1 Definitions and examples

Exercise 1.1. Determine which of the following sets are groups under the specified operations:

1. the integers under the operation of subtraction;
2. the set $\mathbb{R}$ of real numbers under the operation $\circ$ given by $a \circ b = a + b + 2$;
3. the set of odd integers under the operation of multiplication;
4. the set of $n \times n$ real matrices whose determinant is either 1 or -1, under matrix multiplication.

Solution.

1. No, since no identity exists, because $x - e = x$ implies $e = 0$, but $0 - x = x$ does not hold for arbitrary x.
2. Yes, since:
   (a) $a + b + 2 \in \mathbb{R}$
   (b)
   $$\begin{aligned}(a \circ b) \circ c = a \circ (b \circ c) &\Leftrightarrow (a + b + 2) + c + 2 = a + (b + c + 2) + 2 \\ &\Leftrightarrow a + b + c + 4 = a + b + c + 4\end{aligned}$$
   , which holds.
   (c) -2 is the identity element:
   $$-2 \circ a = -2 + a + 2 = a = a \circ (-2)$$
   (d) $g^{-1} = -g - 4$:
   $$g \circ g^{-1} = g - g - 4 + 2 = -2 = g^{-1} \circ g$$
3. No, since there is no multiplicative inverse in integers.
4. Yes, since:
   (a) A matrix product of $n \times n$ is an $n \times n$ matrix, and a determinant of such a product is a product of determinants of those matrices. Since the set $\{-1, 1\}$ is closed under multiplication, the set at hand is closed under matrix multiplication.
   (b) Matrix product is associative.
   (c) The identity matrix is the identity element and has det $= 1$.
   (d) The inverse element is the matrix inverse. A^{-1} has determinant of ± 1 because $AA^{-1} = I$ and det is distributive with respect to the matrix product:
   $$AA^{-1} = I$$

$$\begin{aligned} \det(AA^{-1}) &= \det I \\ \det A \cdot \det A^{-1} &= 1 \\ \pm 1 \cdot \det A^{-1} &= 1 \\ \det A^{-1} &= \mp 1 \end{aligned}$$

□

Exercise 1.2. Calculate the multiplication table for the following eight 2×2 complex matrices, and deduce that they form a non-abelian group:

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad A = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}, \quad B = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}, \quad C = \begin{pmatrix} -i & 0 \\ 0 & i \end{pmatrix},$$
$$D = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad E = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}, \quad F = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}, \quad G = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Solution.

	I	A	B	C	D	E	F	G
I	I	A	B	C	D	E	F	G
A	A	B	C	I	E	F	G	D
B	B	C	I	A	F	G	D	E
C	C	I	A	B	G	D	E	F
D	D	G	F	E	I	C	B	A
E	E	D	G	F	A	I	C	B
F	F	E	D	G	B	A	I	C
G	G	F	E	D	C	B	A	I

Non-commutativity is trivial since $CD \neq DC$. Closure follows from the table, associativity is trivial, the identity element is I, and the inverse element can be found in the table for each element. □

Exercise 1.3. Find the multiplication table for the eight symmetries of a square.

Solution. None, since I can't automate it and I'm not calculating this by hand. □

Exercise 1.4. Find the symmetry groups of

1. a non-square rectangle,
2. a parallelogram with unequal sides which is not a rectangle,
3. a non-square rhombus.

Solution.

1. e, 180 degree rotations, reflection on both axis parallel to the rectangle's sides.
2. e, 180 degree rotations.
3. e, 180 degree rotations, reflection on both axis parallel to the rhombus's sides.

□

Exercise 1.5. Write down the multiplication tables for the groups $C_2 \times C_3$ and $C_3 \times C_3$.

Solution.

