



AY2019 Q2

MA08

Applied Algebra, 応用代数

(Abstract Algebra, 抽象代数学)

Class Information

Lectures: Period 1, 2 Monday and Period 1, 2 Thursday

Grades: 20% Assignments (10, Attendance $> 2/3$)

30% Middle Examination

50% Final Examination

+5 Bonus Points from Quizzes

Office hours: Period 3, 4 Monday and Thursday; @研究棟#247C

Textbook: [Eng] **Abstract Algebra Theory and Applications, 2018,**

(教科書)

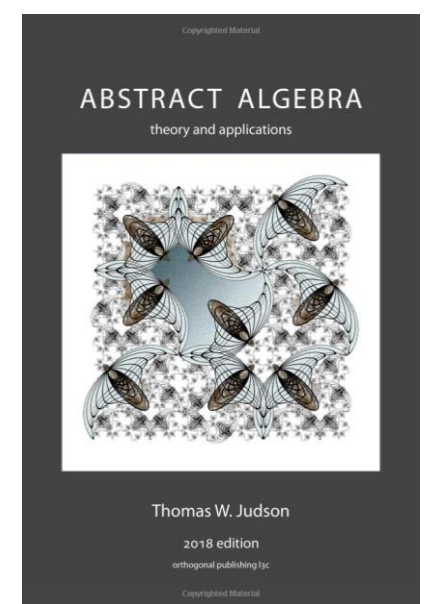
Thomas W. Judson etc.

Free online: <http://abstract.ups.edu/download/aata-20180801-sage-8.2.pdf>


参考書: [Eng] **Introduction to Abstract Algebra, 2007, D. S. Malik, John N. Mordeson, M.K. Sen**

Free online: https://www.researchgate.net/publication/238669835_MTH_581-582_Introduction_to_Abstract_Algebra

[Jap] **工学のための応用代数, 1999, 杉原 厚吉, 今井 敏行, 共立出版**



Hint for Middle & Final Exams

90%  Lecture Slides (Example, Definition, Theorem)
Assignments

10% Other questions

About Lecture Notes & Assignments

Please Check <https://github.com/uoaworks/Applied-Algebra>

before and after each lecture for slides and assignments.

What we will cover

Syllabus on course website

01 promenade to algebraic system

02 remainder of integer and polynomial

03 group(1): Lagrange theorem

04 group(2): quotient group and homomorphism theorem

05 group(3): analysis of group structure

06 applications of group



07 Mid-exam

08 ring and field(1): ideal, quotient ring

09 ring and field(2): polynomial ring

10 ring and field(3): reversible

11 application(1): quotient field and operator theory

12 ring and field(4): extension of field

13 application(2): M-sequence random number generation

14 application(3): error correct coding

Prerequisites

MA03 Calculus I

*MA01 Linear Algebra I

Notice: * is optional.

Important related courses:

NS03 Quantum Mechanics



Lecture 1

Promenade to Algebraic System

0.1 Why abstract algebra

0.1 Why Abstract Algebra

- **Abstract Algebra** is the study of **algebraic structures** (代数構造).
- Algebraic structures include **groups (群)**, **rings (環)**, **fields (体)**, modules, vector spaces, lattices, and algebras.

0.1 Why Abstract Algebra

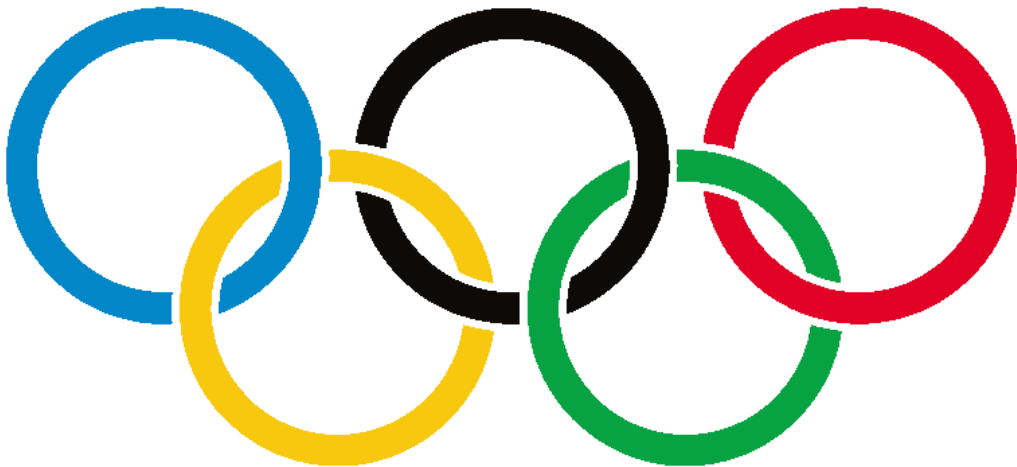
The first time we hear the names of group, ring, field ...



