Lecture 3

§6. Lagrange's theorem

Let G be a group and H be a subgroup of G . We say that the elements $x, y \in G$ are (left) equivalent modulo H if $x^{-1}y \in H$. We will use the following notation:

$$x \equiv y \pmod{H} \iff x^{-1}y \in H. \quad (3.1)$$

Exercise 6.1. Prove that (3.1) is an equivalence relation, that is

- 1) $x \equiv x \pmod{H}$ for all x ;
- 2) if $x \equiv y \pmod{H}$, then $y \equiv x \pmod{H}$; and
- 3) if $x \equiv y \pmod{H}$ and $y \equiv z \pmod{H}$, then $x \equiv z \pmod{H}$.

The equivalence classes of this equivalence relation modulo H are the sets of the form $xH = \{xh : h \in H\}$, as the class of an element $x \in G$ is the set

$$\{y \in G : x \equiv y \pmod{H}\} = \{y \in G : x^{-1}y \in H\} = \{y \in G : y \in xH\} = xH.$$

The set xH is called a **left coset** of H in G and x is a **representative** of xH .

Having an equivalence relation modulo H in G allows us to decompose G as a disjoint union of certain subsets related to H .

Proposition 6.2. *Let G be a group and H be a subgroup of G .*

- 1) *If $xH \cap yH \neq \emptyset$, then $xH = yH$.*
- 2) *The group G decomposes as a disjoint union of different left cosets of H .*

Proof. Let us prove the first claim. If $g \in xH \cap yH$, we write $g = xh$ for some $h \in H$. Then

$$gH = (xh)H = x(hH) = xH.$$

Similarly, $gH = yH$. Hence $xH = yH$. The second claim follows from the first one. \square

One can also define right cosets: $x \equiv y \pmod H$ if and only if $xy^{-1} \in H$. In this case, the equivalence classes are the sets of the form Hx with $x \in X$. The set Hx is called a **right coset** with **representative** x of H in G .

Proposition 6.3. *If H is a subgroup of G , then $|Hx| = |H| = |xH|$ for all $x \in G$.*

Proof. Let $x \in G$. The map $H \rightarrow Hx$, $h \mapsto hx$, is bijective with inverse $hx \mapsto h$. Similarly, the map $H \rightarrow xH$, $h \mapsto xh$, is bijective. \square

The map

$$\{\text{right cosets of } H \text{ in } G\} \rightarrow \{\text{left cosets of } H \text{ in } G\}$$

given by $Hx \mapsto x^{-1}H$ is a bijection, as

$$Hx = Hy \iff xy^{-1} \in H \iff (x^{-1})^{-1}y^{-1} \in H \iff x^{-1}H = y^{-1}H.$$

In particular, the number of right cosets of H in G equals the number of left cosets of H in G .

Definition 6.4. If H is a subgroup of G , the **index** of H in G is the number $(G : H)$ of left (or right) cosets of H in G .

Example 6.5. If $G = \mathbb{Z}$ and $S = n\mathbb{Z}$, then

$$a + S = \{a + nq : q \in \mathbb{Z}\} = \{k \in \mathbb{Z} : k \equiv a \pmod n\}.$$

Example 6.6. The subgroups of \mathbb{S}_3 are $\{\text{id}\}$, the order-two subgroups \mathbb{S}_3 , $\langle(12)\rangle$, $\langle(13)\rangle$ and $\langle(23)\rangle$, and the order-three subgroup $\langle(123)\rangle = \{\text{id}, (123), (132)\}$. If $H = \langle(12)\rangle = \{\text{id}, (12)\}$, then

$$\begin{aligned} H &= (12)H = \{\text{id}, (12)\}, \\ (123)H &= (13)H = \{(13), (123)\}, \\ (132)H &= (23)H = \{(23), (132)\}. \end{aligned}$$

Note that our group decomposes as

$$\mathbb{S}_3 = H \cup (123)H \cup (132)H \quad (\text{disjoint union}).$$

Example 6.7. Let $G = \mathbb{R}^2$ with the usual addition and $v \in \mathbb{R}^2$. The line

$$L = \{\lambda v : \lambda \in \mathbb{R}\}$$

is a subgroup of G . For each $p \in \mathbb{R}^2$, the coset $p + L$ is the line parallel to L that passes through p .

The following important theorem will be used extensively.

Theorem 6.8 (Lagrange). *If G is a finite group and H is a subgroup of G , then $|G| = |H|(G : H)$. In particular, $|H|$ divides $|G|$.*

§6 Lagrange's theorem

Proof. We decompose G into equivalence classes modulo H , that is

$$G = \bigcup_{i=1}^n x_i H \quad (\text{disjoint union})$$

for some $x_1, \dots, x_n \in G$, where $n = (G : H)$. Since each of these equivalence classes has exactly $|H|$ elements,

$$|G| = \sum_{i=1}^n |x_i H| = \sum_{i=1}^n |H| = |H|(G : H). \quad \square$$

Let us discuss some corollaries.

Corollary 6.9. *If G is a finite group and $g \in G$, then $g^{|G|} = 1$.*

Proof. By definition, $|g| = |\langle g \rangle|$. Apply Lagrange's theorem to the subgroup $H = \langle g \rangle$ to obtain that

$$g^{|G|} = g^{|H|(G:H)} = (g^{|H|})^{(G:H)} = 1. \quad \square$$

Corollary 6.10. *If G has prime order, then G is cyclic.*

Proof. Let $g \in G \setminus \{1\}$ and $H = \langle g \rangle$. By Lagrange's theorem, $|H|$ divides $|G|$. Thus $|H| = |G|$, as $|G|$ is prime. Therefore $G = H = \langle g \rangle$. \square

Corollary 6.11. *If G is an abelian group and $g, h \in G$ are elements of finite coprime orders, then $|gh| = |g||h|$.*

Proof. Let $n = |g|$, $m = |h|$ and $l = |gh|$. Since G is abelian,

$$(gh)^{nm} = (g^n)^m (h^m)^n = 1.$$

Thus l divides nm . Since $(gh)^l = 1$, $g^l = h^{-l} \in \langle g \rangle \cap \langle h \rangle = \{1\}$ (because $|\langle g \rangle| = n$ and $|\langle h \rangle| = m$ are coprime, nm divides l by Lagrange's theorem). \square

Fermat's little theorem is a particular case of Lagrange's theorem.

Exercise 6.12 (Fermat's little theorem). Let p be a prime number. Prove that

$$a^{p-1} \equiv 1 \pmod{p}$$

for all $a \in \{1, 2, \dots, p-1\}$.

For the next corollary, we need Euler's totient function. Recall that $\varphi(n)$ is the number of positive integers $k \in \{1, \dots, n\}$ coprime with n . The group of units of \mathbb{Z}/n has $\varphi(n)$ elements (because $x \in \mathbb{Z}/n$ is invertible if and only if x and n are coprime).

Exercise 6.13 (Euler's theorem). Let a and n be coprime integers. Prove that $a^{\varphi(n)} \equiv 1 \pmod{n}$.

The converse of Lagrange's theorem does not hold.

Example 6.14. Consider the **alternating group**

$$\mathbb{A}_4 = \{\text{id}, (234), (243), (12)(34), (123), (124), (132), (134), (13)(24), (142), (143), (14)(23)\} \leq \mathbb{S}_4.$$

We claim that \mathbb{A}_4 has no subgroups of order six. If $H \leq \mathbb{A}_4$ is such that $|H| = 6$, then, since $(\mathbb{A}_4 : H) = 2$, for every $x \notin H$ we can decompose \mathbb{A}_4 as disjoint union $\mathbb{A}_4 = H \cup xH$.

For each $g \in \mathbb{A}_4$ we have that $g^2 \in H$ (if $g \notin H$, then, since $g^2 \in \mathbb{A}_4 = H \cup gH$, it follows that $g^2 \in H$). In particular, since $(ijk) = (ikj)^2$, order-three elements of \mathbb{A}_4 belong to H , a contradiction, because \mathbb{A}_4 has eight elements of order three.

We all need a favorite group. Mine is $\mathbf{SL}_2(3)$, the group of 2×2 matrices with coefficients in $\mathbb{Z}/3$ and determinant one.

Exercise 6.15. Prove that

$$\mathbf{SL}_2(3) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : ad - bc = 1, a, b, c, d \in \mathbb{Z}/3 \right\}$$

has order 24 and does not contain subgroups of order 12.

Lecture 4

§7. The symmetric group

Let $\sigma \in \mathbb{S}_n$. We say that σ is an r -cycle if there are $a_1, \dots, a_r \in \{1, \dots, n\}$ such that $\sigma(j) = j$ for all $j \notin \{a_1, \dots, a_r\}$ and

$$\sigma(a_i) = \begin{cases} a_{i+1} & \text{if } i < r, \\ a_1 & \text{if } i = r. \end{cases}$$

For example, (12), (13) and (23) are 2-cycles of \mathbb{S}_3 . We often say that 2-cycles are **transpositions**. The permutations (123) and (132) are 3-cycles of \mathbb{S}_3 .

We say that the permutations $\sigma, \tau \in \mathbb{S}_n$ are **disjoint** if for all $j \in \{1, \dots, n\}$ one has $\sigma(j) = j$ or $\tau(j) = j$. For example, (134) and (25) are disjoint. The permutations (134) and (24) are not disjoint.

If $\sigma \in \mathbb{S}_n$ and j is such that $\sigma(j) = j$, then j is a fixed point of σ . The elements j such that $\sigma(j) \neq j$ are the points moved by σ .

Claim. Disjoint permutations commute.

We now prove that every permutation can be written as a product of disjoint cycles. The proof of the theorem can be omitted in a first lecture. We start with a lemma.

Lemma 7.1. *Let $\sigma = \alpha\beta \in \mathbb{S}_n$ with α and β disjoint permutations. If $\alpha(i) \neq i$, then $\sigma^k(i) = \alpha^k(i)$ for all $k \geq 0$.*

Proof. Without loss of generality, we may assume that $k > 0$. Then

$$\sigma^k(i) = (\alpha\beta)^k(i) = \alpha^k(\beta^k(i)) = \alpha^k(i). \quad \square$$

Theorem 7.2. *Each $\sigma \in \mathbb{S}_n \setminus \{\text{id}\}$ can be written as a product of disjoint cycles of length ≥ 2 . The decomposition is unique up to the order of the factors.*

Proof. We proceed by induction on the number k of elements of $\{1, \dots, n\}$ moved by σ . If $k = 2$, the result is trivial. Assume that the result holds for all permutations moving $< k$ points. Let $i_1 \in \{1, \dots, n\}$ be such that $\sigma(i_1) \neq i_1$. We consider the cycle that contains i_1 . So let $i_2 = \sigma(i_1)$, $i_3 = \sigma(i_2)$... We know that there exists r such that $\sigma(i_r) = i_1$ (otherwise, if $\sigma(i_r) = i_j$ for some $j \in \{2, \dots, n\}$, then

$$\sigma(i_{j-1}) = i_j = \sigma(i_r),$$

a contradiction to the bijectivity of σ). Let $\sigma_1 = (i_1 \cdots i_r)$. By the inductive hypothesis, since $\sigma_1^{-1}\sigma$ moves $< k$ points (because the i_j are fixed points of $\sigma_1^{-1}\sigma$), we can write $\sigma_1^{-1}\sigma = \sigma_2 \cdots \sigma_s$, where $\sigma_2, \dots, \sigma_s$ are disjoint cycles. This implies that $\sigma = \sigma_1 \sigma_2 \cdots \sigma_s$.

We now prove the uniqueness of the decomposition. Assume that

$$\sigma = \sigma_1 \cdots \sigma_s = \tau_1 \cdots \tau_t$$

with $s > 0$. Let $i_1 \in \{1, \dots, n\}$ be such that $\sigma(i_1) \neq i_1$. By the previous lemma, $\sigma^k(i_1) = \sigma_1^k(i_1)$ for all $k \geq 0$. There exists $j \in \{1, \dots, t\}$ such that $\tau_j(i_1) \neq i_1$. Since the τ_k 's commute, without loss of generality, we may assume that $j = 1$. Thus $\sigma^k(i_1) = \tau_1^k(i_1)$ for all $k \geq 0$. This implies that $\sigma_1 = \tau_1$, as σ_1 and τ_1 are cycles. Thus $\sigma_2 \cdots \sigma_s = \tau_2 \cdots \tau_t$. Repeating this procedure, we obtain that $s = t$. Therefore $\sigma_j = \tau_j$ for all j . \square

Corollary 7.3.

- 1) $\mathbb{S}_n = \langle (ij) : i < j \rangle$.
- 2) $\mathbb{S}_n = \langle (12), (13), \dots, (1n) \rangle$.
- 3) $\mathbb{S}_n = \langle (12), (23), \dots, (n-1)n \rangle$.
- 4) $\mathbb{S}_n = \langle (12), (12 \cdots n) \rangle$.

Proof. The first claim follows from the previous theorem, as

$$(a_1 \cdots a_r) = (a_1 a_r)(a_1 a_{r-1}) \cdots (a_1 a_2).$$

If we write $\sigma \in \mathbb{S}_n$ as a product of disjoint cycles, the previous formula implies that $\mathbb{S}_n \subseteq \langle (ij) : i < j \rangle$. The other inclusion is trivial.

For the second claim, one uses the first claim and the formulas

$$(1i)(1j)(1i) = (ij),$$

where $i \neq j$.

To prove the third claim, write σ as a product of transpositions and note that

$$(13) = (12)(23)(12), \quad (1k+1) = (kk+1)(1k)(kk+1)$$

for all $k \geq 3$.

Finally, the fourth claim follows from the third claim and the formula

$$(12 \cdots n)^{k-1}(12)(12 \cdots n)^{1-k} = (k \ k+1),$$

where $k \geq 1$. □

Here is an alternative proof of the first claim of Corollary 7.3. We must show that every permutation can be written as a product of transpositions. Let us assume that n persons are invited to a concert. They sit in the first row without following the seat number on their tickets. How can we put each person in the right seat? First, we locate the person that should be seated in the first place. Then we ask this person to interchange seats with the person seated in the first place. Then we identify the person that should be seated in the second spot. We then ask this person to interchange seats with the person seated in the second spot. We do the same with the third spot, the fourth spot... Once the process is finished, we have decomposed our permutation into a product of transpositions.

Exercise 7.4. Following the tricks of the proof of Corollary 7.3, find the different decompositions of the permutation $(1324)(56)(789) \in \mathbb{S}_9$.

Every permutation yields a permutation matrix. For example, the matrix corresponding to $\sigma = \text{id} \in \mathbb{S}_3$ is the 3×3 identity matrix. The permutation $\sigma = (123)$ yields the matrix

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

If e_1, e_2, e_3 is the standard basis of $\mathbb{R}^{3 \times 1}$, then

$$P_\sigma(e_1) = e_2, \quad P_\sigma(e_2) = e_1, \quad P_\sigma(e_3) = e_3.$$

The permutation matrix P_σ associated with $\sigma \in \mathbb{S}_n$, permutes the elements of the standard basis of $\mathbb{R}^{n \times 1}$ in the way σ permutes the elements of $\{1, 2, \dots, n\}$.

If $\sigma \in \mathbb{S}_n$, then

$$P_\sigma = \sum_{i=1}^n E_{\sigma(i), i},$$

where $E_{i,j}$ is the matrix with a one in position (i, j) and zero in all other entries. Recall the following formulas:

$$E_{i,j}E_{k,l} = \begin{cases} E_{i,l} & \text{if } j = k, \\ 0 & \text{if } j \neq k. \end{cases} \quad (4.1)$$

The determinant of a permutation matrix equals ± 1 . Why?

Proposition 7.5. If $\sigma, \tau \in \mathbb{S}_n$, then $P_{\sigma\tau} = P_\sigma P_\tau$.

Proof. We compute

$$\begin{aligned}
P_\sigma P_\tau &= \left(\sum_{i=1}^n E_{\sigma(i),i} \right) \left(\sum_{j=1}^n E_{\tau(j),j} \right) \\
&= \sum_{i=1}^n \sum_{j=1}^n E_{\sigma(i),i} E_{\tau(j),j} \\
&= \sum_{j=1}^n E_{\sigma(\tau(j)),j} \\
&= P_{\sigma\tau},
\end{aligned}$$

where the double sum is zero unless $i = \tau(j)$. \square

Definition 7.6. The **sign** of a permutation $\sigma \in \mathbb{S}_n$ is the determinant of the matrix P_σ , that is $\text{sign}(\sigma) = \det P_\sigma$. A permutation σ is said to be **even** if $\text{sign}(\sigma) = 1$ and **odd** if $\text{sign}(\sigma) = -1$.

The identity is an even permutation. Every 3-cycle is an even permutation. Each transposition is an odd permutation.

Proposition 7.7. If $\sigma, \tau \in \mathbb{S}_n$, then $\text{sign}(\sigma\tau) = (\text{sign } \sigma)(\text{sign } \tau)$.

Proof. We compute

$$\text{sign}(\sigma\tau) = \det(P_\sigma P_\tau) = (\det P_\sigma)(\det P_\tau) = \text{sign}(\sigma) \text{sign}(\tau). \quad \square$$

Each permutation can be written as a product of transpositions. There is no uniqueness of this decomposition. For example,

$$(13) = (12)(23)(12) = (12)(23)(12)$$

However, the following result holds: If $\sigma = \sigma_1 \cdots \sigma_s$ is a product of transpositions, then $\text{sign}(\sigma) = (-1)^s$. In particular, σ is even if and only if s is even.