	(c_0, c_0)	(c_0, c_1)	(c_0, c_2)	(c_1, c_0)	(c_1, c_1)	(c_1, c_2)
(c_0, c_0)	(c_0, c_0)	(c_0, c_1)	(c_0, c_2)	(c_1, c_0)	(c_1, c_1)	(c_1, c_2)
(c_0, c_1)	(c_0, c_1)	(c_0, c_2)	(c_0, c_0)	(c_1, c_1)	(c_1, c_2)	(c_1, c_0)
(c_0, c_2)	(c_0, c_2)	(c_0, c_0)	(c_0, c_1)	(c_1, c_2)	(c_1, c_0)	(c_1, c_1)
(c_1, c_0)	(c_1, c_0)	(c_1, c_1)	(c_1, c_2)	(c_0, c_0)	(c_0, c_1)	(c_0, c_2)
(c_1, c_1)	(c_1, c_1)	(c_1, c_2)	(c_1, c_0)	(c_0, c_1)	(c_0, c_2)	(c_0, c_0)
(c_1, c_2)	(c_1, c_2)	(c_1, c_0)	(c_1, c_1)	(c_0, c_2)	(c_0, c_0)	(c_0, c_1)

Not doing the other one. □

Exercise 1.6. Show that $G \times H$ is abelian if and only if G and H are each abelian.

Solution.

$\Rightarrow$ Since $G \times H$ is abelian,

$$\forall i, j, k, l \quad (g_i, h_j)(g_k, h_l) = (g_k, h_l)(g_i, h_j)$$

$$(g_i g_k, h_j h_l) = (g_i, h_j)(g_k, h_l) = (g_k, h_l)(g_i, h_j) = (g_k g_i, h_l h_j)$$
$$(g_i g_k, h_j h_l) = (g_k g_i, h_l h_j)$$
$$g_i g_k = g_k g_i \quad h_j h_l = h_l h_j$$

$\Leftarrow$ The same argument from the bottom up follows.

□

2 Maps and relations on sets

Exercise 2.1. Let $X = \{a, b, c\}$ and $Y = \{u, v\}$. List all the maps from X to Y and list all the maps from Y to X.

Solution. Maps from X to Y:

$$\begin{pmatrix} a & b & c \\ u & u & u \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ u & u & v \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ u & v & u \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ u & v & v \end{pmatrix}$$

$$\begin{pmatrix} a & b & c \\ v & u & u \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ v & u & v \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ v & v & u \end{pmatrix} \quad \begin{pmatrix} a & b & c \\ v & v & v \end{pmatrix}$$

Maps from Y to X:

$$\begin{pmatrix} u & v \\ a & a \end{pmatrix} \quad \begin{pmatrix} u & v \\ a & b \end{pmatrix} \quad \begin{pmatrix} u & v \\ a & c \end{pmatrix} \quad \begin{pmatrix} u & v \\ b & a \end{pmatrix} \quad \begin{pmatrix} u & v \\ b & b \end{pmatrix} \quad \begin{pmatrix} u & v \\ b & c \end{pmatrix} \quad \begin{pmatrix} u & v \\ c & a \end{pmatrix} \quad \begin{pmatrix} u & v \\ c & b \end{pmatrix} \quad \begin{pmatrix} u & v \\ c & c \end{pmatrix}$$

□

Exercise 2.2. Let $g : X \to Y$ and $f : Y \to Z$ be functions. Show that:

1. if f and g are both injective then fg is injective;
2. if f and g are both surjective then fg is surjective.

Give examples to show that if f is injective and g is surjective then fg need neither be injective nor surjective.

Solution.

1. If $x_1 \neq x_2$ then $f(x_1) \neq f(x_2)$, therefore $g(f(x_1)) \neq g(f(x_1))$
2. $$\forall z \in Z \;\; \exists y \in Y : g(y) = z, \exists x \in X : f(x) = y \Rightarrow g(f(x)) = z$$

Let:

$$X = \{1, 2\}, \quad Y = \{3, 4, 5\}, \quad Z = \{6, 7\}, \quad f = \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}, \quad g = \begin{pmatrix} 3 & 4 & 5 \\ 6 & 6 & 7 \end{pmatrix}$$

Then fg is:

$$fg = \begin{pmatrix} 1 & 2 \\ 6 & 6 \end{pmatrix}$$

, which is neither injective nor surjective. □

Exercise 2.3. When $X = \{a, b, c\}$, list all the maps $f : X \to X$ which are constant (so that $f(a) = f(b) = f(c)$), Write down the composition table for these maps. Do these maps form a group?

Solution.

$$f = \begin{pmatrix} a & b & c \\ a & a & a \end{pmatrix} \quad g = \begin{pmatrix} a & b & c \\ b & b & b \end{pmatrix} \quad h = \begin{pmatrix} a & b & c \\ c & c & c \end{pmatrix}$$

	f	g	h
f	f	g	h
g	f	g	h
h	f	g	h

These maps do not form a group since no neutral element exists. □

Exercise 2.4. Prove that the relation on the set $\mathbb{Z}$ defined by xRy if $x + y$ is an even integer is an equivalence relation, and determine the equivalence classes. Is the relation xRy if $x + y$ is divisible by 3 an equivalence relation?