Group (群)

Ring (環)

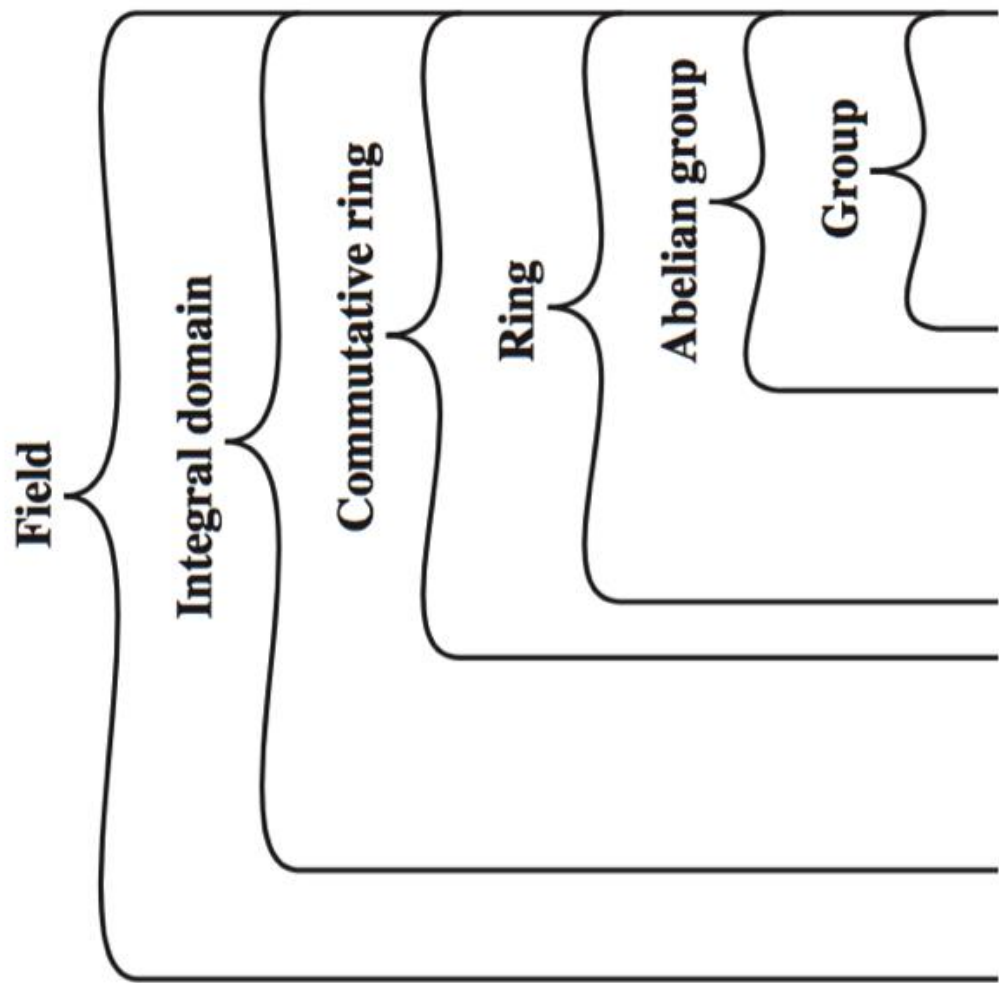
Field (体)



0.1 Why Abstract Algebra

理論の土台となる約束事・前提事項。
(証明の必要は無い。)

Algebra Structure (代数構造)



Component Axioms (公理)