Example 7.8. We claim that if $n \geq 3$ then $Z(\mathbb{S}_n) = \{\text{id}\}$. Assume that $Z(\mathbb{S}_n) \neq \{\text{id}\}$. Let $\sigma \in Z(\mathbb{S}_n)$ be such that $\sigma(i) = j$ for some $i \neq j$. Since $n \geq 3$, there exists $k \in \{1, \dots, n\} \setminus \{i, j\}$. Thus $\tau = (jk) \in \mathbb{S}_n$. Since σ is central,

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

a contradiction.

The **alternating group**

$$\mathbb{A}_n = \{\sigma \in \mathbb{S}_n : \text{sign}(\sigma) = 1\}$$

is the subgroup of \mathbb{S}_n formed by even permutations.

Proposition 7.9. $|\mathbb{A}_n| = n!/2$.

§7 The symmetric group

Proof. Let $\sigma = (12) \notin \mathbb{A}_n$. We claim that $\mathbb{S}_n = \mathbb{A}_n \cup \mathbb{A}_n\sigma$ (disjoint union), where $\mathbb{A}_n\sigma = \{\tau\sigma : \tau \in \mathbb{A}_n\}$. If $\tau \in \mathbb{S}_n$ is such that $\tau \notin \mathbb{A}_n$, then

$$\text{sign}(\tau\sigma) = (\text{sign } \tau)(\text{sign } \sigma) = 1.$$

Thus $\tau\sigma \in \mathbb{A}_n$. Therefore $\tau \in \mathbb{A}_n\sigma$. Since $|\mathbb{A}_n\sigma| = |\mathbb{A}_n|$ (because the map $\mathbb{A}_n \rightarrow \mathbb{A}_n\sigma$, $x \mapsto x\sigma$, is bijective), we conclude that $n! = |\mathbb{S}_n| = 2|\mathbb{A}_n|$. \square

Example 7.10. A direct calculation shows that $\mathbb{A}_3 = \{\text{id}, (123), (132)\}$. Similarly,

$$\begin{aligned} \mathbb{A}_4 = \{ & \text{id}, (234), (243), (12)(34), (123), (124), \\ & (132), (134), (13)(24), (142), (143), (14)(23) \} \end{aligned}$$

The group \mathbb{A}_3 is abelian. If $n \geq 4$, then \mathbb{A}_n is non-abelian. For example, (123) and (124) do not commute.

Proposition 7.11. $\mathbb{A}_n = \langle \{3\text{-cycles}\} \rangle$.

Proof. Each 3-cycle is an even permutation, as $(ijk) = (ik)(ij)$. To prove the other inclusion, let $\sigma \in \mathbb{A}_n$. Write $\sigma = \sigma_1 \cdots \sigma_s$ for some even integer s and transpositions $\sigma_1, \dots, \sigma_s$. Now the claim follows from the formulas

$$(kl)(ij) = (kl)(ki)(ki)(ij) = (kil)(ijk), \quad (ik)(ij) = (ijk). \quad \square$$

Proposition 7.11 has several important applications.

Example 7.12. If $n \geq 5$, then $[\mathbb{A}_n, \mathbb{A}_n] = \mathbb{A}_n$. To prove the non-trivial inclusion, it is enough to note that \mathbb{A}_n is generated by 3-cycles and that, since $n \geq 5$, each 3-cycle is a product of commutators:

$$(abc) = [(acd), (ade)][(ade), (abd)],$$

where $\#\{a, b, c, d, e\} = 5$.

Can you compute the commutator subgroup of \mathbb{A}_4 ?

Example 7.13. If $n \geq 3$, then $[\mathbb{S}_n, \mathbb{S}_n] = \mathbb{A}_n$. First, we prove that $[\mathbb{S}_n, \mathbb{S}_n] \subseteq \mathbb{A}_n$. If $\sigma \in [\mathbb{S}_n, \mathbb{S}_n]$, say $\sigma = [\sigma_1, \tau_1][\sigma_2, \tau_2] \cdots [\sigma_k, \tau_k]$, then

$$\text{sign}(\sigma) = \text{sign}([\sigma_1, \tau_1]) \cdots \text{sign}([\sigma_k, \tau_k]) = 1.$$

Conversely, if $\sigma \in \mathbb{A}_n$, by the previous proposition, we can write σ as a product of 3-cycles. From this, the claim follows, as each 3-cycle is a commutator:

$$(abc) = (ab)(ac)(ab)(ac) = [(ab), (ac)] \in [\mathbb{S}_n, \mathbb{S}_n].$$

Lecture 5

§8. Quotients

If G is a group and N is a subgroup of G , we want to know when the set G/N of left cosets of N in G is a group with the operation

$$G/N \times G/N \rightarrow G/N, \quad (xN, yN) \mapsto xyN, \quad (5.1)$$

that is, when this operation is well-defined. What does this mean? We need to check that (5.1) is indeed a function. For that purpose, we need to prove that (5.1) does not depend on the representatives of left cosets used. Thus we need to show that $xN = x_1N$ and $yN = y_1N$, then $xyN = x_1y_1N$.

Let us try to understand this condition. If $x^{-1}x_1 \in N$ and $y^{-1}y_1 \in N$, then $x_1 = xn$ and $y_1 = ym$ for some $m, n \in N$. Thus

$$(xy)^{-1}(x_1y_1) = y^{-1}x^{-1}x_1y_1 = y^{-1}nym \in N$$

if and only if $y^{-1}ny \in N$.

Example 8.1. If $G = \mathbb{S}_3$ and $H = \langle (12) \rangle$, then $(xN, yN) \mapsto xyN$ is not a function. Recall that $G/H = \{H, (123)H, (132)H\}$, where $H = (12)H$, $(123)H = (13)H$ and $(132)H = (23)H$. Then

$$(132)N = (13)(23)N = (13)N(23)N = (123)N(132)N = N,$$

a contradiction.

Definition 8.2. Let G be a group. A subgroup N of G is said to be **normal** if $gNg^{-1} \subseteq N$ for all $g \in G$. Notation: If N is normal in G , then $N \trianglelefteq G$.

In an abelian group, every subgroup is normal.

Proposition 8.3. Let N be a subgroup of G . The following statements are equivalent:

1) $gNg^{-1} \subseteq N$ for all $g \in G$.

- 2) $gNg^{-1} = N$ for all $g \in G$.
 3) $gN = Ng$ for all $g \in G$.

Proof. We only prove that 1) \implies 2), as the other implications are trivial. If $n \in N$ and $g \in G$, then $n = g(g^{-1}ng)g^{-1} \in gNg^{-1}$. \square

Proposition 8.4. Let N be a subgroup of G . The following statements are equivalent:

- 1) N is normal in G .
 2) $(gN)(hN) = (gh)N$ for all $g, h \in G$.

Proof. We first prove that 1) \implies 2). Let $g \in G$. Since $gNg^{-1} = N$,

$$(gN)(hN) = g(Nh)N = g(hN)N = (gh)N.$$

We now prove that 2) \implies 1). If $g \in G$, then

$$gNg^{-1} \subseteq (gN)(g^{-1}N) = (gg^{-1})N = N. \quad \square$$

If G is a group, then $\{1\}$ and G are always normal subgroups.

Example 8.5. If G is a group, then $Z(G)$ is a normal subgroup of G . Moreover, if $N \leq Z(G)$, then $N \trianglelefteq G$.

Example 8.6. If G is a group, then $[G, G]$ is a normal subgroup of G . If $x \in [G, G]$ and $g \in G$, then $gxg^{-1} = (gxg^{-1}x^{-1})x = [g, x]x \in [G, G]$. Alternatively,

$$g \left(\prod_{i=1}^k [x_i, y_i] \right) g^{-1} = \prod_{i=1}^k [gx_i g^{-1}, gy_i g^{-1}]$$

for all $g, x_1, \dots, x_k, y_1, \dots, y_k \in G$.

Example 8.7. Let $n \geq 2$. Then \mathbb{A}_n is a normal subgroup of \mathbb{S}_n . If $\sigma \in \mathbb{A}_n$ and $\tau \in \mathbb{S}_n$, then $\tau\sigma\tau^{-1} \in \mathbb{A}_n$, as

$$\text{sign}(\tau\sigma\tau^{-1}) = \text{sign}(\sigma) = 1.$$

Example 8.8. If N is a subgroup of G such that $(G : N) = 2$, then N is normal in G . We need to show that $gN = Ng$ for all $g \in G$. Let $g \in G$. If $g \in N$, then $gN = Ng$. If $g \notin N$, then $gN \neq N$. Since $(G : N) = 2$, we can decompose G as the disjoint union $G = N \cup gN$. Hence $gN = G \setminus N$. Similarly, $Ng = G \setminus N$ and therefore $gN = Ng$.

Example 8.9. As a particular case of the previous example, $\langle (123) \rangle \trianglelefteq \mathbb{S}_3$. Note that $\langle (12) \rangle$ is not normal in \mathbb{S}_3 . For example, $(13)(12)(13) = (23) \notin \langle (12) \rangle$.

Example 8.10. $\mathbf{SL}_n(\mathbb{R})$ is normal in $\mathbf{GL}_n(\mathbb{R})$. If $g \in \mathbf{GL}_n(\mathbb{R})$ and $x \in \mathbf{SL}_n(\mathbb{R})$, then $\det(gxg^{-1}) = (\det g)(\det x)(\det g)^{-1} = 1$.

Example 8.11. The Klein group $K = \{\text{id}, (12)(34), (13)(24), (14)(23)\}$ is normal in \mathbb{S}_4 . We need to show that $\sigma K \sigma^{-1} \subseteq K$ for all $\sigma \in \mathbb{S}_4$. Do we need to check this for every element of \mathbb{S}_4 ? No. One always has tricks! Recall that \mathbb{S}_4 is generated by (12) and (1234) . Since every element of \mathbb{S}_4 is a word on (12) and (1234) , it is enough to see that $\sigma K \sigma^{-1} \subseteq K$ for all $\sigma \in \{(12), (1234)\}$. We left as an exercise to show that

$$(12)K(12)^{-1} \subseteq K, \quad (1234)K(1234)^{-1} \subseteq K.$$

Exercise 8.12. Let $G = \mathbb{R} \times \mathbb{R}^\times$ with the operation

$$(x, y)(u, v) = (x + yu, yv).$$

Prove that $\{(x, 1) : x \in \mathbb{R}\}$ is normal in G and that $\{(0, y) : y \in \mathbb{R}^\times\}$ is not.

Let us compute the list of normal subgroups of \mathbb{A}_4 .

Example 8.13. We claim that $\{\text{id}\}$, $K = \{\text{id}, (12)(34), (13)(24), (14)(23)\}$ and \mathbb{A}_4 are the normal subgroups of \mathbb{A}_4 .

Since $\mathbb{A}_4 = \{3\text{-cycles}\} \cup K$, K is the only subgroup of \mathbb{A}_4 of order four. This implies that K is normal in \mathbb{A}_4 (because every conjugate gKg^{-1} of K is a subgroup of \mathbb{A}_4 of order four). Let $N \neq \{\text{id}\}$ be a normal subgroup of \mathbb{A}_4 .

If N contains a 3-cycle, say $(abc) \in N$, then

$$(acd) = (bcd)(abc)(bcd)^{-1} \in N$$

and hence $N = \mathbb{A}_4$ (because N contains every 3-cycle).

Assume that N does not contain 3-cycles. Then some non-trivial element of K belongs to N , say $(ab)(cd) \in N$. Hence

$$(ac)(bd) = (bcd)(ab)(cd)(bcd)^{-1} \in N, \quad (ad)(bc) = (ab)(cd)(ac)(bd) \in N$$

and therefore $N = K$.

Normality is not transitive.

Exercise 8.14. Let $G = \mathbb{D}_4$ be the dihedral group of order eight. Let $N = \langle s, r^2 \rangle$ and $H = \langle s \rangle$. Prove that H is normal in N , N is normal in G but H is not normal in G .

Example 8.15. We claim that $\{\text{id}\}$, K , \mathbb{A}_4 and \mathbb{S}_4 are the normal subgroups of \mathbb{S}_4 .

Let N be a normal subgroup of \mathbb{S}_4 . If $N \subseteq \mathbb{A}_4$, then N is normal in \mathbb{A}_4 and hence either $N = \{\text{id}\}$, $N = K$ or $N = \mathbb{A}_4$. Assume that $N \not\subseteq \mathbb{A}_4$, that is N contains an odd permutation. If $\sigma \in \mathbb{S}_4$ is odd, then σ is either a transposition or a 4-cycle.

If N contains a transposition, then all transpositions belong to N , as

$$\tau(ij)\tau^{-1} = (\tau(i)\tau(j))$$

for all $\tau \in \mathbb{S}_4$. In this case, $N = \mathbb{S}_4$ because the transpositions generate \mathbb{S}_4 .

If N contains a 4-cycle, all 4-cycles belong to N , as

$$\tau(ijkl)\tau^{-1} = (\tau(i)\tau(j)\tau(k)\tau(l))$$

for all $\tau \in \mathbb{S}_4$ and $K \subseteq N$ because

$$(ac)(bd) = (abcd)^2.$$

This implies that $|N| \geq 10$. Since $K \subseteq N$, $|N \cap \mathbb{A}_4| \geq 5$. Moreover, $N \cap \mathbb{A}_4$ is a normal subgroup of \mathbb{A}_4 . Hence $N \cap \mathbb{A}_4 = \mathbb{A}_4 \subseteq N$. Therefore $N = \mathbb{S}_4$.

The following theorem is crucial.

Theorem 8.16. *If N is a normal subgroup of G , then G/N is a group with the operation $(xN)(yN) = (xy)N$.*

Exercise 8.17. Prove Theorem 8.16.

We will see examples of quotient groups later.

Exercise 8.18. Let H be a normal subgroup of G . Prove that G/H is abelian if and only if $[G, G] \subseteq H$.

As an application, we compute the commutator subgroup of \mathbb{A}_4 .

Example 8.19. $[\mathbb{A}_4, \mathbb{A}_4] = K = \{\text{id}, (12)(34), (13)(24), (14)(23)\}$. We know that K is normal in \mathbb{A}_4 . Since \mathbb{A}_4/K has order three, it is abelian. Then $[\mathbb{A}_4, \mathbb{A}_4] \subseteq K$. Since

$$(ab)(cd) = [(abc), (cda)],$$

we conclude that $K \subseteq [\mathbb{A}_4, \mathbb{A}_4]$.

Exercise 8.20. If $G/Z(G)$ is cyclic, then G is abelian.

Exercise 8.21. If S is a subgroup of G , the **normalizer** of S in G is the set

$$N_G(S) = \{g \in G : gSg^{-1} = S\}.$$

Prove the following statements:

- 1) $N_G(S) \leq G$.
- 2) $S \trianglelefteq N_G(S)$.
- 3) If $S \leq T \leq G$ and $S \trianglelefteq T$, then $T \leq N_G(S)$.

The normalizer of a subgroup S in G is the largest subgroup of G that contains S as a normal subgroup.

Definition 8.22. A group G is **simple** if $G \neq \{1\}$ and G and $\{1\}$ are the only normal subgroups of G .

If p is a prime number, then Lagrange's theorem implies that \mathbb{Z}/p is a simple group. For $n \geq 5$, the alternating group \mathbb{A}_n is simple. However, we will not prove this in this course.

Exercise 8.23. Let H be a subgroup of G such that $p = (G : H)$ is a prime number. Prove that the following statements are equivalent:

- 1) H is normal in G .
- 2) If $g \in G \setminus H$, then $g^p \in H$.
- 3) If $g \in G \setminus H$, then $g^n \in H$ for some n with no prime divisors $< p$.
- 4) If $g \in G \setminus H$, then $g^k \notin H$ for all $k \in \{2, \dots, p-1\}$.

We now present two applications of the previous exercise.

Exercise 8.24. Let G be a finite group and p be the smallest prime number dividing G . Prove that if H is a subgroup of G with $(G : H) = p$, then H is normal in G .

Exercise 8.25. Let p be a prime number and G be a group such that every element of G has order a power of p . If H is a subgroup of G of index p , then H is normal in G .

Lecture 6

§9. Permutable subgroups

If H and K are subgroups of G , let

$$HK = \{hk : h \in H, k \in K\}.$$

Note that

$$H \cup K \subseteq HK \subseteq \langle H \cup K \rangle.$$

When HK is a subgroup of G ? Note that $HK \leq G$ if and only if $\langle H \cup K \rangle = HK$.

Proposition 9.1. *Let H and K be subgroups of G . Then HK is a subgroup of G if and only if $HK = KH$.*

Proof. Assume that $HK = KH$. Since $1 \in H \cap K$, $HK \neq \emptyset$. If $h \in H$ and $k \in K$, then $(hk)^{-1} = k^{-1}h^{-1} \in KH = HK$. Moreover,

$$(HK)(HK) = H(KH)K = H(HK)K = (HH)(KK) = HK.$$

Thus HK is closed under multiplication.

Now assume that HK is a subgroup of G . Since $H \subseteq HK$, $K \subseteq HK$ and HK closed under multiplication, $KH \subseteq (HK)(HK) \subseteq HK$. Conversely, let $g \in HK$. Since $g^{-1} \in HK$, there exist $h \in H$ and $k \in K$ such that $g^{-1} = hk$. Thus $HK \subseteq KH$, as $g = k^{-1}h^{-1} \in KH$. \square

Exercise 9.2. Let H and K be subgroups of G . Prove that if H is normal in G , then HK is a subgroup of G .

Example 9.3. Let $G = \mathbb{S}_4$. The subgroups $H = \langle (12) \rangle$ and $K = \langle (34) \rangle$ satisfy that $HK = KH = \{\text{id}, (12), (34), (12)(34)\}$ is a subgroup of \mathbb{S}_4 . Note that neither H nor K are normal in G .