Solution.

1. $xRy : x + y \equiv 0 \mod 2$ is an equivalence relation:
   (a) xRx since $x + x = 2x \equiv 0 \mod 2$
   (b) Symmetry follows from commutativity of addition.
   (c) $xRy \Rightarrow y - x \equiv 0 \mod 2, yRz \Rightarrow z - y \equiv 0 \mod 2 \Rightarrow z - x \equiv 0 \mod 2 \Rightarrow z + x \equiv 0 \mod 2 \Rightarrow zRx \Rightarrow xRz$
2. Equivalence classes:

$$[(x, y) : x \equiv y \mod 2] \quad [(x, y) : x \not\equiv y \mod 2]$$

3. No, because $1 + 1 \not\equiv 0 \mod 3$, therefore R is not reflective.

□

Exercise 2.5. Write down the addition table for the congruence classes modulo 4, and the multiplication table for the non-zero congruence classes modulo 5.

Solution. Denoting congruence classes by smallest positive member of each class:

+	0	1	2	3
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	0	1	2

·	1	2	3	4
1	1	2	3	4
2	2	4	1	3
3	3	1	4	2
4	4	3	2	1

□

Exercise 2.6. Show that multiplication of congruence classes modulo n is well-defined.

Solution. Need to prove that if $[x_1]_n = [x_2]_n$ and $[y_1]_n = [y_2]_n$ then $[x_1y_1]_n = [x_2y_2]_n$.

Let $x_1 = an + b, x_2 = cn + b, y_1 = en + d, y_2 = fn + d$

$$x_1y_1 = aen^2 + n(ab + be) + bd \equiv bd \mod n$$

$$x_2y_2 \equiv bd \mod n$$

Therefore x_1y_1 and x_2y_2 lie in the same congruence class. □

3 Elementary consequences of the definitions

Exercise 3.1. Let G be a group in which $g^2 = 1$ for all g in G. Prove that G is abelian.

Solution. Proving from the bottom up:

$$\begin{aligned} xy &= yx \\ y &= x^{-1}yx \\ yx &= x^{-1}yx^2 \\ yx &= x^{-1}y \\ xy &= x^{-1}y \\ xy^2 &= x^{-1}y^2 \\ x &= x^{-1} \\ x^2 &= 1 \end{aligned}$$

, which holds. □

Exercise 3.2. Let a, b and c be elements of the group G. Find the solutions x of the equations

1. $axa^{-1} = 1$,
2. $axa^{-1} = a$,
3. $axb = c$ and
4. $ba^{-1}xab^{-1} = ba$

Solution.

1.
$$\begin{aligned} axa^{-1} &= 1 \\ ax &= a \\ x &= a^{-1}a \\ x &= 1 \end{aligned}$$

2.
$$\begin{aligned} axa^{-1} &= a \\ ax &= a^2 \\ x &= a^{-1}a^2 \\ x &= a \end{aligned}$$

3.
$$\begin{aligned} axb &= c \\ ax &= cb^{-1} \\ x &= a^{-1}cb^{-1} \end{aligned}$$

4.
$$\begin{aligned} ba^{-1}xab^{-1} &= ba \\ ba^{-1}xa &= bab \\ ba^{-1}x &= baba^{-1} \\ a^{-1}x &= aba^{-1} \\ x &= a^2ba^{-1} \end{aligned}$$

□

Exercise 3.3. Let G be a group and c be a fixed element of G. Define a new operation $*$ on G by

$$x * y = xc^{-1}y$$

for all x and y in G. Prove that G is a group under the operation $*$.

Solution.

1. Closure is trivial.
2. $$(x * y) * z \stackrel{?}{=} x * (y * z)$$
   $$(xc^{-1}y)c^{-1}z \stackrel{?}{=} xc^{-1}(yc^{-1}z)$$

   , which holds by "extended associativity", i.e. that brackets are meaningless.
3. The neutral element is c:

   $$x * c = xc^{-1}c = x1 = x = 1x = cc^{-1}x = c * x$$

4. The inverse element is $cx^{-1}c$:

   $$x * cx^{-1}c = xc^{-1}cx^{-1}c = x1x^{-1}c = xx^{-1}c = c$$

   $$cx^{-1}c * x = cx^{-1}cc^{-1}x = c$$

□

Exercise 3.4. List the orders of all the elements of the group $D(3)$ of Example 1.9.