- (A1) Closure under addition:
- (A2) Associativity of addition:
- (A3) Additive identity:
- (A4) Additive inverse:
- (A5) Commutativity of addition:
- (M1) Closure under multiplication:
- (M2) Associativity of multiplication:
- (M3) Distributive laws:
- (M4) Commutativity of multiplication:
- (M5) Multiplicative identity:
- (M6) No zero divisors:
- (M7) Multiplicative inverse:

Explanation of Axiom

If a and b belong to S , then $a + b$ is also in S
 $a + (b + c) = (a + b) + c$ for all a, b, c in S
There is an element 0 in R such that
 $a + 0 = 0 + a = a$ for all a in S
For each a in S there is an element $-a$ in S such that $a + (-a) = (-a) + a = 0$
 $a + b = b + a$ for all a, b in S
If a and b belong to S , then ab is also in S
 $a(bc) = (ab)c$ for all a, b, c in S
 $a(b + c) = ab + ac$ for all a, b, c in S
 $(a + b)c = ac + bc$ for all a, b, c in S
 $ab = ba$ for all a, b in S
There is an element 1 in S such that
 $a1 = 1a = a$ for all a in S
If a, b in S and $ab = 0$, then either $a = 0$ or $b = 0$
If a belongs to S and $a \neq 0$, there is an element a^{-1} in S such that $aa^{-1} = a^{-1}a = 1$

Figure 4.2 Groups, Ring, and Field

0.1 Why Abstract Algebra

The **three main areas** that were to give rise to **group theory** are:

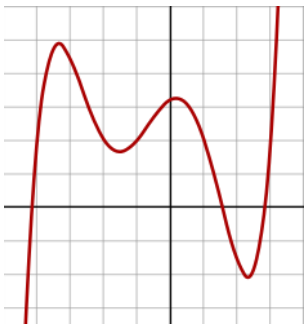
- **geometry** at the beginning of the 19th Century,
studied properties invariant
- **number theory** at the end of the 18th Century,
studied modular arithmetic
- **the theory of algebraic equations** at the end of the 18th Century
lead to the study of permutations (置換).

Reference: https://www-history.mcs.st-and.ac.uk/HistTopics/Development_group_theory.html

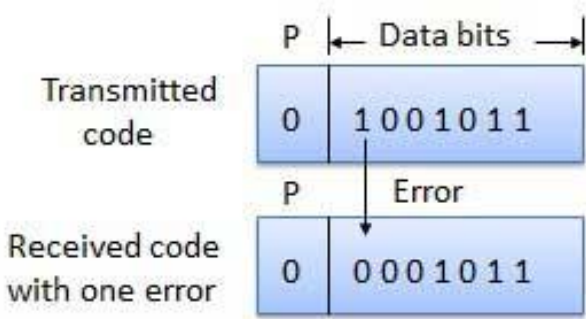
0.1 Why Abstract Algebra

Quintic Equation

$$ax^5 + bx^4 + cx^3 + dx^2 + ex + f = 0$$



Error Correction



Rubik's Cube

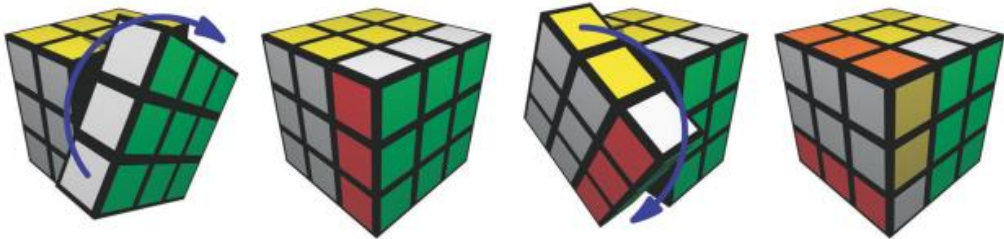


Figure 1.2. The leftmost cube shows the green face rotating 90 degrees clockwise; the next cube shows the result of that move. The third cube shows the white face rotating 90 degrees clockwise; the final cube shows the result of that move.