Exercise 9.4. Let G be a group and S be a subgroup of G . If $T \leq N_G(S)$, then TS is a group and $S \leq TS$.

Two subgroups H and K of G are said to be **permutable** if $HK = KH$.

Theorem 9.5. *Let H and K be finite subgroups of G . Then*

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

Proof. Let $L = H \cap K$. We decompose H as a disjoint union of left cosets of L , say $H = \cup_{i=1}^k x_i L$, where $k = (H : L)$. Note that $LK = K$, as $L \subseteq K$. Moreover, $K \subseteq 1K \subseteq LK$. Then

$$HK = \bigcup_{i=1}^k x_i LK = \bigcup_{i=1}^k x_i K,$$

In particular, since the union is disjoint,

$$|HK| = \sum_{i=1}^k |x_i K| = k|K| = \frac{|H||K|}{|H \cap K|}. \quad \square$$

In the theorem, we do not assume that HK is a subgroup of G .

As an application, the theorem yields a different solution to Exercise 8.24 of page 29. If $\{gHg^{-1} : g \in G\} = \{H\}$, then H is normal in G . Assume that there exists $g \in G$ such that $H \neq g^{-1}Hg = K$. Since $(H : H \cap K)$ divides $|H|$ and all prime divisors of $|G|$ are $\geq p$, it follows that $(H : H \cap K) \geq p$. Thus

$$|HK| = \frac{|H||K|}{|H \cap K|} \geq p|K| = |G|$$

as $(G : H) = p$ y $|K| = |H|$. In particular, $HK = G$. Since $K = g^{-1}Hg$, $g = h(g^{-1}h_1g)$ for some $h, h_1 \in H$. Thus

$$1 = hg^{-1}h_1 \implies h_1h = g \in H \implies H = K,$$

a contradiction.

Example 9.6. Let $G = \mathbb{S}_3$, $H = \langle (12) \rangle$ and $K = \langle (23) \rangle$. Then

$$HK = \{\text{id}, (12), (23), (123)\}$$

is not a subgroup of G , as by Lagrange's theorem, G cannot have subgroups of four elements. Another way to see that HK is not a subgroup of G follows from the fact that $KH = \{\text{id}, (12), (23), (132)\} \neq HK$.

Example 9.7. Let $G = \mathbb{S}_3$, $H = \langle (12) \rangle$ and $K = \langle (123) \rangle$. Since K is normal in G , HK is a subgroup of G . By Lagrange's theorem, $|HK| = 6$ and hence $G = HK$. Each $g \in G$ can be written uniquely as $g = hk$ for some $h \in H$ and $k \in K$ (one can prove this either considering all possible cases or using the fact that $H \cap K = \{\text{id}\}$). It follows that the map

$$H \times K \rightarrow G, \quad (h, k) \mapsto hk,$$

is bijective. Note that this bijective map is not compatible with the operation of G , as $(h_1 k_1)(h_2 k_2) \neq (h_1 h_2)(k_1 k_2)$.

§10. Homomorphisms

Definition 10.1. Let G and H be groups. A map $f: G \rightarrow H$ is said to be a **group homomorphism** if $f(xy) = f(x)f(y)$ for all $x, y \in G$.

If $f: G \rightarrow H$ is a group homomorphism, then $f(1) = 1$. Why?

If a group homomorphism is injective, it will be called a **monomorphism**. If it is surjective, an **epimorphism**. If it is bijective, an **isomorphism**. Two groups G and H are said to be **isomorphic** (notation: $G \simeq H$) if there exists an isomorphism $G \rightarrow H$.

Example 10.2.

- 1) If G is a group, the identity map $\text{id}: G \rightarrow G$ is a group homomorphism.
- 2) If G and H are groups, the map $e: G \rightarrow H$, $e(g) = 1_H$, is a group homomorphism.
- 3) For each $n \in \mathbb{Z}$, the map $\mathbb{Z} \rightarrow \mathbb{Z}$, $x \mapsto nx$, is a group homomorphism.
- 4) If G is an abelian group and $n \in \mathbb{Z}$, the map $G \rightarrow G$, $g \mapsto g^n$, is a group homomorphism.

Example 10.3. Let G be a group and $g \in G$. The map $\gamma_g: G \rightarrow G$, $\gamma_g(x) = gxg^{-1}$, is called **conjugation** by g and it is a group homomorphism.

Example 10.4. The map $\exp: \mathbb{R} \rightarrow \mathbb{R}^\times$, $\exp(x) = e^x$, is a group homomorphism.

Example 10.5. The inclusion map $\mathbb{Z} \hookrightarrow \mathbb{Q}$ is an injective group homomorphism.

Generally, if S is a subgroup of G , then the **inclusion map** $S \hookrightarrow G$ is a group homomorphism.

Example 10.6. $\det: \text{GL}_2(\mathbb{R}) \rightarrow \mathbb{R}^\times$ is a group homomorphism.

Example 10.7. Let $f: G \rightarrow H$ be a group homomorphism and S be a subgroup of G . The **restriction** $f|_S: S \rightarrow H$ is a group homomorphism.

Example 10.8. The map $f: \mathbb{R} \rightarrow \mathbb{C}^\times$, $f(x) = \cos x + i \sin x$, is a group homomorphism, as $f(x+y) = f(x)f(y)$ for all $x, y \in \mathbb{R}$.

Exercise 10.9. Let $f: G \rightarrow H$ be a group homomorphism. Prove that $f(1) = 1$, $f(g^{-1}) = f(g)^{-1}$ and $f(g^n) = f(g)^n$ for all $g \in G$ and $n \in \mathbb{Z}$.

Example 10.10. Let $f: \mathbb{R}_{>0} \rightarrow \mathbb{R}$, $f(x) = \log(x)$. The formula

$$\log(xy) = \log(x) + \log(y)$$

implies that f is a group homomorphism. The previous exercise resembles the following properties of the logarithm function:

$$\log(1) = 0, \quad \log\left(\frac{1}{x}\right) = -\log(x), \quad \log(x^n) = n\log(x).$$

Definition 10.11. Let $f: G \rightarrow H$ be a group homomorphism. The **kernel** of f is the set $\ker f = \{x \in G : f(x) = 1\}$.

The following property of the kernel is crucial: If $f: G \rightarrow H$ is a group homomorphism, then $f(x) = f(y)$ if and only if $x = yk$ for some $k \in \ker f$.

Example 10.12. Let $f: \mathcal{U}(\mathbb{Z}/21) \rightarrow \mathcal{U}(\mathbb{Z}/21)$, $f(x) = x^3$. Then f is a group homomorphism and $\ker f = \{1, 4, 16\}$ y $f(\mathcal{U}(\mathbb{Z}/21)) = \{1, 8, 13, 20\}$.

Exercise 10.13. Let

$$\text{Aff}(\mathbb{R}) = \left\{ \begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix} : a \in \mathbb{R}^\times, b \in \mathbb{R} \right\} \leq \text{GL}_2(\mathbb{R}).$$

Prove that the map

$$f: \text{Aff}(\mathbb{R}) \rightarrow \mathbb{R}^\times, \quad \begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix} \mapsto a$$

is a group homomorphism such that

$$\ker f = \left\{ \begin{pmatrix} 1 & b \\ 0 & 1 \end{pmatrix} \right\}.$$

Show that $g: \text{Aff}(\mathbb{R}) \rightarrow \mathbb{R}$, $\begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix} \mapsto b$, is not a group homomorphism

Example 10.14. Sea $f: \mathbb{R} \rightarrow \mathbb{C}^\times$, $f(x) = \cos x + i \sin x$. Entonces

$$\ker f = \{2\pi k : k \in \mathbb{Z}\} = 2\pi\mathbb{Z}.$$

Definition 10.15. The **image** of a group homomorphism $f: G \rightarrow H$ is the set

$$f(G) = \{f(x) : x \in G\}.$$

Proposition 10.16. Let $f: G \rightarrow H$ be a group homomorphism. The following properties hold:

- 1) $\ker f$ is a normal subgroup of G .
- 2) $f(G)$ is a subgroup of H .

Proof. We only prove the first claim. We first need to show that $\ker f$ is a subgroup of G . Note that $1 \in \ker f$. If $x, y \in \ker f$, then $xy^{-1} \in \ker f$ (because f is a group homomorphism, $f(xy^{-1}) = f(x)f(y)^{-1} = 1$). Now we prove that $\ker f$ is normal in G . Let $x \in \ker f$ and $g \in G$. Then $gxg^{-1} \in \ker f$, as

$$f(gxg^{-1}) = f(g)f(x)f(g)^{-1} = f(g)f(g)^{-1} = 1. \quad \square$$

The image of a group homomorphism is not always a normal subgroup.

Example 10.17. The inclusion map $\langle (12) \rangle \hookrightarrow \mathbb{S}_3$ is a group homomorphism. Its image is not a normal subgroup of \mathbb{S}_3 .

Example 10.18. Recall that $\mathcal{U}(\mathbb{Z}/21) = \{1, 2, 4, 5, 8, 10, 11, 13, 16, 17, 19, 20\}$ is an abelian group. The map $f: \mathcal{U}(\mathbb{Z}/21) \rightarrow \mathcal{U}(\mathbb{Z}/21)$, $f(x) = x^3$, is a group homomorphism. The image of f equals $\{1, 8, 13, 20\}$, a subgroup of $\mathcal{U}(\mathbb{Z}/21)$.

Example 10.19. The map $\text{sign}: \mathbb{S}_n \rightarrow \{-1, 1\}$ is a surjective group homomorphism and $\ker(\text{sign}) = \mathbb{A}_n$. In particular, \mathbb{A}_n is a normal subgroup of \mathbb{S}_n .

Example 10.20. If N is a normal subgroup of G , the map $\pi: G \rightarrow G/N$, $x \mapsto xN$, is a surjective group homomorphism such that $\ker \pi = N$. The map π is called the **canonical homomorphism** $G \rightarrow G/N$.

The previous example implies that every normal subgroup of a group G is the kernel of a group homomorphism with domain G .

Exercise 10.21. Let $f: G \rightarrow H$ be a group homomorphism. Prove the following statements:

- 1) If $S \leq G$, then $f(S) \leq H$ and $f^{-1}(f(S)) = S \ker f$.
- 2) If $T \leq H$, then $\ker f \leq f^{-1}(T) \leq G$ and $f(f^{-1}(T)) = T \cap f(G)$.
- 3) f is injective if and only if $\ker f = \{1\}$.
- 4) If $g \in G$ has finite order, then $|f(g)|$ divides $|g|$.

If $f: G \rightarrow H$ is a group isomorphism, then $f^{-1}: H \rightarrow G$ is an isomorphism. A group homomorphism $f: G \rightarrow H$ is an isomorphism if and only if there exists a group homomorphism $g: H \rightarrow G$ such that $g \circ f = \text{id}_G$ and $f \circ g = \text{id}_H$.

Example 10.22. $\mathbb{S}_2 \simeq \mathbb{Z}/2 \simeq G_2$.

Example 10.23. $\mathbb{D}_3 \simeq \mathbb{S}_3$ and an isomorphism is given by $\mathbb{D}_3 \rightarrow \mathbb{S}_3$,

$$1 \mapsto \text{id}, \quad r \mapsto (123), \quad r^2 \mapsto (132), \quad s \mapsto (12), \quad rs \mapsto (13), \quad r^2s \mapsto (23).$$

Example 10.24. $\mathbb{Z}/2 \times \mathbb{Z}/3 \simeq \mathbb{Z}/6$ and an isomorphism is given by

$$(0, 0) \mapsto 0, \quad (1, 0) \mapsto 3, \quad (0, 1) \mapsto 4, \quad (1, 1) \mapsto 1, \quad (0, 2) \mapsto 2, \quad (1, 2) \mapsto 5.$$

Example 10.25. The map $\log: \mathbb{R}_{>0} \rightarrow \mathbb{R}$ is a group homomorphism. Since \log is bijective, $\mathbb{R}_{>0} \simeq \mathbb{R}$.

If $f: G \rightarrow H$ is an isomorphism, then $|g| = |f(g)|$ for all $g \in G$.

Example 10.26. $\mathbb{Z}/2 \times \mathbb{Z}/2 \not\simeq \mathbb{Z}/4$, as $\mathbb{Z}/2 \times \mathbb{Z}/2$ has no elements of order four.

Example 10.27. $\mathbb{Q}/\mathbb{Z} \neq \mathbb{Q}$. Both groups are abelian, but they are not isomorphic. To show this, note that every non-trivial element of \mathbb{Q} has infinite order (if $kx = 0$ for some $k \in \mathbb{Z}$ and $x \in \mathbb{Q} \setminus \{0\}$, then $k = 0$). However, every non-trivial element of \mathbb{Q}/\mathbb{Z} has finite order. In fact, if $x = r/s \in \mathbb{Q}$, then, since

$$s(x + \mathbb{Z}) = sx + \mathbb{Z} = r + \mathbb{Z} = \mathbb{Z}$$

we conclude that $|x + \mathbb{Z}| \leq s$.

Example 10.28. Note that $\mathcal{U}(\mathbb{Z}/5) \simeq \mathcal{U}(\mathbb{Z}/10)$, as both groups are cyclic of order four.

Exercise 10.29. Prove that $\mathcal{U}(\mathbb{Z}/10) \neq \mathcal{U}(\mathbb{Z}/12)$.

Exercise 10.30. Prove that $F = \{\sigma \in \mathbb{S}_n : \sigma(n) = n\} \leq \mathbb{S}_n$ and $F \simeq \mathbb{S}_{n-1}$.

If G and H are groups, let

$$\text{Hom}(G, H) = \{f : G \rightarrow H : f \text{ is a group homomorphism}\}.$$

Example 10.31. We claim that $\text{Hom}(\mathbb{Q}, \mathbb{Z}) = \{0\}$. Let $f \in \text{Hom}(\mathbb{Q}, \mathbb{Z})$ and p be a prime number. If $x \in \mathbb{Q}$, then, since

$$f(x) = f(p(x/p)) = pf(x/p),$$

p divides $f(x)$. It follows that $f(x) = 0$ for all $x \in \mathbb{Q}$, as p is arbitrary.

Example 10.32. If G is a group, then $\text{Hom}(\mathbb{Z}, G) = \{k \mapsto g^k : g \in G\}$. For each $g \in G$, the map $\mathbb{Z} \rightarrow G$, $k \mapsto g^k$, is a group homomorphism, as $k+l \mapsto g^{k+l} = g^k g^l$. Let $f \in \text{Hom}(\mathbb{Z}, G)$ and $g = f(1)$. If $k > 0$,

$$f(k) = f(\underbrace{1 + \cdots + 1}_{k\text{-times}}) = f(1)^k = g^k.$$

If $k < 0$, then

$$f(k) = f(\underbrace{(-1) + \cdots + (-1)}_{|k|\text{-times}}) = f(-1)^{-k} = (g^{-1})^{-k} = g^k.$$

Example 10.33. We claim that $\text{Hom}(\mathbb{Z}/8, \mathbb{Z}/10)$ has exactly two elements. Let $f : \mathbb{Z}/8 \rightarrow \mathbb{Z}/10$ be a non-trivial homomorphism. If $n = |f(1)|$, then n divides 8, that is $n \in \{1, 2, 4, 8\}$. Since $f(1) \in \mathbb{Z}/10$ and f is non-trivial, $n = 2$. Thus $f(1) = 5$ and f is univocally determined. This means that $f(k) = 5k$ for $k \in \{0, 1, \dots, 7\}$.

Exercise 10.34. Compute $\text{Hom}(\mathbb{Z}/n, G)$ for any group G .

Exercise 10.35. Let A , B and C be groups. If $f \in \text{Hom}(A, B)$ and $g \in \text{Hom}(B, C)$, then $g \circ f \in \text{Hom}(A, C)$.

Exercise 10.36. Prove that $\mathbb{Z}/2 \times \mathbb{Z}/2$ and $\mathbb{Z}/4$ are the only groups of order four (up to isomorphism). In particular, groups of order four are abelian.

The following example is harder than Exercise 10.36.

Example 10.37. If G is a group of order six, then either $G \cong \mathbb{S}_3$ or G is cyclic of order six. Since $|G|$ is even, there exists an element of G that has order two (see Exercise 5.11). If every element of $G \setminus \{1\}$ has order two, then $xy = yx$ for all $x, y \in G$. Hence

$$\langle x, y \rangle = \{1, x, y, xy\} \leq G,$$

a contradiction to Lagrange's theorem. Thus there exist $x \in G$ of order two and $y \in G \setminus \{1\}$ of order > 2 . By Lagrange's theorem, $|y| \in \{3, 6\}$, as the order of y divides $|G|$. If $|y| = 6$, then $G \cong \mathbb{Z}/6$. It follows that there exists $z \in G$ of order three. Thus

$$\langle x, z \rangle = \{1, x, z, z^2, xz, xz^2\} = G.$$

Now we have the group $\langle x, z \rangle$. To “recognize” this group, we need to understand the product zx . We know that $zx \in \{xz, xz^2\}$. If $xz = zx$, then $|xz| = 6$ (because $(xz)^k \neq 1$ for all $k \in \{1, \dots, 5\}$ and $(xz)^6 = 1$). Thus $G = \langle xz \rangle \cong \mathbb{Z}/6$. If, otherwise, $zx = xz^2$, then $G = \langle x, z : x^2 = z^3 = 1, xzx^{-1} = z^2 \rangle \cong \mathbb{D}_3$.

How many (isomorphism classes of) groups are there? We are now ready to collect our results and give a classification of isomorphism classes of groups of order ≤ 7 ; see Table 6.1. For the classification of groups of order eight, we need more tools.