Solution.

Element	e	a	b	c	d	f
Order	1	2	2	1	1	1

□

Exercise 3.5. Give an example of a group G with elements x and y such that $(xy)^{-1}$ is not equal to $x^{-1}y^{-1}$.

Solution. $G = C_4, x = g, y = g^2$

$$xy = g^3 \quad (xy)^{-1} = g \quad x^{-1} = g^3 \quad y^{-1} = g^2 \quad x^{-1}y^{-1} = g^2 \neq (xy)^{-1}$$

□

Exercise 3.6. Let G be a group in which $(xy)^2 = x^2y^2$ for all x and y in G. Prove that G is abelian.

Solution.

$$
\begin{aligned}
xy &\stackrel{?}{=} yx \\
xxyy &\stackrel{?}{=} xyxy \\
x^2y^2 &= (xy)^2
\end{aligned}
$$

, which holds by the definition of G. ☐

Exercise 3.7. Let x and g be elements of a group G. Prove, using mathematical induction, that for all positive integers k,

$$(x^{-1}gx)^k = x^{-1}g^kx$$

Deduce that g and $x^{-1}gx$ have the same order.

Solution.

Base. $k = 0$.

$$(x^{-1}gx)^k = 0 = x^{-1}x = x^{-1}g^0x$$

Induction step.

$$(x^{-1}gx)^k = x^{-1}gx(x^{-1}gx)^{k-1} = x^{-1}gxx^{-1}g^{k-1}x = x^{-1}g^kx$$

Order:

$\Rightarrow$

$$g^k = 1 \Rightarrow x^{-1}g^kx = 1 \Rightarrow (x^{-1}gx)^k = 1$$

$\Leftarrow$

$$x^{-1}gx = 1 \Rightarrow x^{-1}g^kx = 1 \Rightarrow g^kx = x \Rightarrow g^k = 1$$

☐

Exercise 3.8. Let ω denote the complex number $e^{2\pi i/6}$, so that $\omega^6 = 1$. Let

$$X = \begin{pmatrix} \omega & 0 \\ 0 & \omega^{-1} \end{pmatrix}$$

Show that $X^6 = I$ and calculate X^{-1}. Find a 2×2 matrix Y such that

$$XY = YX^{-1} \text{ and } Y^2 = X^3.$$

Show that the set $G = \{X^i, YX^j : 1 \leq i, j \leq 6\}$ with 12 elements is a group under matrix multiplication, and find the order of each element of G.

Solution.

$$X^6 = \begin{pmatrix} \omega^6 & 0 \\ 0 & \omega^{-6} \end{pmatrix} = I$$

$$X^{-1} = \begin{pmatrix} \omega^{-1} & 0 \\ 0 & \omega \end{pmatrix}$$

Let $Y = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$.

$$Y^2 = \begin{pmatrix} a^2 + bc & ab + bd \\ ac + cd & bc + d^2 \end{pmatrix} = X^3 = \begin{pmatrix} \omega^3 & 0 \\ 0 & \omega^{-3} \end{pmatrix}$$

$$XY = \begin{pmatrix} a\omega & b\omega \\ c\omega^{-1} & d\omega^{-1} \end{pmatrix} \quad YX^{-1} = \begin{pmatrix} a\omega^{-1} & b\omega \\ c\omega^{-1} & d\omega \end{pmatrix}$$

This implies that $a = d = 0$. Therefore $bc = \omega^3 = -1$. Let $c = -b^{-1}$.

The following is a proof of G being a group.