Fifteen Puzzle



Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin				
$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z boson	
$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	

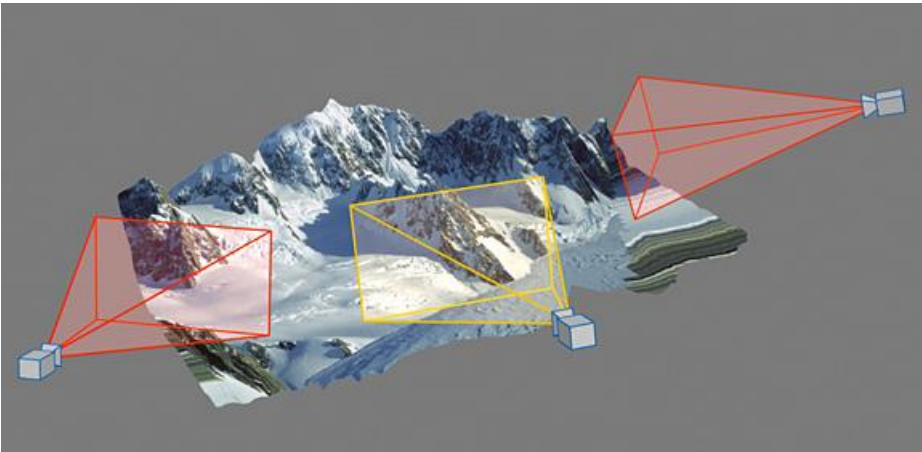
QUARKS

LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

3D Mapping in Computer Vision



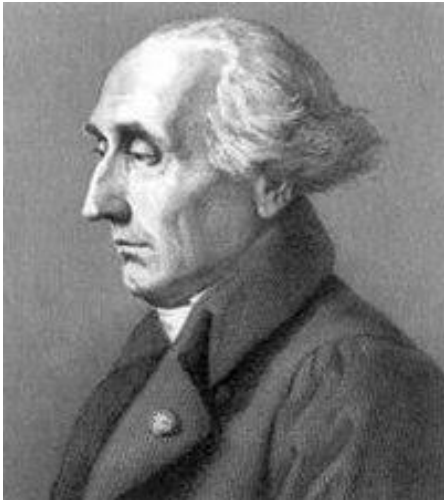
0.1 Why Abstract Algebra

Birth of Group Theory (群論)

General Quintic Equation

$$ax^5 + bx^4 + cx^3 + dx^2 + ex + f = 0$$

They reveal Non-existence of a formula that is comprised of these coefficients, arithmetic operations and roots for general quantic equation



Joseph-Louis Lagrange
(ラグランジュ)
France, 1736 ~ 1813



Évariste Galois (ガロア)
France, 1811 ~ 1832



Niels Henrik Abel (アーベル)
Norway, 1802 ~ 1829

0.1 Why Abstract Algebra

Lagrange firstly studied **Permutations** (置換) in his 1770 paper on the theory of algebraic equations. Lagrange's main object was to find out why cubic (三次) and quartic (四次) equations (方程式) could be solved algebraically.

Cauchy played a major role in **developing the theory of permutations**. His first paper on the subject was in 1815 but at this stage Cauchy is motivated by permutations of roots of equations.

Abel, in 1824, **gave the first accepted proof of the insolubility of the quantic equation (五次方程式)**, and he used the existing ideas on permutations of roots but little new in the development of group theory.

Galois in 1831 was the first to really understand that the algebraic solution of an equation **was related to the structure of a group** le groupe of permutations related to the equation. By 1832 **Galois had discovered that special subgroups (部分群) (now called normal subgroups) are fundamental**. He calls **the decomposition of a group into cosets (剰余類) of a subgroup a proper decomposition if the right and left coset decompositions coincide**. Galois then shows that the non-abelian simple group of smallest order has order 60.

Galois' work was not known until Liouville published Galois' papers in 1846. Liouville saw clearly the connection between Cauchy's theory of permutations and Galois' work. However Liouville failed to grasp that the importance of Galois' work lay in the group concept.

Reference: https://www-history.mcs.st-and.ac.uk/HistTopics/Development_group_theory.html

0.2 A Short Note on Proofs

In studying **abstract mathematics**, we take what is called an **axiomatic approach**; that is, we **take a collection of objects S and assume some rules about their structure**.

These rules are called **axioms (公理)**. Using the axioms for S , we wish to derive other information about S by using logical arguments.