Order	Number	Group(s)
1	1	$\{1\}$
2	1	$\mathbb{Z}/2$
3	1	$\mathbb{Z}/3$
4	2	$\mathbb{Z}/4$
		$\mathbb{Z}/2 \times \mathbb{Z}/2$
5	1	$\mathbb{Z}/5$
6	2	$\mathbb{Z}/6$
		\mathbb{S}_3
7	1	$\mathbb{Z}/7$

Table 6.1 Groups of order ≤ 7 (up to isomorphism).

Exercise 10.38. Prove that, up to isomorphism, the groups of order nine are $\mathbb{Z}/9$ and $\mathbb{Z}/3 \times \mathbb{Z}/3$. In particular, groups of order nine are abelian.

§11. Isomorphism theorems

The following theorem is fundamental. For example, it allows us to recognize quotient groups.

Theorem 11.1 (First isomorphism theorem). *If $f: G \rightarrow H$ is group homomorphism, then $G/\ker f \simeq f(G)$.*

Proof. Let $K = \ker f$ and $\varphi: G/K \rightarrow H$, $xK \mapsto f(x)$. We need to show that φ is well-defined. This means that we need to show that if $xK = yK$, then $f(x) = f(y)$. If $xK = yK$, then, since $y^{-1}x \in K$,

$$f(y)^{-1}f(x) = f(y^{-1}x) \in f(K) = \{1\}.$$

Thus $f(x) = f(y)$.

We now show that φ is a group homomorphism:

$$\varphi(xKyK) = \varphi(xyK) = f(xy) = f(x)f(y) = \varphi(xK)\varphi(yK).$$

To compute $\ker \varphi$ we proceed as follows:

$$\pi(x) = xK \in \ker \varphi \iff \varphi(xK) = 1 \iff f(x) = 1 \iff x \in K.$$

Therefore $\ker \varphi$ is trivial and φ is injective. Since φ is surjective, we conclude that $G/K \simeq f(G)$. \square

Examples 11.2. If G is a group, then $G/\{1\} \simeq G$ and $G/G \simeq \{1\}$.

Example 11.3. Since $f: \mathbb{Z} \rightarrow \mathbb{Z}/n$, $x \mapsto x \bmod n$, is a group homomorphism with $\ker f = n\mathbb{Z}$, it follows that $\mathbb{Z}/n\mathbb{Z} \simeq \mathbb{Z}/n$.

Example 11.4. Let G be an infinite cyclic group, say $G = \langle g \rangle$. The map $f: \mathbb{Z} \rightarrow G$, $k \mapsto g^k$, is a group isomorphism. Thus $G \simeq \mathbb{Z}$ by the first isomorphism theorem. In particular, $G = \langle g^k \rangle$ if and only if $k \in \{-1, 1\}$.

Example 11.5. We claim that $\mathbb{Z}/n\mathbb{Z} \simeq G_n$. Let

$$f: \mathbb{Z} \rightarrow G_n, \quad f(k) = \exp(2\pi i k/n).$$

Then f is a surjective group homomorphism and $\ker f = n\mathbb{Z}$. By the first isomorphism theorem, the claim follows.

Example 11.6. Note that $2\mathbb{Z} \simeq 3\mathbb{Z}$, as both groups are infinite (alternatively, one can also consider the map $2k \mapsto 3k$). Moreover,

$$\mathbb{Z}/2 \simeq \mathbb{Z}/2\mathbb{Z} \neq \mathbb{Z}/3\mathbb{Z} \simeq \mathbb{Z}/3.$$

Example 11.7. Since

$$f: \mathbb{C}^\times \rightarrow \mathbb{C}^\times, \quad f(z) = \frac{z}{|z|},$$

is a group homomorphism with $\ker f = \mathbb{R}_{>0}$ and $f(\mathbb{C}^\times) = S^1$, the first isomorphism theorem implies that $\mathbb{C}^\times/\mathbb{R}_{>0} \simeq S^1$.

Example 11.8. If we apply the first isomorphism theorem to the map $f: S^1 \rightarrow S^1$, $f(z) = z^2$, we obtain that $S^1/\{\pm 1\} \simeq S^1$, as $\ker f = \{-1, 1\}$ y $f(S^1) = S^1$.

Example 11.9. Let $f: \mathbb{C}^\times \rightarrow \mathbb{C}^\times$, $f(z) = |z|$. Since $\ker f = S^1$ and $f(\mathbb{C}^\times) = \mathbb{R}_{>0}$, the first isomorphism theorem implies that $\mathbb{C}^\times/S^1 \simeq \mathbb{R}_{>0}$.

Example 11.10. We claim that $(\mathbb{Z} \times \mathbb{Z})/\langle(1, 3)\rangle \simeq \mathbb{Z}$. We consider the surjective group homomorphism $f: \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$, $f(x, y) = 3x - y$. Since

$$\ker f = \{(x, 3x) : x \in \mathbb{Z}\} = \langle(1, 3)\rangle,$$

the first isomorphism theorem implies that $(\mathbb{Z} \times \mathbb{Z})/\langle(1, 3)\rangle \simeq \mathbb{Z}$.

Exercise 11.11. Prove that $\mathbb{R}/\mathbb{Z} \simeq S^1$.

Exercise 11.12. Prove that $\mathbb{Q}/\mathbb{Z} \simeq \bigcup_{n \geq 1} G_n$.

Exercise 11.13. Prove that $(\mathbb{Z} \times \mathbb{Z})/\langle(6, 3)\rangle \simeq \mathbb{Z} \times (\mathbb{Z}/3)$.

Let us see another application that shows that the first isomorphism theorem is quite familiar.

Example 11.14. Let V be a vector space and W be a subspace of V . In particular, V is an abelian group and W is a normal subgroup of V . The abelian group V/W is then a vector space with

$$\lambda(v + W) = (\lambda v) + W, \quad \lambda \in \mathbb{R}, v \in V,$$

and the canonical homomorphism $\pi: V \rightarrow V/W$ is also a linear map. As an exercise, the reader needs to show that $\dim(V/W) = \dim V - \dim W$ if $\dim V < \infty$.

If $f: V \rightarrow U$ is a linear map, then $V/\ker f \simeq f(V)$ as abelian groups (by the first isomorphism theorem). The map realizing this isomorphism is moreover linear, so $V/\ker f \simeq f(V)$ as vector spaces. In particular, if $\dim V < \infty$, then

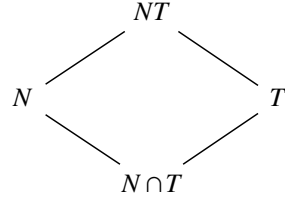
$$\dim V - \dim \ker f = \dim f(V).$$

Exercise 11.15. Let $f: G \rightarrow H$ be a group homomorphism and K a normal subgroup of G such that $K \subseteq \ker f$. Prove that there exists a unique group homomorphism $\varphi: G/K \rightarrow H$ such that the diagram

$$\begin{array}{ccc} G & \xrightarrow{f} & H \\ \pi \downarrow & \nearrow \varphi & \\ G/K & & \end{array}$$

commutes. The commutativity of the diagram means that $\varphi \circ \pi = f$, where $\pi: G \rightarrow G/K$ is the canonical group homomorphism. Moreover, $\ker \varphi = \pi(\ker f)$ and $\varphi(G/K) = f(G)$. In particular, φ is injective if and only if $\ker f = K$ and φ is surjective if and only if f is surjective.

We now discuss the second isomorphism theorem. As a rule to remember what the theorem is about, one has the following diagram:



Exercise 11.16 (Second isomorphism theorem). If N is a normal subgroup of G and T is a subgroup of G , then $N \cap T$ is normal in T and

$$T/N \cap T \simeq NT/N.$$

Exercise 11.17. Let N be a normal subgroup of G and $\pi: G \rightarrow G/N$ the canonical homomorphism. Prove that if L is a subgroup of G , then $\pi^{-1}(\pi(L)) = NL$.

The following example uses additive groups.

Example 11.18. Let $G = \mathbb{Z}/24$, $H = \langle 4 \rangle$ and $N = \langle 6 \rangle$. Since G is abelian, H and N are normal in G . Then $H + N = \langle 2 \rangle$ and $H \cap N = \{0, 12\}$. Let us compute the left cosets of N in $H + N$:

$$0 + N = \{0, 6, 12, 18\}, \quad 2 + N = \{2, 8, 14, 20\}, \quad 4 + N = \{4, 10, 16, 22\}.$$

The left cosets of $H \cap N$ in H are

$$0 + (H \cap N) = \{0, 12\}, \quad 4 + (H \cap N) = \{4, 16\}, \quad 8 + (H \cap N) = \{8, 20\}.$$

By the second isomorphism theorem, $(H + N)/N \simeq H/H \cap N$. The isomorphism is given by $f: H/(H \cap N) \rightarrow (H + N)/N$, $h + (H \cap N) \mapsto h + N$. In our particular case,

$$\begin{aligned} f(0 + (H \cap N)) &= 0 + N, \\ f(4 + (H \cap N)) &= 4 + N, \\ f(8 + (H \cap N)) &= 8 + N = 2 + N. \end{aligned}$$

Let us discuss some applications.

Example 11.19. Let $a, b \in \mathbb{Z}$ be non-zero integers. Then $a\mathbb{Z} + b\mathbb{Z} = \gcd(a, b)\mathbb{Z}$ and $a\mathbb{Z} \cap b\mathbb{Z} = \text{lcm}(a, b)\mathbb{Z}$. By the second isomorphism theorem,

$$\frac{\gcd(a, b)\mathbb{Z}}{b\mathbb{Z}} = \frac{a\mathbb{Z} + b\mathbb{Z}}{b\mathbb{Z}} \simeq \frac{a\mathbb{Z}}{a\mathbb{Z} \cap b\mathbb{Z}} = \frac{a\mathbb{Z}}{\text{lcm}(a, b)\mathbb{Z}}.$$

Since the formula involves finite groups, computing orders yields

$$ab = \gcd(a, b)\text{lcm}(a, b).$$

A group G is said to be **meta-abelian** if it contains an abelian normal subgroup N and G/N is abelian. Abelian groups are meta-abelian. However, the group \mathbb{S}_3 is

meta-abelian and not abelian. The following exercise present another application of the second isomorphism theorem.

Exercise 11.20. Prove that if G is a mete-abelian group and H is a subgroup of G , then H is meta-abelian.

There is a third isomorphism theorem.

Exercise 11.21 (Third isomorphism theorem). Let S and T be normal subgroups of G such that $S \subseteq T$. Prove that S is normal in T , T/S is normal in G/S and

$$\frac{G/S}{T/S} \simeq G/T,$$

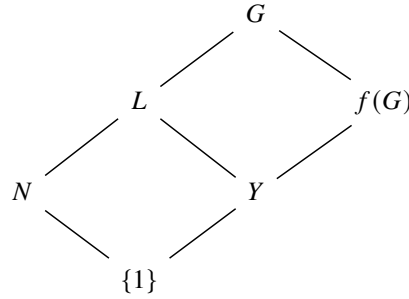
where $T/S = \{tS : t \in T\}$.

The following example helps to visualize the third isomorphism theorem.

Example 11.22. If m divides n , then $n\mathbb{Z} \leq m\mathbb{Z} \leq \mathbb{Z}$. Thus

$$\frac{\mathbb{Z}/n\mathbb{Z}}{m\mathbb{Z}/n\mathbb{Z}} \simeq \mathbb{Z}/m\mathbb{Z}.$$

The following theorem is known as the *correspondence theorem*. It is powerful and essential. It helps to have in mind the following diagram:



Theorem 11.23 (Correspondence theorem). Let $f: G \rightarrow H$ be a group homomorphism and $K = \ker f$. There exists a bijective correspondence

$$\mathcal{A} = \{L : K \leq L \leq G\} \xrightleftharpoons[\tau]{\sigma} \{Y : Y \leq f(G)\} = \mathcal{B}$$

The correspondence is given by $\sigma(L) = f(L)$ and $\tau(Y) = f^{-1}(Y)$. Moreover, the following statements hold:

- 1) $L_1 \leq L_2$ if and only if $\sigma(L_1) \leq \sigma(L_2)$.
- 2) $L \trianglelefteq G$ if and only if $\sigma(L) \trianglelefteq f(G)$.

Proof. Note that σ and τ are well-defined, as $f(L) \leq f(G)$ and $K \leq f^{-1}(Y) \leq G$.

Let us prove that $\tau \circ \sigma = \text{id}_{\mathcal{A}}$. We need to show that $\tau(\sigma(L)) = L$ for all $L \in \mathcal{A}$. If $x \in f^{-1}(f(L))$, then $f(x) \in f(L)$. Thus $f(x) = f(l)$ for some $l \in L$. Hence $xl^{-1} \in K$ and therefore $x \in Kl \subseteq L$, as $K \subseteq L$. Conversely, if $l \in L$, then $f(l) \in f(L)$. Thus $l \in f^{-1}(f(L))$.

We now prove that $\sigma \circ \tau = \text{id}_{\mathcal{B}}$. If $Y \in \mathcal{B}$, then $\sigma(\tau(Y)) = Y$. If $y \in Y \subseteq f(G)$, then $y = f(x)$ for some $x \in G$, that is $x \in f^{-1}(y)$. This implies that $y = f(x) \in f(f^{-1}(Y))$. Conversely, if $y \in f(f^{-1}(Y))$, then $y = f(x)$ for some $x \in f^{-1}(Y)$. This implies that $y = f(x) \in Y$.

It is an exercise to show that $X \leq Y$ if and only if $f(X) \leq f(Y)$.

We now show that $L \trianglelefteq G$ if and only if $f(L) \trianglelefteq f(G)$. If $L \trianglelefteq G$ and $x \in G$, then $xLx^{-1} = L$. This implies that $f(L) = f(xLx^{-1}) = f(x)f(L)f(x)^{-1}$, that is to say that $f(L)$ is normal in $f(G)$. Conversely, if $f(L) \trianglelefteq f(G)$ and $x \in G$, then

$$f(xLx^{-1}) = f(x)f(L)f(x)^{-1} = f(L).$$

This implies that $xLx^{-1} \subseteq LK \subseteq L$. Thus $xLx^{-1} \subseteq L$, which means that L is normal in G . \square

Proposition 11.24. *If $f: G \rightarrow f(G)$ is a surjective group homomorphism and $H \leq G$ is such that $K = \ker f \subseteq H$, then $(G : H) = (f(G) : f(H))$.*

Proof. By the correspondence theorem, there is a bijective correspondence

$$\{L : K \leq L \leq G\} \xrightarrow{\quad \quad} \{Y : Y \leq f(G)\}$$

given by $H \mapsto f(H)$ and $f^{-1}(T) \mapsto T$. Let $H \leq G$ be such that $\ker f \subseteq H$ and $\alpha: G/H \rightarrow f(G)/f(H)$, $\alpha(gH) = f(g)f(H)$. It is an exercise to show that α is well-defined. We need to show that α is bijective, as then

$$(G : H) = |G/H| = |f(G)/f(H)| = (f(G) : f(H)).$$

First, we show that α is surjective. If $yf(H) \in f(G)/f(H)$, then $y = f(g)$ for some $g \in G$ (because f is surjective). Thus

$$yf(H) = f(g)f(H) = f(gH) = \alpha(gH).$$

We now show that α is injective. If $\alpha(gH) = \alpha(g_1H)$, then,

$$f(g)^{-1}f(g_1) = f(h) \in f(H)$$

for some $h \in H$, that is $f(g_1) = f(g)f(h) = f(gh)$ for some $h \in H$. This implies that $g_1 = ghk$ for some $k \in \ker f \subseteq H$ y luego $g_1 = gh_1$ for some $h_1 \in H$, that is $g_1H = gH$. \square

In the case of the canonical homomorphism $\pi: G \rightarrow G/N$, the previous result reads as follows. If N is a normal subgroup of G , then $K \mapsto K/N$ is a bijection

between the set of (normal) subgroups of G containing N and the set of (normal) subgroups of G/N . If H is a subgroup of G , then

$$\pi(H) = HN/N.$$

Example 11.25. Let us show that every subgroup of

$$Q_8 = \{1, -1, i, -i, j, -j, k, -k\}$$

is normal in Q_8 . Let $N = \{-1, 1\}$. Then N is normal in Q_8 , as $N \subseteq Z(Q_8)$. Since $|Q_8/N| = 4$, Q_8/N is an abelian group.

We claim that N is included in every non-trivial subgroup of Q_8 . If K is a non-trivial subgroup of Q_8 , then $-1 \in K$ (because, for example, if $-i \in K$, then $-1 = (-i)^2 \in K$). Then every subgroup of Q_8 corresponds to a subgroup of Q_8/N . Since Q_8/N is abelian, every subgroup of Q_8/N is normal. Thus if $S \leq Q_8$, then $\pi(S)$ is normal in Q_8/N . Since $N \subseteq S$, it follows that $S = \pi^{-1}(\pi(S))$. Hence S is normal in Q_8 .

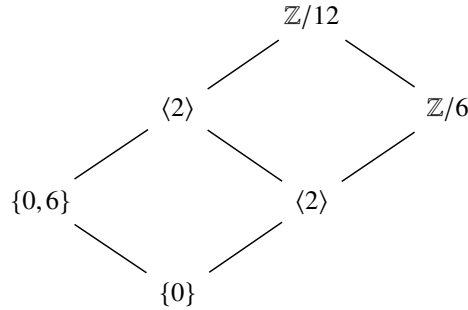
Example 11.26. Let $f: \mathbb{Z}/12 \rightarrow \mathbb{Z}/6$ be the group homomorphism given by $1 \mapsto 1$. Then $K = \ker f = \{0, 6\}$. The subgroups of $\mathbb{Z}/12$ containing K are

$$\langle 1 \rangle = \{0, 1, \dots, 11\}, \quad \langle 2 \rangle = \{0, 2, 4, 6, 8, 10\}, \quad \langle 3 \rangle = \{0, 3, 6, 9\}, \quad \langle 6 \rangle = \{0, 6\}.$$

These subgroups correspond via f to the subgroups

$$\langle 1 \rangle = \{0, 1, \dots, 5\}, \quad \langle 2 \rangle = \{0, 2, 4\}, \quad \langle 3 \rangle = \{0, 3\}, \quad \{0\}$$

of $\mathbb{Z}/6$, respectively. For example,



The correspondence theorem helps to transport properties from the image of a group homomorphism to the domain. Let us discuss a concrete example.