1. $\{X^i : 1 \le i \le 6\}$ is isomorphic to C_6 by a map that takes the first element of the first row and an inverse map $\omega^i \mapsto \begin{pmatrix} \omega^i & 0 \\ 0 & \omega^{-i} \end{pmatrix}$. Closure of $\{X^i\}$ is therefore trivial. Moreover, $YX^j \times X^i = YX^{j+i \mod 6} \in G$. The following is the proof of two other cases.

$$\begin{aligned} X^i \times YX^j &= \begin{pmatrix} \omega^i & 0 \\ 0 & \omega^{-i} \end{pmatrix} \times \left(\begin{pmatrix} 0 & b \\ -b^{-1} & 0 \end{pmatrix} \times \begin{pmatrix} \omega^j & 0 \\ 0 & \omega^{-j} \end{pmatrix} \right) \\ &= \begin{pmatrix} \omega^i & 0 \\ 0 & \omega^{-i} \end{pmatrix} \times \begin{pmatrix} 0 & b\omega^{-j} \\ -b^{-1}\omega^j & 0 \end{pmatrix} \\ &= \begin{pmatrix} 0 & b\omega^{i-j} \\ -b^{-1}\omega^{j-i} & 0 \end{pmatrix} \\ &= YX^{j-i \mod 6} \end{aligned}$$

$$\begin{aligned} YX^i \times YX^j &= \begin{pmatrix} 0 & b\omega^{-i} \\ -b^{-1}\omega^i & 0 \end{pmatrix} \times \begin{pmatrix} 0 & b\omega^{-j} \\ -b^{-1}\omega^j & 0 \end{pmatrix} \\ &= \begin{pmatrix} \omega^{j-i} & 0 \\ 0 & \omega^{i-j} \end{pmatrix} \\ &= X^{j-i \mod 6} \end{aligned}$$

2. Matrix product is associative.
3. The identity matrix is the identity element and is X^6.
4. The inverse for X^i is X^{6-i}, for YX^i is YX^{6-i}, which follows from the closure proof.

□

4 Subgroups

Exercise 4.1. Which of the following sets H are subgroups of the given group G?

1. G is the set of integers under addition, H is the set of even integers;
2. $G = S(3), H = \{1, (12), (23), (13)\}$;
3. $G = GL(2, \mathbb{R}), H$ is the set of matrices of the form $\begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix}$, where a is any real number.

Solution.

1. The identity element of $\mathbb{Z}_+$ is 0, which is contained in H. Moreover, even integers are closed under addition and the additive inverse of an integer is even. Therefore, all conditions of 4.2 (2) hold.
2. No, $(12)(23) \notin G$.
3. Let A_a denote $\begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix}$. $A_a \times A_b = A_{a+b} \in H$, because reals are closed under addition. The identity element of G, I is A_0 and is therefore contained in H. The inverse of A_a is A_{-a}, which follows from the statements above.

□

Exercise 4.2. Give an example of a group G with subgroups H and K such that $H \cup K$ is not a subgroup of G.

Solution. Let G be an abelian group with distinct elements $1, k, h, hk$. Let $H = \langle h \rangle = \{1, h\}, K = \langle k \rangle = \{1, k\}$. $H \cup K$ does not contain hk, but contains h and k. □

Exercise 4.3. Let G be the group in Question 2 of Exercises 1. Find the number of elements in $\langle A, D \rangle$. Is $\langle A, C \rangle$ cyclic? Write down the multiplication table for $\langle B, F \rangle$.

Solution. $\langle A, D \rangle = \{I, A, D, B, E, G, C, F\}, |\langle A, D \rangle| = 8$

$\langle A, C \rangle = \{I, A, C, B\}$. This group is cyclic, which can be seen from its' Cayley table (see 1.2)

$\langle B, F \rangle = \{I, B, F, D\}$

	I	B	F	D
I	I	B	F	D
B	B	I	D	F
F	F	D	I	B
D	D	F	B	I

□

Exercise 4.4. Let G be the group with presentation $\{x, y : x^4 = 1, x^2 = y^2, xy = yx^{-1}\}$. Decide how many elements are in G and determine its multiplication table.

Solution. Consider the order of y. Since $y^4 = x^4 = 1$, it is ≤ 4.

If $y^3 = 1$, $x^2y = 1$ and therefore $1 = xyx^{-1}$, which implies $y = 1, x^2 = 1$, which contradicts the definition.

If $y^2 = 1, x^2 = 1$, which contradicts the definition.

The only case left is $y^4 = 1$. Clearly, G contains all 3 powers of x and y.

	1	x	x^2	x^3	y	y^3	xy	x^2y
1	1	x	x^2	x^3	y	y^3	xy	x^2y
x	x	x^2	x^3	1	xy	xy^3	x^2y	x^3y
x^2	x^2							
x^3	x^3							
y	y							
y^3	y^3							
xy	xy							
x^2y	x^2y							

$\square$