Example 11.27. Let G be a finite group and N be a normal subgroup of G such that $N \simeq \mathbb{Z}/5$ and $G/N \simeq \mathbb{S}_4$. The following statements hold:

- 1) $|G| = 120$

- 2) G contains a normal subgroup of order 20.
- 3) G contains three subgroups of order 15, none of them normal in G .

To prove the first claim we note that Lagrange's theorem implies that

$$24 = |G/N| = \frac{|G|}{|N|} = |G|/5.$$

We prove the second claim. Let K be the subgroup of G/N isomorphic to the Klein group. Then K is normal in G/N and $|K| = 4$. Since $(G/N : K) = 6$, the subgroup K of G/N corresponds to a normal subgroup H of G such that $(G : H) = 6$. Using Lagrange's theorem and the correspondence theorem, $|H| = 20$, as

$$6 = (G/N : K) = (G : H) = \frac{|G|}{|H|}.$$

For the third claim, note that $G/N \simeq \mathbb{S}_4$ has four subgroups of order 3 (these are the subgroups generated by a 3-cycle), none normal in G/N . By the correspondence theorem, these subgroups correspond with four non-normal subgroups of G , all of order 15.

If G is a group, $\mathbb{S}_G = \{f : G \rightarrow G : f \text{ bijective}\}.$

Theorem 11.28 (Cayley). *Every group G is isomorphic to a subgroup of \mathbb{S}_G .*

Proof. Let $f : G \rightarrow \mathbb{S}_G, g \mapsto L_g$, where $L_g : G \rightarrow G, L_g(x) = gx$. Then f is a group homomorphism, as

$$L_{gh}(x) = (gh)x = g(hx) = L_g(hx) = L_g L_h(x)$$

for all $g, h, x \in G$. Moreover, f is injective (if $f(g) = f(h)$, then $L_g = L_h$, and this implies that $gx = L_g(x) = L_h(x) = hx$ for all $x \in G$, which ultimately implies $g = h$). It follows that $G \simeq f(G)$, which is a subgroup of \mathbb{S}_G . \square

Every finite group is isomorphic to a subgroup of some \mathbb{S}_n . In particular, using permutation matrices, we see that every finite group is isomorphic to a subgroup of $\mathbf{GL}_n(\mathbb{Z})$ for some n . Those groups are known as **linear groups**.

Proposition 11.29. *Every finite simple group G is contained in some \mathbb{A}_n .*

Proof. If $|G| = 2$, the result is trivial, as $G \simeq \mathbb{A}_2$. Assume that $|G| > 2$. Let $f : G \rightarrow \mathbb{S}_n$ by the injective group homomorphism given by Cayley's theorem. If $H = f(G)$, then $G \simeq H$ by the first isomorphism theorem. We claim that $H \subseteq \mathbb{A}_n$. If H is not a subgroup of \mathbb{A}_n , there exists $h \in H$ such that $h \notin \mathbb{A}_n$. Write $h = f(g)$ for some $g \in G$. Since $h \notin \mathbb{A}_n$, $\text{sign}(f(g)) = \text{sign}(h) = -1$, that is $g \notin \ker(\text{sign} \circ f)$. Let $K = \ker(\text{sign} \circ f)$. Then $K = \{1\}$, as G is simple. Moreover, $\text{sign} \circ f$ is a bijective map, as $\text{sign}(f(1)) = 1$ and $\text{sign}(f(g)) = -1$. Therefore $G \simeq G/K \simeq \mathbb{Z}/2$, by the first isomorphism theorem. In particular, $|G| = 2$, a contradiction. Thus $H \subseteq \mathbb{A}_n$. \square

§11 Isomorphism theorems

Let us briefly discuss another application of Cayley's theorem. We use the theorem to show that in a group, no product needs parenthesis. By Cayley's theorem, a group G is (isomorphic to) a subgroup of \mathbb{S}_G . The composition of maps is an associative operation. Moreover, no composition of finitely many maps needs parenthesis. Thus

$$(f_1 \circ \cdots \circ f_n)(g) = f_1(f_2(\cdots f_n(g)) \cdots).$$

Lecture 7

§12. Semi-direct products

We first start with an exercise of **direct products**.

Exercise 12.1. Let G be a group and H and K be normal subgroups of G . If $G = HK$ and $H \cap K = \{1\}$, then $G \simeq H \times K$.

Exercise 12.2. Let A be a normal subgroup of H , and B be a normal subgroup of K . Prove that $A \times B$ is a normal subgroup of $H \times K$ and

$$\frac{H \times K}{A \times B} \simeq (H/A) \times (K/B).$$

We say that a group G admits an exact factorization through the subgroups H and K if $G = HK$ and $H \cap K = \{1\}$. By Exercise 12.1, if G admits an exact factorization through two normal subgroups, then it is isomorphic to the direct product of these subgroups.

Exercise 12.3. Let G be a group that admits an exact factorization through the subgroups H and K . Prove that every $g \in G$ can be written uniquely as $g = hk$ for some $h \in H$ and $k \in K$.

Example 12.4. Let $G = \mathbb{S}_3$, $H = \langle (123) \rangle \trianglelefteq G$ and $K = \langle (12) \rangle$. Since K is not normal in G , we cannot apply Exercise 12.1. We do have $G = HK$ and $H \cap K = \{\text{id}\}$, but $H \times K \simeq \mathbb{Z}/3 \times \mathbb{Z}/2 \neq \mathbb{S}_3$, as $\mathbb{Z}/3 \times \mathbb{Z}/2$ is abelian and \mathbb{S}_3 is not.

Definition 12.5. Let G be a group, K a normal subgroup of G , and Q a subgroup of G . We say that Q **complements** K in G if $K \cap Q = \{1\}$ y $G = KQ$.

Example 12.6. Let $G = \mathbb{S}_3$ and $K = \langle (123) \rangle \trianglelefteq G$. The subgroups $\langle (12) \rangle$, $\langle (13) \rangle$ and $\langle (23) \rangle$ complement K in G .

The previous example shows that complements are not unique. However, complements are unique under isomorphism, as

$$G/K = KQ/K \simeq Q/K \cap Q = Q/\{1\} \simeq Q.$$

Definition 12.7. We say that a group G is a **semi-direct product** of Q and K if K is normal in G and K admits a complement in G isomorphic to Q . Notation: $G = K \rtimes Q$.

Let us discuss some characterizations:

Proposition 12.8. Let K be a normal subgroup of G . The following statements are equivalent:

- 1) K admits a complement in G .
- 2) There exists a subgroup Q of G such that each $g \in G$ can be written uniquely as $g = xy$ for some $x \in K$ and $y \in Q$.
- 3) There exists a group homomorphism $s: G/K \rightarrow G$ such that $\pi \circ s = \text{id}_{G/K}$, where $\pi: G \rightarrow G/K$, $g \mapsto Kg$, is the canonical homomorphism.
- 4) There exists a group homomorphism $\rho: G \rightarrow G$ such that $\ker \rho = K$ and the restriction $\rho|_{\rho(G)}$ equals the identity.

Proof. We first prove that (1) \implies (2). If Q complements K , then $G = KQ$ and $K \cap Q = \{1\}$. In particular, if $g \in G$, then $g = xy$ para $x \in K$ e $y \in Q$. To show that the decomposition is unique, suppose that $g = x_1y_1$ with $x_1 \in K$ and $y_1 \in Q$. Then $x_1^{-1}x = yy_1^{-1} \in K \cap Q = \{1\}$ and hence $x = x_1$ and $y = y_1$.

It is an exercise to show that (2) \implies (1).

We now prove that (2) \implies (3). Let $s: G/K \rightarrow G$, $s(Kg) = y$ if $g = xy$ with $x \in K$ and $y \in Q$. (Note that here we use right cosets, as it is more convenient.) Let us check that s is well-defined. For that purpose, we must show that $Kg = Kg_1$ implies $s(Kg) = s(Kg_1)$. If $g = xy$ and $g_1 = x_1y_1$ with $x, x_1 \in K$ and $y, y_1 \in Q$, then, since $Kg = Kg_1$, $xyy_1^{-1}x_1^{-1} = gg_1^{-1} \in K$, that is $yy_1^{-1} \in x^{-1}Kx_1 = K$ because $x, x_1 \in K$. Hence $yy_1^{-1} \in K \cap Q = \{1\}$ and thus $y = y_1$. We now show that $\pi \circ s = \text{id}_{G/K}$. If $g = xy$ with $x \in K$ e $y \in Q$, then $(\pi \circ s)(Kg) = \pi(y) = Ky = Kxy = Kg$. It is left to the reader to prove that s is a group homomorphism.

We now prove that (3) \implies (4). Let $\rho = s \circ \pi$. Then ρ is a group homomorphism (because it is the composition of homomorphisms). We compute:

$$\rho(\rho(g)) = \rho((s \circ \pi)(g)) = \rho(s(Kg)) = ((s \circ \pi) \circ s)(Kg) = s(Kg) = \rho(g).$$

We now compute $\ker \rho$. If $g \in \ker \rho$, then $s(\pi(g)) = \rho(g) = 1$. Thus

$$\pi(g) = \pi(s(\pi(g))) = \pi(1) = 1_{G/K},$$

that is $g \in \ker \pi = K$. Conversely, if $x \in K$, then

$$\rho(x) = \rho(s(Kx)) = \rho(s(K)) = \rho(1) = 1$$

and hence $x \in \ker \rho$.

Finally, we prove that (4) \implies (1). We claim that $Q = \rho(G)$ complements K in G . We first show that $K \cap Q = \{1\}$: if $x \in K \cap Q$, then $x = \rho(g)$ for some $g \in G$. Moreover,

$$1 = \rho(x) = \rho(\rho(g)) = \rho(g).$$

Hence $g \in \ker \rho = K$ and $x = 1$. We now prove that $G = KQ$. For the inclusion $G \subseteq KQ$,

$$g = (g\rho(g^{-1}))\rho(g)$$

and $g\rho(g^{-1}) \in K = \ker \rho$, as $\rho(g\rho(g^{-1})) = \rho(g)\rho(g^{-1}) = 1$. \square

Example 12.9. $\mathbb{S}_n = \mathbb{A}_n \rtimes \mathbb{Z}/2$, as $Q = \langle (12) \rangle \simeq \mathbb{Z}/2$ complements the normal subgroup \mathbb{A}_n of \mathbb{S}_n .

For a group G , the set

$$\text{Aut}(G) = \{f: G \rightarrow G : f \text{ bijective}\}$$

is a group with the composition of maps. It is called the **automorphism group** of G . Examples of automorphism groups are the identity map and conjugations homomorphisms.

Example 12.10. $\text{Aut}(\mathbb{Z}) \simeq \mathbb{Z}/2$, as $\text{Aut}(\mathbb{Z}) = \{\text{id}, -\text{id}\}$.

Example 12.11. $\text{Aut}(\mathbb{Z}) \simeq \mathbb{Z}/2$, as $\text{Aut}(\mathbb{Z}) = \{\text{id}, -\text{id}\}$.

Example 12.12. Let G be a group and $g \in G$. The conjugation map $\gamma_g: G \rightarrow G$, $x \mapsto gxg^{-1}$, is an automorphism of G , as

$$\gamma_g(xy) = g(xy)g^{-1} = (gxg^{-1})(gyg^{-1}) = \gamma_g(x)\gamma_g(y).$$

Moreover, $\gamma: G \rightarrow \text{Aut}(G)$, $g \mapsto \gamma_g$, is a group homomorphism:

$$\gamma_{gh}(x) = (gh)x(gh)^{-1} = g(\gamma_h(x))g^{-1} = \gamma_g(\gamma_h(x)) = (\gamma_g \circ \gamma_h)(x).$$

The group of **inner automorphisms** of G is the group $\text{Inn}(G) = \gamma(G)$. Note that $\ker \gamma = Z(G)$, as if $g \in G$ is such that $\gamma_g = \text{id}$, then

$$\gamma_g(x) = gxg^{-1} = x$$

for all $x \in G$. By the first isomorphism theorem,

$$G/Z(G) \simeq \gamma(G) = \text{Inn}(G).$$

Exercise 12.13. Prove that $\text{Aut}(\mathbb{S}_3) \simeq \mathbb{S}_3$.

Exercise 12.14. Let G be a group. Prove that $\text{Inn}(G)$ is a normal subgroup of $\text{Aut}(G)$.

For a group G , the quotient $\text{Aut}(G)/\text{Inn}(G)$ is called the group of **outer automorphisms** of G . Note that

$$\text{Inn}(G) \text{ is cyclic} \iff |\text{Inn}(G)| = 1 \iff G \text{ is abelian.}$$

Exercise 12.15. Let G be a group. Prove that if $\text{Aut}(G)$ is cyclic, then G is abelian.

Exercise 12.16. Prove that if G is finite, then $\text{Aut}(G)$ is finite.

The following exercise constructs semi-direct products.

Exercise 12.17. Let K and Q be groups and $\theta: Q \rightarrow \text{Aut}(K)$, $x \mapsto \theta_x$, a group homomorphism. Prove that $K \rtimes Q$ with

$$(a, x)(b, y) = (a\theta_x(b), xy)$$

is a group. This group will be written as $K \rtimes_\theta Q$.

The group of Exercise 12.17 is the semi-direct product of the subgroups

$$K \times \{1\} = \{(a, 1) : a \in K\} \simeq K, \quad \{1\} \times Q = \{(1, x) : x \in Q\} \simeq Q$$

of $K \rtimes_\theta Q$. Note that $K \times \{1\}$ is normal in $K \rtimes_\theta Q$. We can identify $K \rtimes \{1\}$ with K and $\{1\} \rtimes Q$ with Q . Thus we can write

$$\theta_x(a) = xax^{-1}$$

for all $x \in Q$ and $a \in K$.

Exercise 12.18. Prove that if G is a semi-direct product of the normal subgroup K with the subgroup Q , there exists a group homomorphism $\theta: Q \rightarrow \text{Aut}(K)$ such that $G \simeq K \rtimes_\theta Q$.

Let us discuss some examples.

Example 12.19. Let $N \simeq \mathbb{Z}/n$ and $H \simeq \mathbb{Z}/2 = \{0, 1\}$. The map $\theta: H \rightarrow \text{Aut}(N)$, $1 \mapsto (x \mapsto x^{-1})$, is a group homomorphism. Let $G = N \rtimes_\theta H$. Then $G \simeq \mathbb{D}_n$, the dihedral group of order $2n$. Recall that

$$\mathbb{D}_n = \langle r, s : r^n = s^2 = 1, srs^{-1} = r^{-1} \rangle.$$

Assume that $N = \langle x \rangle$ and $H = \langle y \rangle$. Then $|(x, 1)| = n$ and $|(1, y)| = 2$. Moreover,

$$\begin{aligned} (1, y)(x, 1)(1, y)^{-1} &= (\varphi_y(x), y)(1, y) \\ &= (\varphi_y(x), y^2) \\ &= (\varphi_y(x), 1) \\ &= (x^{-1}, 1) \\ &= (x, 1)^{-1}. \end{aligned}$$

If $u = (x, 1)$ y $v = (1, y)$, then $u^n = v^2 = (1, 1)$ and $vuv^{-1} = u^{-1}$. Thus there exists a surjective group homomorphism $\mathbb{D}_n \rightarrow G$ (because G is generated by u and v). Moreover, $|G| = |N||H| = 2n$. Hence G has order $2n$ and therefore $G \simeq \mathbb{D}_n$.

Example 12.20. Let $K = \{\text{id}, (12)(34), (13)(24), (14)(23)\}$. Then K is normal in \mathbb{A}_4 . Let $H = \langle (123) \rangle \simeq \mathbb{Z}/3$. Since $K \cap H$ is a subgroup of H and K and, moreover, K and H have coprime orders, $H \cap K = \{\text{id}\}$. Hence $\mathbb{A}_4 = K \rtimes H$.

Example 12.21. Let

$$K = \{\text{id}, (12)(34), (13)(24), (14)(23)\}, \quad H = \{\sigma \in \mathbb{S}_4 : \sigma(4) = 4\}.$$

Note that H is a subgroup of \mathbb{S}_4 isomorphic to \mathbb{S}_3 . Then $H \cap K = \{\text{id}\}$ and hence $\mathbb{S}_4 = K \rtimes H$.

Let $n \geq 5$. Using the fact that \mathbb{A}_n is a simple group, one proves that \mathbb{A}_n cannot be written as a semi-direct product of proper subgroups.

Example 12.22. Let $K = \mathbb{Z}/3$ and $Q = \mathbb{Z}/4$. Since $\text{Hom}(Q, \text{Aut}(K)) = \{1, \tau\}$, where

$$\tau : \mathbb{Z}/4 \rightarrow \text{Aut}(\mathbb{Z}/3) = \{\text{id}, \rho\} \simeq \mathbb{Z}/2, \quad 1 \mapsto \rho,$$

the semi-direct product $T = K \rtimes_{\tau} Q$ is a non-abelian group of order 12. Moreover, $T \neq \mathbb{A}_4$ as $|(2, 2)| = 6$ and \mathbb{A}_4 has no elements of order six.

Lecture 8

§13. Actions

Definition 13.1. Let G be a group and X a set. A (left) **action** of G on X is a map $G \times X \rightarrow X$, $(g, x) \mapsto g \cdot x$, such that

- 1) $1 \cdot x = x$ for all $x \in X$,
- 2) $g \cdot (h \cdot x) = (gh) \cdot x$ for all $g, h \in G$ and $x \in X$.

If a group G acts on a set X , we also say that X is a G -set.

Example 13.2. Every group G acts on G trivially: $g \cdot h = h$ for all $g, h \in G$.

Example 13.3. Every group G acts on G by left multiplication, that is $g \cdot h = gh$ for all $g, h \in G$.

Example 13.4. Every group G acts on G by conjugation, that is $g \cdot h = hg^{-1}$ for all $g, h \in G$. More generally, if N is a normal subgroup of G , then G acts on N by conjugation: $g \cdot x = gxg^{-1}$ for all $g \in G$ and $x \in N$.

Example 13.5. Let G be a group and H be a subgroup of G . Then G acts on the set of left cosets G/H by left multiplication, that is $g \cdot (xH) = (gx)H$ for all $g, x \in G$.

There is a bijective correspondence between left actions of a group G on a set X and group homomorphisms $\rho: G \rightarrow \mathbb{S}_X$. The correspondence is given by the formula

$$\rho(g)(x) = g \cdot x, \quad g \in G, x \in X.$$

We will write $\rho_g = \rho(g)$.

As an example, if $G \times X \rightarrow X$, $(g, x) \mapsto g \cdot x$, is an action of G on X , then each $\rho_g: X \rightarrow X$ is a bijective map with inverse $(\rho_g)^{-1} = \rho_{g^{-1}}$. Moreover, ρ is a group homomorphism, as

$$\rho(gh)(x) = (gh) \cdot x = g \cdot (h \cdot x) = \rho_g(h \cdot x) = \rho_g(\rho_h(x))$$

for all $g, h \in G$ and $x \in X$.

Example 13.6. Let $G = \mathbb{S}_3$ and $H = \langle (123) \rangle = \{\text{id}, (123), (132)\}$. Let G act on the set $X = G/H = \{H, (12)H\}$ of left cosets of H by left multiplication. Write $x_1 = H$ and $x_2 = (12)H$. Then

$$(12) \cdot x_1 = x_2, \quad (12) \cdot x_2 = x_1, \quad (123) \cdot x_1 = x_1, \quad (123) \cdot x_2 = x_2.$$

Since $G = \langle (12), (123) \rangle$, one has the group homomorphism $\rho: G \rightarrow \mathbb{S}_X \simeq \mathbb{S}_2$ given by $(12) \mapsto (12)$, $(123) \mapsto \text{id}$.

Example 13.7. As before, let $G = \mathbb{S}_3$ and $H = \langle (12) \rangle = \{\text{id}, (12)\}$. Let G act on the set $X = G/H = \{H, (123)H, (132)H\}$ of left cosets of H by left multiplication. Write $x_1 = H$, $x_2 = (123)H$ and $x_3 = (132)H$. Then

$$\begin{aligned} (12) \cdot x_1 &= x_1, & (12) \cdot x_2 &= x_3, & (12) \cdot x_3 &= x_2, \\ (123) \cdot x_1 &= x_2, & (123) \cdot x_2 &= x_3, & (123) \cdot x_3 &= x_1. \end{aligned}$$

Since $G = \langle (12), (123) \rangle$, one has the group homomorphism $\rho: G \rightarrow \mathbb{S}_X \simeq \mathbb{S}_3$ given by $(12) \mapsto (23)$, $(123) \mapsto (123)$.

Example 13.8. Let $G = Q_8 = \{1, -1, i, -i, j, -j, k, -k\}$ and $N = \{1, -1, i, -i\}$. Since N is normal in G , G acts by conjugation on $X = N$. If $x_1 = 1$, $x_2 = -1$, $x_3 = i$ and $x_4 = -i$, then $i \cdot x = x$ for all $x \in N$. Moreover,

$$j \cdot x_1 = x_1, \quad j \cdot x_2 = x_2, \quad j \cdot x_3 = x_4, \quad j \cdot x_4 = x_3.$$

Since $G = \langle i, j \rangle$, a group homomorphism $\rho: G \rightarrow \mathbb{S}_X \simeq \mathbb{S}_4$ is determined by $\rho_i = \text{id}$ and $\rho_j = (34)$.

The following example is important.

Example 13.9. The group \mathbb{S}_n acts on \mathbb{R}^n by

$$\sigma \cdot (x_1, \dots, x_n) = (x_{\sigma^{-1}(1)}, \dots, x_{\sigma^{-1}(n)}).$$

It is very important to use σ^{-1} and not σ , as we need to permute the elements of the standard basis of \mathbb{R}^3 .

As a concrete example, let us see that the operation

$$\sigma \cdot (x_1, x_2, x_3) = (x_{\sigma(1)}, x_{\sigma(2)}, x_{\sigma(3)})$$

is not an action of \mathbb{S}_3 on \mathbb{R}^3 . If $\sigma = (12)$ and $\tau = (23)$, then $\sigma\tau = (123)$. Since

$$\begin{aligned} (123) \cdot (5, 6, 7) &= (6, 7, 5), \\ (12) \cdot ((23) \cdot (5, 6, 7)) &= (1, 2) \cdot (5, 7, 6) = (7, 5, 6), \end{aligned}$$

this does not define an action. If we compute

$$\sigma \cdot (\tau \cdot (x_1, \dots, x_n)) = \sigma \cdot (x_{\tau(1)}, \dots, x_{\tau(n)})$$

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and for each $i \in \{1, \dots, n\}$ we set $y_i = x_{\tau(i)}$, then

$$\sigma \cdot (\tau \cdot (x_1, \dots, x_n)) = \sigma \cdot (y_1, \dots, y_n) = (y_{\sigma(1)}, \dots, y_{\sigma(n)}) = (x_{\tau\sigma(1)}, \dots, x_{\tau\sigma(n)}),$$

even if σ and τ do not commute.

Now we show that by using inverses, we do have an action. For $j \in \{1, \dots, n\}$, let $y_j = x_{\tau(j)}$, that is

$$(y_1, y_2, \dots, y_n) = \tau \cdot (x_1, x_2, \dots, x_n) = (x_{\tau^{-1}(1)}, x_{\tau^{-1}(2)}, \dots, x_{\tau^{-1}(n)}).$$

Then

$$\begin{aligned} \sigma \cdot (\tau \cdot (x_1, x_2, \dots, x_n)) &= \sigma \cdot (y_1, y_2, \dots, y_n) \\ &= (y_{\sigma^{-1}(1)}, y_{\sigma^{-1}(2)}, \dots, y_{\sigma^{-1}(n)}) \\ &= (x_{\tau^{-1}(\sigma^{-1}(1))}, x_{\tau^{-1}(\sigma^{-1}(2))}, \dots, x_{\tau^{-1}(\sigma^{-1}(n))}) \\ &= (x_{(\sigma\tau)^{-1}(1)}, x_{(\sigma\tau)^{-1}(2)}, \dots, x_{(\sigma\tau)^{-1}(n)}). \end{aligned}$$

The following example is also important:

Example 13.10. The group \mathbb{S}_n acts on the set of polynomials on n variables X_1, \dots, X_n by permuting the variables. For example, for three variables, if $\sigma = (123)$ and $f = X_2X_3 - X_1 + 5X_2X_3^2X_1$, then $\sigma \cdot f = X_3^2X_1 - X_2 + 5X_3X_1^2X_2$.

Restricting the action, we see that \mathbb{S}_n acts on the set

$$\{\lambda_1 X_1 + \dots + \lambda_n X_n : \lambda_1, \dots, \lambda_n \in \mathbb{R}\}.$$

Then

$$\sigma \cdot (\lambda_1 X_1 + \dots + \lambda_n X_n) = (\lambda_1 X_{\sigma(1)} + \dots + \lambda_n X_{\sigma(n)}) = (\lambda_{\sigma(1)} X_1 + \dots + \lambda_{\sigma(n)} X_n).$$

It is relevant to compute the kernel of the action homomorphism.

Example 13.11. Let G be a group and H be a subgroup of G . Then G acts on G/H by left multiplication, that is $g \cdot (xH) = (gx)H$ for all $g, x \in G$. Let $\rho: G \rightarrow \mathbb{S}_{G/H}$ be the group homomorphism induced by the action.

We claim that $\ker \rho = \bigcap_{x \in G} xHx^{-1}$. We first prove \supseteq . If $g \in xHx^{-1}$ for all $x \in G$, then, for a fixed $x \in G$,

$$\rho(g)(xH) = g \cdot (xH) = (gx)H = (xhx^{-1})xH = (xh)H = xH$$

because $g = xhx^{-1}$ for some $h \in H$. Thus $\rho(g) = \text{id}$ and hence $g \in \ker \rho$. We now prove \subseteq . If $g \in \ker \rho$, then $\rho(g) = \text{id}$. So for all $x \in G$,

$$\rho(g)(xH) = xH \iff (gx)H = xH \iff x^{-1}gx \in H \iff g \in xHx^{-1}.$$

It is an exercise to show that $\ker \rho$ is the largest normal subgroup of G contained in H .

With these results, we can provide a third solution to Exercise 8.24 of page 29. We let G act on G/H by left multiplication. The induced group homomorphism $\rho: G \rightarrow \mathbb{S}_p$ has kernel

$$K = \ker \rho = \bigcap_{x \in G} xHx^{-1} \subseteq H.$$

By the first isomorphism theorem, $G/K \simeq \rho(G) \leq \mathbb{S}_p$ (this means that $\rho(G)$ is isomorphic to a subgroup of \mathbb{S}_p). Thus $|G/K|$ divides $p!$. Let $m = (H : K)$. By Lagrange's theorem,

$$(G : K) = (G : H)(H : K) = pm$$

and hence pm divides $p!$. This implies that m divides $(p-1)!$. If q a prime number dividing m , then $q \geq p$, by the minimality of p . Moreover, every prime factor of $(p-1)!$ is $< p$. Hence $m = 1$ and therefore $H = K$.

Exercise 13.12. Let a group G act on a set X . On X , we define the following relation: $x \sim y$ if and only if there exists $g \in G$ such that $g \cdot x = y$. Prove that this is an equivalence relation on X .

Definition 13.13. Let G be a group acting on a set X . If $x \in X$, the orbit of x is the set

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

The orbits of the action of G on X are the equivalence classes of the equivalence relation induced by the action. In particular, every two orbits will be either disjoint or equal. Moreover, X decomposes as a disjoint union of orbits.

Definition 13.14. Let G be a group that acts on X . If $x \in X$, the **stabilizer** of x in G is the set

$$G_x = \{g \in G : g \cdot x = x\}.$$

The reader must prove that the stabilizer is a subgroup.

Definition 13.15. We say that an action of a group G on a set X is **transitive** if for any $x, y \in X$ there exists $g \in G$ such that $g \cdot x = y$.

Example 13.16. Let G be a group and H a subgroup of G . Let G act on G/H by left multiplication. The action is transitive: if $xH, yH \in G/H$, there exists $g \in G$ such that $(gx)H = yH$ (take for example $g = yx^{-1}$).

Example 13.17. Por evaluación, el grupo simétrico \mathbb{S}_n actúa transitivamente en el conjunto $\{1, \dots, n\}$.

In the definition of a transitive action, there is no assumption on the number of elements g such that $g \cdot x = y$.

Definition 13.18. We say that an action of a group G on a set X is **faithful** if $\{g \in G : g \cdot x = x \text{ for all } x \in X\} = \{1\}$.

The definition is equivalent to the injectivity of the group homomorphism induced by the action.

Theorem 13.19 (Fundamental counting principle). *Let G be a finite group acting on a finite set X . If $x \in X$, then $|G \cdot x| = (G : G_x)$.*

Proof. Let $\varphi : G/G_x \rightarrow G \cdot x$, $gG_x \mapsto g \cdot x$. Then φ is well-defined, as

$$gG_x = hG_x \implies h^{-1}g \in G_x \implies h^{-1}g \cdot x = x \implies g \cdot x = h \cdot x.$$

Moreover, φ is injective:

$$\varphi(gG_x) = \varphi(hG_x) \implies g \cdot x = h \cdot x \implies h^{-1}g \in G_x \implies gG_x = hG_x.$$

Finally, φ is surjective. Hence $|G/G_x| = |G \cdot x|$. □

Theorem 13.19 is also known as the orbit–stabilizer theorem.

If G is a group and X and Y are G -sets, we say that a map $\varphi : X \rightarrow Y$ is a **homomorphism** of G -sets if $\varphi(g \cdot x) = g \cdot \varphi(x)$ for all $g \in G$ and $x \in X$. The bijection φ constructed in the proof of Theorem 13.19 is a homomorphism of G -sets, where G acts on G/G_x by left multiplication:

$$\varphi(g \cdot hG_x) = \varphi((gh)G_x) = (gh) \cdot x = g \cdot (h \cdot x) = g \cdot \varphi(hG_x).$$

Thus $G \cdot x \simeq G/G_x$ as G -sets.

Example 13.20. If G acts on G by conjugation, that is $g \cdot x = gxg^{-1}$, the orbits of this action are called the **conjugacy classes** of G . They are sets of the form

$$G \cdot x = \{gxg^{-1} : g \in G\}.$$

In particular, G decomposes as a disjoint union of conjugacy classes. Moreover, the stabilizers are the centralizers:

$$G_x = \{g \in G : g \cdot x = x\} = \{g \in G : gxg^{-1} = x\} = C_G(x).$$

In particular, $|G \cdot x| = (G : C_G(x))$.

Example 13.21. Let H be a subgroup of G and X the set of subsets of G . Let G act on X by conjugation, that is $S \in X$. Then $g \cdot S = gSg^{-1}$. The orbit of H is

$$G \cdot H = \{g \cdot H : g \in G\} = \{gHg^{-1} : g \in G\},$$

the set of conjugates of H . The stabilizer of H in G is

$$G_H = \{g \in G : g \cdot H = H\} = \{g \in G : gHg^{-1} = H\} = N_G(H),$$

the normalizer of H in G . It follows that H has exactly $(G : N_G(H))$ conjugates in G . In particular, if G is finite, the number of conjugates of H divides $|G|$.

As an application, we provide an alternative proof of Theorem 9.5.

Example 13.22. Let G be a group and H and K be subgroups of G . The group $L = H \times K$ acts on $X = HK$ by

$$(h, k) \cdot x = hxk^{-1}, \quad x \in X, h \in H, k \in K.$$

Note that $1 \in HK$ and the action of L on X is transitive, as $(h, k^{-1}) \cdot 1 = hk$. Since

$$L_1 = \{(h, k) \in H \times K : (h, k) \cdot 1 = 1\} = \{(h, k) \in H \times K : h = k\},$$

it follows that $|L_1| = |H \cap K|$ because there exists a bijection between L_1 and $H \cap K$. By the fundamental counting principle,

$$|HK| = (L : L_1) = \frac{|H \times K|}{|H \cap K|} = \frac{|H||K|}{|H \cap K|}.$$

As another application, we compute the order of the group $\mathbf{GL}_n(p)$ for $n \geq 1$ and a prime number p . The argument also works for the group $\mathbf{GL}_n(q)$ in the case where q is a power of the prime number p .

Example 13.23. Let $K = \mathbb{Z}/p$. We claim that

$$|\mathbf{GL}_n(p)| = (p^n - 1)p^{n-1}|\mathbf{GL}_{n-1}(p)|,$$

and hence

$$|\mathbf{GL}_n(p)| = (p^n - 1)(p^n - p) \cdots (p^n - p^{n-1}).$$

The formula is valid if $n \in \{1, 2\}$. Assume that it holds for $n - 1 \geq 1$. The group $G = \mathbf{GL}_n(p)$ acts on K^n by left multiplication. There are two orbits, so

$$X = \{0\} \cup (K^n \setminus \{0\}),$$

as if $v, w \in K^n \setminus \{0\}$, then there exists $g \in G$ such that $gv = w$. By the fundamental counting principle,

$$p^{n+1} - 1 = |K^{n+1} \setminus \{0\}| = (G : G_{e_1}),$$

where $e_1 = (1, 0, \dots, 0)^T$. If $g = (g_{ij}) \in G$ is such that $ge_1 = e_1$, then

$$g = \begin{pmatrix} 1 & g_{12} & \cdots & g_{1n} \\ 0 & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & g_{n1} & \cdots & g_{nn} \end{pmatrix}.$$

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Therefore $|G_{e_1}| = p^{n-1}|\mathbf{GL}_{n-1}(p)|$, as the submatrix $(g_{ij})_{2 \leq i, j \leq n}$ is invertible and the g_{1j} 's can be chosen arbitrarily for all $j \in \{2, \dots, n\}$. Hence

$$p^n - 1 = \frac{|G|}{|G_{e_1}|} = \frac{|\mathbf{GL}_n(p)|}{p^{n-1}|\mathbf{GL}_{n-1}(p)|},$$

which implies the formula we wanted to prove.

Lecture 9

§14. p -groups

Let G be a group and X be a finite G -set. Then X decomposes as a disjoint union of orbits. Let

$$\text{Fix}(X) = \{x \in X : g \cdot x = x \text{ for all } g \in G\}$$

be the set of **fixed points** of X . Gather the one-element orbits and apply cardinality. By the fundamental counting principle,

$$|X| = |\text{Fix}(X)| + \sum_{i=1}^k |G \cdot x_i| = |\text{Fix}(X)| + \sum_{i=1}^k (G : G_{x_i}), \quad (9.1)$$

where the x_j 's are the representatives of the orbits of size ≥ 2 . Equality (9.1) is extremely useful and is called the **class equation**.

Example 14.1. Let a finite group G act on G by conjugation. Then $\text{Fix}(G) = Z(G)$ and

$$|G| = |Z(G)| + \sum_{i=1}^k (G : C_G(x_i)),$$

for some $x_1, \dots, x_k \in G$ such that $(G : C_G(x_i)) \geq 2$ for all $i \in \{1, \dots, k\}$.

Definition 14.2. Let p be a prime number. We say that G is a **p -group** if $|G| = p^m$ for some $m \geq 0$.

Theorem 14.3. Let p be a prime number and G a p -group. If $\{1\} \neq N \trianglelefteq G$, then $N \cap Z(G) \neq \{1\}$.

Proof. Since N is normal in G , G acts on N by conjugation. By the fundamental counting principle, each orbit has prime-power size. Write

$$N = \underbrace{O_1 \cup \dots \cup O_k}_{\text{one-element orbits}} \cup \underbrace{O_{k+1} \cup \dots \cup O_m}_{\text{orbits of size } > 1},$$

Since $N \cap Z(G) = O_1 \cup \dots \cup O_k$, the integers $k = |N \cap Z(G)|$ and $|N \setminus (N \cap Z(G))|$ are divisible by p . Thus

$$|N| \equiv |N \cap Z(G)| \pmod{p}.$$

Since $1 \in N \cap Z(G)$, then $|N \cap Z(G)| > 1$. In particular, $N \cap Z(G) \neq \{1\}$. \square

The following corollary follows immediately:

Corollary 14.4. *Let p be a prime number and G a p -group. Then $Z(G) \neq \{1\}$.*

In Exercises 10.36 and 10.38 we proved that groups of order four and nine are always abelian.

Corollary 14.5. *Let p be a prime number. If G is a group of order p^2 , then G is abelian.*

Proof. By Lagrange's theorem, $|Z(G)| \in \{1, p, p^2\}$. Since G is a p -group, $Z(G) \neq \{1\}$. If $|Z(G)| = p$, then $G/Z(G)$ is cyclic. By Exercise 8.20, G is abelian, a contradiction. Thus $|Z(G)| = p^2$ and hence $G = Z(G)$. \square

§15. Cauchy's theorem

Theorem 15.1 (Cauchy). *Let G be a finite group, and p be a prime number that divides $|G|$. Then there exists $g \in G$ of order p .*

Proof. Let $C = \mathbb{Z}/p$ and

$$X = \{(x_1, \dots, x_p) \in G \times \dots \times G : x_1 \cdots x_p = 1\}.$$

Then C acts on X by $k \cdot (x_1, \dots, x_p) = (x_{k+1}, \dots, x_{k+p})$, where the indices are taken modulo p . To see that this is an action, note that

$$x_{i_1} \cdots x_{i_p} = 1 \implies (x_{i_1}^{-1} x_{i_1}) x_{i_2} \cdots x_{i_p} = x_{i_1}^{-1} \implies x_{i_2} \cdots x_{i_p} x_{i_1} = 1.$$

If x_1, \dots, x_{p-1} are fixed, then $x_p = x_{p-1}^{-1} \cdots x_1^{-1}$. Thus $|X| = |G|^{p-1}$. Each C -orbit has either one or p elements, as $|C| = p$. Write

$$X = \underbrace{O_1 \cup \dots \cup O_k}_{\text{one-element orbits}} \cup \underbrace{O_{k+1} \cup \dots \cup O_m}_{\text{orbits of size } p}.$$

Hence $0 \equiv |G|^{p-1} = |X| \equiv k \pmod{p}$, that is p divides k . Since $(1, 1, \dots, 1) \in X$, $k \geq 1$. Therefore $p \leq k$. In particular, there exists $x \in G \setminus \{1\}$ such that $(x, x, \dots, x) \in X$. Hence $|x| = p$. \square

Corollary 15.2. *Let p be a prime number and G be a finite group. Then G is a p -group if and only if every element of G has order a power of p .*

Proof. If G is a p -group, then, by Lagrange's theorem, every element has order a power of p . Conversely, if q is a prime divisor of $|G|$, by Cauchy's theorem, there exists $g \in G$ of order q . Thus $q = p$. \square

Corollary 15.3. *Let $p > 2$ be a prime number and G be a group of order $2p$. Then either $G \simeq \mathbb{Z}/2p$ or $G \simeq \mathbb{D}_p$.*

Proof. By Cauchy's theorem, there exist $r, s \in G$ such that $|r| = p$ and $|s| = 2$. Let $H = \langle r \rangle$. Then $(G : H) = 2$ and $H \trianglelefteq G$. We can decompose G as $G = H \cup Hs$ (disjoint union), as $s \notin H$. In particular,

$$G = \{1, r, \dots, r^{p-1}, s, rs, \dots, r^{p-1}s\}.$$

Since $sr s^{-1} \in H$, it follows that $sr s^{-1} = r^k$ for some $k \in \{0, 1, \dots, p-1\}$. Since $s^2 = 1$,

$$r = s^2 r s^{-2} = s(sr s^{-1})s^{-1} = sr^k s^{-1} = r^{k^2}.$$

Thus $k^2 \equiv 1 \pmod{p}$ and either $k \equiv 1 \pmod{p}$ or $k \equiv -1 \pmod{p}$. If $k \equiv -1 \pmod{p}$, then $sr s^{-1} = r^{-1}$ and hence $G \simeq \mathbb{D}_p$. If $k \equiv 1 \pmod{p}$, then $rs = sr$ and hence, since G is abelian, $G \simeq \mathbb{Z}/2p$. \square

Theorem 15.4. *A group of order p^m has a normal subgroup of order p^n for every $n \leq m$.*

Proof. We proceed by induction on m . The case where $m = 1$ is trivial. Assume that the result holds for groups of order p^m . Let G be a group of order p^{m+1} . We claim that if $n \leq m$, G contains a normal subgroup of order p^n . Since $Z(G) \neq \{1\}$, there exists $g \in Z(G) \setminus \{1\}$ of order p . Let $N = \langle g \rangle \trianglelefteq G$. The quotient group G/N has order p^m . By the inductive hypothesis, there exists a normal subgroup Y of G/N of order p^n . By the correspondence theorem, G contains a normal subgroup K of G that contains N , that is $N \leq K \leq G$. In fact, $Y = \pi(K)$ and $(G : K) = (\pi(G) : \pi(K)) = p^{m-n}$. Hence $|K| = p^n$. \square

Lecture 10

§16. Sylow's theorems

Definition 16.1. Let G be a group of $p^\alpha m$, where p is a prime number coprime with m . A subgroup S of G is said to be a **Sylow p -subgroup** of G if $|S| = p^\alpha$.

A subgroup S of G is a Sylow p -subgroup of G if and only if S is a p -group and the prime p does not divide $(G : S)$.

Example 16.2.

- 1) If p does not divide $|G|$, then $\{1\}$ is a Sylow p -subgroup of G .
- 2) If G is a p -group, then G is a Sylow p -subgroup of G .

Example 16.3. Let $G = \mathbb{S}_3$. Then $\langle(12)\rangle$, $\langle(13)\rangle$ and $\langle(23)\rangle$ are the Sylow 2-subgroups of G . Moreover, $\langle(123)\rangle$ is the only Sylow 3-subgroup of G .

Example 16.4. Let $G = \mathbb{S}_4$. The subgroup $\langle(1234), (13)\rangle$ is a Sylow 2-subgroup of G and $\langle(123)\rangle$ is a Sylow 3-subgroup of G .

Example 16.5. Let $G = \mathbb{Z}/18$. The subgroup $\langle 2 \rangle = \{0, 2, 4, 6, 8, 10, 12, 14, 16\}$ is the only Sylow 3-subgroup of G and $\langle 9 \rangle = \{0, 9\}$ is the only Sylow 2-subgroup of G .

Example 16.6. Let p be a prime number and $G = \mathbf{GL}_n(p)$. Since

$$\begin{aligned} |\mathbf{GL}_n(p)| &= (p^n - 1)(p^n - p) \cdots (p^n - p^{n-1}) \\ &= p^{1+2+\cdots+n} (p^n - 1)(p^{n-1} - 1) \cdots (p - 1), \end{aligned}$$

we can write $|\mathbf{GL}_n(p)| = p^\alpha m$, where $\alpha = 1 + 2 + \cdots + n$ and m is an integer not divisible by p . The subgroup of matrices of the form

$$\begin{pmatrix} 1 & * & \cdots & * \\ 0 & 1 & \cdots & * \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{pmatrix},$$

that is the set of matrices (g_{ij}) with

$$g_{ij} = \begin{cases} 1 & \text{si } i = j, \\ 0 & \text{si } i > j, \end{cases}$$

has order p^α . Thus it is a Sylow p -subgroup of $\mathbf{GL}_n(p)$.

We will prove three crucial theorems that go back to Sylow. The first one guarantees the existence of Sylow subgroups. We shall need a lemma.

Lemma 16.7. *If p is a prime number, $\alpha \geq 0$ and $m \geq 1$, then*

$$\binom{p^\alpha m}{p^\alpha} \equiv m \pmod{p}.$$

Proof. By the binomial theorem,

$$(1+X)^p = \sum_{j=0}^p \binom{p}{j} X^{p-j} \equiv 1+X^p \pmod{p},$$

because $\binom{p}{j}$ is divisible by p for all $j \in \{1, \dots, p-1\}$. By using induction, one proves that

$$(1+X)^{p^j} \equiv 1+X^{p^j} \pmod{p}$$

holds for all j . Thus

$$(1+X)^{p^\alpha m} \equiv (1+X^{p^\alpha})^m \pmod{p}.$$

Comparing the coefficient of X^{p^α} in the previous formula, we get the result we wanted to prove. \square

Theorem 16.8 (Sylow's first theorem). *Let G be a finite group and p a prime number. Then there exists a Sylow p -subgroup of G .*

Proof. Write $|G| = p^\alpha m$ with $\gcd(p, m) = 1$ and $\alpha \geq 1$. Let

$$X = \{S : S \subseteq G \text{ subsets of size } p^\alpha\}.$$

Let G act on X by left multiplication, as $|g \cdot S| = |gS| = |S|$ for all $g \in G$ and $S \in X$. Decompose X into G -orbits and note that the previous lemma implies that

$$|X| = \binom{p^\alpha m}{p^\alpha} \equiv m \not\equiv 0 \pmod{p}.$$

Thus there exists an orbit \mathcal{O} of size not divisible by p . If $S \in \mathcal{O}$, let G_S be the stabilizer of S in G . Since $|\mathcal{O}| = (G : G_S)$ and $|\mathcal{O}|$ is not divisible by p , we obtain that p^α divides $|G_S|$. In particular, $p^\alpha \leq |G_S|$. If $g \in G_S$, then $gS = S$. If $x \in S$, then $G_S x \subseteq S$. Thus

$$|G_S| = |G_S x| \leq |S| = p^\alpha$$

as $S \in X$. Therefore G_S is a Sylow p -subgroup of G . \square

If G is a finite group and p is a prime divisor of $|G|$, let

$$\text{Syl}_p(G) = \{\text{Sylow } p\text{-subgroups of } G\}.$$

The first Sylow's theorem states that $\text{Syl}_p(G)$ is non-empty.

Before proving Sylow's second theorem, we state and prove a slightly more technical result.

Theorem 16.9. *Let G be a finite group. If P is a p -subgroup of G and $S \in \text{Syl}_p(G)$, then $P \subseteq gSg^{-1}$ for some $g \in G$.*

Proof. Let $X = \{xS : x \in G\}$ be the set of left cosets of S in G . Then $|X| = (G : S)$ is not divisible by p . Let G act on X by left multiplication. In particular, P also acts on X by left multiplication. Decompose X into P -orbits. There exists a P -orbit O of size not divisible by p , as $|X|$ is not divisible by p . Since $|O|$ divides $|P|$ and p does not divide $|O|$, it follows that $|O| = 1$, that is $O = \{gS\}$ for some $g \in G$. Since $P(gS) = gS$, in particular, $xg \in gS$ for all $x \in P$. This means that if $x \in P$, then $x \in gSg^{-1}$. Hence $P \subseteq gSg^{-1}$. \square

An application:

Corollary 16.10. *Let p be a prime number. If G is a finite group and P is a p -subgroup of G , then P is contained in some Sylow p -subgroup of G .*

Proof. If $S \in \text{Syl}_p(G)$, then $gSg^{-1} \in \text{Syl}_p(G)$, as $|gSg^{-1}| = |S|$. By the previous theorem, $P \subseteq gSg^{-1}$ for some $g \in G$. Thus the claim follows. \square

Theorem 16.11 states that any two Sylow p -subgroups are conjugate, that is, G acts transitively by conjugation on $\text{Syl}_p(G)$.

Theorem 16.11 (Sylow's second theorem). *Let G be a finite group and p a prime number. If $S, T \in \text{Syl}_p(G)$, then there exists $g \in G$ such that $gSg^{-1} = T$.*

Proof. Use the previous theorem with $P = T$. Then $T \subseteq gSg^{-1}$ for some $g \in G$. Since $|S| = |T|$ and $|T| \leq |gSg^{-1}| = |S|$, we conclude that $T = gSg^{-1}$. \square

Corollary 16.12. *Let G be a finite group, p a prime number and $S \in \text{Syl}_p(G)$. If S is normal in G , then $\text{Syl}_p(G) = \{S\}$.*

Proof. If $T \in \text{Syl}_p(G)$, then $T = gSg^{-1} = S$ for some $g \in G$. \square

For the next theorem, we need some notation. If p is a prime number and G is a finite group of order $p^\alpha m$ with $\gcd(p, m) = 1$, then $n_p(G) = |\text{Syl}_p(G)|$. Note that

$$n_p(G) = (G : N_G(P))$$

for all $P \in \text{Syl}_p(G)$. We will prove that $n_p(G)$ divides m .

Theorem 16.13 (Sylow's third theorem). *Let G be a finite group and p a prime number. Then $n_p(G) \equiv 1 \pmod{p}$.*

Proof. Assume that $|G| = p^\alpha m$ with m not divisible by p . By Sylow's first theorem, $\text{Syl}_p(G)$ is non-empty. Let $P \in \text{Syl}_p(G)$ and $n = n_p(G)$. We consider the set

$$X = \{gPg^{-1} : g \in G\} = \{P = P_1, P_2, \dots, P_n\}.$$

By Sylow's second theorem, $|X| = n$.

Let G act on X by conjugation. Then P also acts on X by conjugation. Each P -orbit has size a power of p .

We claim that $\{P\}$ is the only P -orbit of size one. Since $xPx^{-1} = P$ if $x \in P$, it follows that $\{P\}$ is a P -orbit. Let $\{P_i\}$ be a P -orbit of size one. Then $xP_i x^{-1} = P_i$ for all $x \in P$. Thus $P \subseteq N_G(P_i)$. The group $N_G(P_i)/P_i$ has order not divisible by p , as $P_i \in \text{Syl}_p(G)$. If $xP_i \in N_G(P_i)/P_i$ for $x \in P$, then $xP_i = P_i$. That is $x \in P_i$, since $(xP_i)^{p^\alpha} = x^{p^\alpha} P_i = P_i$ implies that $|xP_i|$ divides p^α . Hence $|xP_i| = 1$, as $N_G(P_i)/P_i$ has order coprime with p . Therefore $x \in P_i$. This implies that $P \subseteq P_i$. Hence $P = P_i$, as both sets have size p^α . Now

$$X = \{P\} \cup \underbrace{O_1 \cup O_2 \cup \dots \cup O_k}_{\text{of size } > 1 \text{ divisible by } p}.$$

Thus $n_p(G) = |X| \equiv 1 \pmod{p}$. □

We now discuss some applications of Sylow's theorems.

Example 16.14. If G is a group of order 15, then G is cyclic.

Let $n_3 = n_3(G)$ and $n_5 = n_5(G)$. Then $n_3 \equiv 1 \pmod{3}$ and n_3 divides 5. Thus $n_3 = 1$ and hence there exists a unique $H \in \text{Syl}_3(G)$. This group is then normal in G and isomorphic to $\mathbb{Z}/3$. Similarly, $n_5 = 1$ and there is a unique subgroup $K \in \text{Syl}_5(G)$ such that $K \trianglelefteq G$ and $K \simeq \mathbb{Z}/5$. Since $H \cap K = \{1\}$ by Lagrange's theorem,

$$|HK| = \frac{|H||K|}{|H \cap K|} = |H||K| = 15 = |G|.$$

Hence $G = HK \simeq H \times K \simeq \mathbb{Z}/3 \times \mathbb{Z}/5 \simeq \mathbb{Z}/15$.

Example 16.15. If G is a group of order 455, then G is cyclic.

For every prime number p dividing $|G|$, let $n_p = n_p(G)$. Since n_5 divides 7×13 and $n_5 \equiv 1 \pmod{5}$, then $n_5 \in \{1, 91\}$. A direct calculation shows that $n_7 = n_{13} = 1$. Let $P \in \text{Syl}_7(G)$ and $Q \in \text{Syl}_{13}(G)$, both normal subgroups of G . Since P and Q have coprime orders, Lagrange's theorem implies that $P \cap Q = \{1\}$. We now apply Sylow's theorems to the quotients G/P and G/Q . Let $m_5 = n_5(G/P)$ and $m_{13} = n_{13}(G/P)$. Since m_5 divides 13 and $m_5 \equiv 1 \pmod{5}$, it follows that $m_5 = 1$. Similarly, $m_{13} = 1$ and hence $G/P \simeq \mathbb{Z}/5 \times \mathbb{Z}/13$. The same argument shows that $G/Q \simeq \mathbb{Z}/5 \times \mathbb{Z}/7$. Thus both G/P and G/Q are abelian. This means that $[G, G] \subseteq P \cap Q = \{1\}$. Hence G is also abelian. In particular, $n_5 = 1$ and

$$G \simeq \mathbb{Z}/5 \times \mathbb{Z}/7 \times \mathbb{Z}/13 \simeq \mathbb{Z}/455.$$

Example 16.16. If G is a group of order 21, then either

$$G \simeq \mathbb{Z}/21 \quad \text{or} \quad G \simeq \langle x, y : x^7 = y^3 = 1, yx = x^2y \rangle.$$

Let $n_3 = n_3(G)$ and $n_7 = n_7(G)$. Since $n_7 \equiv 1 \pmod{7}$ and n_3 divides 3, it follows that $n_7 = 1$. There is a unique $H \in \text{Syl}_7(G)$. This subgroup H is such that $H \trianglelefteq G$ and $H \simeq \mathbb{Z}/7$. Thus $H = \langle x \rangle$, where $x^7 = 1$. Let $K \in \text{Syl}_3(G)$. Since n_3 divides 7 and $n_3 \equiv 1 \pmod{3}$, it follows that $n_3 \in \{1, 7\}$. Hence $K \simeq \mathbb{Z}/3$ and thus $K = \langle y \rangle$ where $y^3 = 1$. By Lagrange's theorem, $H \cap K = \{1\}$ and $G = HK$. In particular,

$$G = \{x^i y^j : 0 \leq i \leq 6, 0 \leq j \leq 2\}.$$

Since H is normal in G , $xyx^{-1} \in H$. That is $xyx^{-1} = x^i$ for some $i \in \{1, \dots, 6\}$. Therefore $x^7 = y^3 = 1$ and $yx = x^i y$ for some $i \in \{1, \dots, 6\}$. What can we say about this i ? We note that

$$x = y^3 xy^{-3} = y^2 (xyx^{-1}) y^{-2} = y^2 x^i y^{-2} = y (x^i)^2 y^{-1} = (x^i)^3.$$

Then $i^3 \equiv 1 \pmod{7}$, that is $i \in \{1, 2, 4\}$. There are three cases:

- (a) If $xyx^{-1} = x$, then $xy = yx$. Thus $K \trianglelefteq G$ and $G \simeq H \times K \simeq \mathbb{Z}/21$.
- (b) If $xyx^{-1} = x^2$, then we can compute the table of G . In particular, G can be obtained as a certain subgroup of $\mathbf{GL}_2(\mathbb{Z}/7)$, that is

$$x = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \quad y = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}, \quad G \simeq \langle x, y \rangle \leq \mathbf{GL}_2(\mathbb{Z}/7).$$

- (c) If $xyx^{-1} = x^4$, then $y^2 xy^{-2} = x^2$. Since $|y^2| = |y| = 3$, if $z = y^2$, then $H = \langle y \rangle = \langle z \rangle$. So we are in the previous case.

Example 16.17. If G is a group of order $5 \cdot 7 \cdot 17$, then G is cyclic.

For $p \in \{5, 7, 17\}$, let $n_p = n_p(G)$. Since $n_5 \equiv 1 \pmod{5}$ and n_5 divides $7 \cdot 17$, it follows that $n_5 = 1$. Let $H \in \text{Syl}_5(G)$. This is the only Sylow 5-subgroup of G , so H is normal in G . Let $K \in \text{Syl}_7(G)$ and $L \in \text{Syl}_{17}(G)$. Since H is normal in G , HK is a subgroup of G . By Lagrange's theorem, $H \cap K = \{1\}$ because H and K have coprime orders. Thus $|HK| = 5 \cdot 7$. We now apply Sylow's theorems to the group HK . If $m_7 = n_7(HK)$, then $m_7 = 1$. In particular, $K \in \text{Syl}_7(HK)$ and K is normal in HK . Thus $HK \subseteq N_G(K)$ and $|HK| \leq |N_G(K)|$. Since

$$n_7 = (G : N_G(K)) = \frac{|G|}{|N_G(K)|} \leq \frac{|G|}{|HK|} = \frac{5 \cdot 7 \cdot 17}{5 \cdot 7} = 17$$

and $n_7 \in \{1, 5 \cdot 17\}$, we conclude that $n_7 = 1$. The same argument shows that $n_{17} = 1$. Therefore both K and L are normal in G . By Lagrange's theorem,

$$L \cap H = H \cap K = L \cap K = \{1\}$$

It follows that

$$L \cap (HK) = H \cap (LK) = K \cap (LH) = \{1\}.$$

Hence $G = HKL \simeq \mathbb{Z}/5 \times \mathbb{Z}/7 \times \mathbb{Z}/17 \simeq \mathbb{Z}/(5 \cdot 7 \cdot 17)$.

Example 16.18. If G is a group of order 12 such that $n_3(G) \neq 1$, then $G \simeq \mathbb{A}_4$.

Let $P \in \text{Syl}_3(G)$ and $n_3 = n_3(G) = 4$. Then P is not normal in G . Let G act on the set G/P by left multiplication. This induces a group homomorphism

$$\rho: G \rightarrow \mathbb{S}_{G/P} \simeq \mathbb{S}_4.$$

We claim that ρ is injective. Note that $\ker \rho \subseteq P$, as

$$x \in \ker \rho \implies \rho_x = \text{id} \implies xP \subseteq P \implies x \in P.$$

Since P is not normal in G , $P \neq \ker \rho$. Thus $\ker \rho$ is a proper subgroup of P . Hence $\ker \rho = \{1\}$ since $|P| = 3$. Let $S, T \in \text{Syl}_3(G)$. Since $S \simeq T \simeq \mathbb{Z}/3$, Lagrange's theorem implies that $S \cap T = \{1\}$. Thus G contains exactly eight elements of order three. Since the elements of order three of \mathbb{S}_4 belong to \mathbb{A}_4 , the subgroup $\rho(G) \cap \mathbb{A}_4$ of \mathbb{S}_4 contains at least eight elements. Therefore $G \simeq \rho(G) \simeq \mathbb{A}_4$.

Sylow's theorems can be used to detect non-simple groups.

Example 16.19. If G is a group of order 36, then G is not simple.

Assume that G is simple. Then $n_3 = n_3(G) = 4$. Let $P \in \text{Syl}_3(G)$ and let G act on $X = \{gPg^{-1} : g \in G\}$ by conjugation. This induces a group homomorphism

$$\rho: G \rightarrow \mathbb{S}_X \simeq \mathbb{S}_4.$$

Since G is simple, either $\ker \rho = \{1\}$ or $\ker \rho = G$. If $\ker \rho = G$, P is normal in G , a contradiction. Thus $\ker \rho = \{1\}$ and hence ρ is injective. In particular, by the first isomorphism theorem,

$$G \simeq G/\ker \rho \simeq \rho(G) \leq \mathbb{S}_4.$$

This implies that 36 divides 24, a contradiction.

Example 16.20. If G is a group of order 30, then G is not simple.

For every prime number p dividing 30, let $n_p = n_p(G)$. Assume that $n_2 > 1$, $n_3 > 1$ and $n_5 > 1$. Then $n_3 = 10$. There are ten Sylow 3-subgroups, any two of them with trivial intersection. In fact, if $P, Q \in \text{Syl}_3(G)$ are such that $P \neq Q$, then $P \cap Q \leq P$ and hence $|P \cap Q| \in \{1, 3\}$. If $|P \cap Q| = 3$, then $P \cap Q = P$ and $P = Q$, a contradiction. Similarly, there are six Sylow 5-subgroups of G , any two of them with trivial intersection. In conclusion,

$$|G| \geq 1 + 10 \times 2 + 6 \times 4 > 30,$$

a contradiction.

More about Sylow's theorems (optional)

Theorem 16.21. *Let N be a normal subgroup of a finite group G and $P \in \text{Syl}_p(N)$. Then $P \cap N \in \text{Syl}_p(N)$. Moreover, every Sylow p -subgroup of N can be obtained this way.*

Proof. Since N is normal, by Theorem 16.9, there exists $g \in G$ such that

$$g(P \cap N)g^{-1} = gPg^{-1} \cap gNg^{-1} = gPg^{-1} \cap N \in \text{Syl}_p(N).$$

Then $P \cap N$ is a Sylow p -subgroup of $g^{-1}Ng = N$.

Let $Q \in \text{Syl}_p(N)$ and $P \in \text{Syl}_p(G)$ be such that $Q \subseteq P$. Then $Q \subseteq P \cap N$. Hence $Q = P \cap N$, as $P \cap N$ is a Sylow p -subgroup of N . \square

As a corollary, if G is a finite group and N is a normal subgroup of G , then $n_p(N) \leq n_p(G)$.

Theorem 16.22. *Let p be a prime number, G be a finite group, $P \in \text{Syl}_p(G)$, and N be a normal subgroup of G . Let $\pi: G \rightarrow G/N$ be the canonical homomorphism. Then $\pi(P) \in \text{Syl}_p(G/N)$ and every Sylow p -subgroup of G/N can be obtained this way.*

Proof. Since $\pi(P) = \pi|_P(P) \simeq P/N \cap P$, the second isomorphism theorem implies that $\pi(P)$ is a p -group. Since $|PN| = |P||N|/|P \cap N|$,

$$(G/N : \pi(P)) = (G : PN)$$

is not divisible by p . Thus $\pi(P) \in \text{Syl}_p(G/N)$.

If $Q \in \text{Syl}_p(G/N)$, then $Q = \pi(H)$ for some subgroup H of G with $N \subseteq H$. In particular,

$$|Q| = |\pi(H)| = \frac{|H|}{|H \cap N|} = \frac{|H|}{|N|}.$$

Thus

$$(G : H) = \frac{|G|/|N|}{|H|/|N|} = (G/N : Q)$$

is not divisible by p . Thus $X \in \text{Syl}_p(H)$ and hence $X \in \text{Syl}_p(G)$. Therefore

$$\pi(X) \subseteq \pi(H) = Q$$

and $\pi(X) = Q$, as $\pi(X) \in \text{Syl}_p(G/N)$. \square

As a corollary, if G is a finite group and N is a normal subgroup of G , then $n_p(G/N) \leq n_p(G)$.

Corollary 16.23. *Let G be a finite group. Assume that G contains only one Sylow p -subgroup. Then every subgroup and every quotient of G contains only one Sylow p -subgroup.*

Proof. If H is a subgroup of G , then $n_p(H) \leq n_p(G) = 1$. If N is a normal subgroup of G , then $n_p(G/N) \leq n_p(G) = 1$. \square

Lecture 11

§17. Double cosets (optional)

The idea used in Example 13.22 can be generalized.

Example 17.1. Sea G un grupo y sean H y K subgrupos de G . Hacemos que el grupo $L = H \times K$ actúe en G por

$$(h, k) \cdot g = h g k^{-1}.$$

Las órbitas son los conjuntos de la forma

$$HgK = \{h g k : h \in H, k \in K\},$$

estos conjuntos se llaman (H, K) -coclases dobles. En particular, dos (H, K) -coclases dobles son disjuntas o iguales. Más aún, G se descompone como unión disjunta

$$G = \bigcup_{i \in I} H g_i K,$$

para algún conjunto I , es decir G es unión disjunta de (H, K) -coclases dobles. Calculamos ahora

$$L_g = \{(h, k) \in H \times K : h g k^{-1} = g\} = \{(h, g^{-1} h g) \in H \times K\}$$

y vemos que $|L_g| = |H \cap g K g^{-1}|$, pues los conjuntos L_g y $H \cap g K g^{-1}$ están en biyección.

Luego, gracias al principio fundamental del conteo,

$$|HgK| = (L : L_g) = \frac{|H \times K|}{|H \cap g K g^{-1}|} = \frac{|H||K|}{|H \cap g K g^{-1}|}.$$

El ejemplo anterior puede generalizarse, lo que nos da una descomposición de un grupo como unión disjunta de **coclases dobles**. Veremos más adelante demostraciones alternativas de los teoremas de Sylow basadas en coclases dobles.

Veamos una demostración alternativa del primer teorema de Sylow que utiliza coclases dobles. Primero demostraremos un resultado auxiliar. Si $P \in \text{Syl}_p(G)$ y $H \leq G$, entonces existe un $g \in G$ tal que $H \cap gPg^{-1} \in \text{Syl}_p(H)$. En efecto, supongamos que $|H| = p^\beta t$ con p coprimo con t . Si descomponemos a G en (H, P) -coclases dobles,

$$|G| = \sum_{i=1}^k \frac{|H||P|}{|H \cap x_i P x_i^{-1}|}.$$

Al simplificar $|P| = p^\alpha$, tenemos que $m = \sum_{i=1}^k (H : H \cap x_i P x_i^{-1})$, lo que nos dice que existe $i \in \{1, \dots, k\}$ tal que $(H : H \cap x_i P x_i^{-1})$ no es divisible por p . Esto significa que que p^β divide a $|H \cap x_i P x_i^{-1}|$ y en consecuencia $H \cap x_i P x_i^{-1} \in \text{Syl}_p(H)$. Por el teorema de Cayley podemos suponer que nuestro subgrupo G es un subgrupo de $\text{GL}_n(p)$ para algún n y algún primo p . Sea P un subgrupo de Sylow del grupo $\text{GL}_n(p)$. La observación que demostramos aplicada al grupo G nos dice que existe $g \in \text{GL}_n(p)$ tal que $G \cap gPg^{-1}$ es un subgrupo de Sylow de G .

Veamos una demostración alternativa del segundo teorema de Sylow que usa coclases dobles. Si $P, Q \in \text{Syl}_p(G)$ y descomponemos a G en (P, Q) -coclases dobles, tenemos

$$p^\alpha m = \sum_{i=1}^k \frac{|P||Q|}{|P \cap x_i Q x_i^{-1}|} \implies m = \sum_{i=1}^k \frac{|P|}{|P \cap x_i Q x_i^{-1}|}$$

para ciertos $x_1, \dots, x_k \in G$. Como m no es divisible por p , existe algún $i \in \{1, \dots, k\}$ tal que $|P| = |P \cap x_i Q x_i^{-1}|$, lo que implica que $P = x_i Q x_i^{-1}$ para algún $i \in \{1, \dots, k\}$.

Una demostración alternativa del tercer teorema de Sylow basada en coclases dobles. Sean $P \in \text{Syl}_p(G)$ y $N = N_G(P)$. Recordemos que $n_p(G) = (G : N)$. Si descomponemos a G en (P, N) -coclases dobles,

$$|G| = \sum_{i=1}^k \frac{|P||N|}{|N \cap x_i P x_i^{-1}|}$$

para ciertos $x_1, \dots, x_k \in G$. Sin perder generalidad podemos suponer que $x_1 = 1$, entonces la fórmula anterior queda

$$n_p(G) = 1 + \sum_{i=2}^k \frac{|P|}{|N \cap x_i P x_i^{-1}|},$$

pues $(G : N) = n_p(G)$. El teorema quedará demostrado si vemos que la suma del miembro de la derecha es divisible por p . Si esto no pasa, es decir si existe $i \in \{2, \dots, k\}$ tal que $|N \cap x_i P x_i^{-1}| = |P|$, entonces $x_i P x_i^{-1} = N \cap x_i P x_i^{-1} \subseteq N$. Como entonces P y también $x_i P x_i^{-1}$ son ambos p -subgrupos de Sylow de N , el segundo teorema de Sylow afirma que estos subgrupos tienen que ser conjugados en N . Por definición del normalizador, P es normal en N . En consecuencia, $x_i P x_i^{-1} = P$, es decir $x_i \in N$, una contradicción pues como $i > 1$ se tiene que $P x_i N$ y $P x_1 N = PN$ son coclases dobles disjuntas.

Some solutions

8.16 Since N is normal in G , the operation is well-defined. Routine calculations show that the operation is associative, that N is the neutral element of G/N and that the inverse of an element xN is $(xN)^{-1} = x^{-1}N$. For example, for the associativity, we note that for $x, y, z \in G$ one has

$$((xN)(yN))(zN) = ((xy)N)zN = (xy)zN,$$

equals

$$(xN)((yN)(zN)) = (xN)((yz)N) = x(yz)N.$$

since $x(yz) = (xy)z$.

8.18 For $x, y \in G$,

$$(xH)(yH) = (yH)(xH) \iff (xy)H = (yx)H \iff x^{-1}y^{-1}xy \in H.$$

Thus G/H is abelian if and only if $[x, y] = xyx^{-1}y^{-1} \in H$ for all $x, y \in G$.

8.20 Assume that $G/Z(G) = \langle gZ(G) \rangle$. Let $x, y \in G$. Write $xZ(G) = g^kZ(G)$ and $yZ(G) = g^lZ(G)$, that is $x = g^kz_1$ and $y = g^lz_2$ for some $k, l \in \mathbb{Z}$ $y, z_1, z_2 \in Z(G)$. Thus $xy = yx$.

8.24 If $g \in G \setminus H$, then $g^n = 1 \in H$, where $n = |G|$. Since p is prime, n has no prime divisors $< p$. By Exercise 8.23, H is normal in G .

9.2 We need to show that $HK = KH$. We first prove that $HK \subseteq KH$. If $x = hk \in HK$, then $x = k(k^{-1}hk) \in KH$, as $k^{-1}hk \in H$. To prove that $HK \supseteq KH$, let $y = kh \in KH$. Then $y = (khk^{-1})k \in HK$, as $khk^{-1} \in H$.

10.29 Just note that $\mathcal{U}(\mathbb{Z}/12)$ has no elements of order four.

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