A **statement** (言明, 命題) in logic or mathematics is an assertion (主張) that **is either true (真) or false (偽)**. Consider the following examples:

1. ~~$3 + 56 - 13 + 8/2.$~~

2. All cats are black.

3. $2 + 3 = 5.$

4. $2x = 6$ exactly when $x = 4.$

5. If $ax^2 + bx + c = 0$ and $a \neq 0$, then

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

6. ~~$x^3 - 4x^2 + 5x - 6.$~~

All examples except the first and last examples are statements, and must be either true or false.

- A mathematical proof is nothing more than a convincing argument about the accuracy of a statement.

Let us examine different types of statements. A statement could be as simple as " $10/5 = 2$ "

however, mathematicians are usually interested in more complex statements such as "**If p , then q ,**" where p and q are both statements.

Here p is called the hypothesis and q is known as the conclusion.

0.2 A Short Note on Proofs

Proof

Consider the **following statement**: If $ax^2 + bx + c = 0$ and $a \neq 0$, then

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

Here the **hypothesis** is $ax^2 + bx + c = 0$ and $a \neq 0$; the **conclusion** is

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

Notice that the **statement** says nothing about whether or not the hypothesis is true. However, if this entire statement is true and we can show that $ax^2 + bx + c = 0$ with $a \neq 0$ is true, then the conclusion *must* be true. A proof of this statement might simply be a series of equations:

Proof:

$$\begin{aligned} ax^2 + bx + c &= 0 \\ x^2 + \frac{b}{a}x &= -\frac{c}{a} && \because a \neq 0 \\ x^2 + \frac{b}{a}x + \left(\frac{b}{2a}\right)^2 &= \left(\frac{b}{2a}\right)^2 - \frac{c}{a} \\ \left(x + \frac{b}{2a}\right)^2 &= \frac{b^2 - 4ac}{4a^2} \\ x + \frac{b}{2a} &= \frac{\pm\sqrt{b^2 - 4ac}}{2a} \\ x &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \end{aligned}$$

If we can prove a statement true or false, then that statement is called a proposition (命題).

A proposition of major importance is called a theorem (定理).

Sometimes instead of proving a theorem or proposition all at once, we break the proof (証明) down into modules; that is, we prove several supporting propositions, which are called lemmas (補題), and use the results of these propositions to prove the main result.

If we can prove a proposition or a theorem, we will often, with very little effort, be able to derive other related propositions called corollaries (系).

What you will learn in Lecture 1

1.1 Sets (集合)

1.2 Relation (関係), Mapping (写像) and Permutation (置換)

1.3 Division (除法), Quotient (商), Remainder (剰余), Great Common Divisor (最大公約数)

1.4 Equivalence Classes (同値類)

1.1 Sets (集合)

1.1 Sets (集合)

We will denote sets by capital letters, such as X .

- A *set* X is a well-defined collection of objects
(集合とは、well-defined なモノの集まりのことである。);
that is, it is defined that we can determine for any given object x whether or not x belongs to the set X .
- The objects that belong to a set are called its *elements* (要素) or *members*.

Given a set X , we use the notation

$x \in X$ to mean x is an element of X

$x \notin X$ to mean x is **not** an element of X

collection of objects

For example, for the set $X = \{1, 2, 3\}$, we have $1 \in X$ and $4 \notin X$.

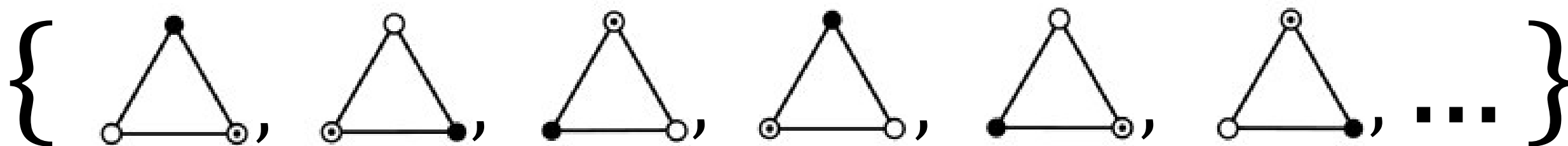
object, i.e. element or member

1.1 Sets (集合)

Example of Sets

$\{1, 2, 3, 4, 5, \dots\}$

$\{\dots, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, \dots\}$



R_{360} or Identity

R_{120}

R_{240}

Reflection

R_{120}

Reflection

R_{240}

Reflection



- A *set* X is a well-defined collection of objects;
that is, it is defined that we can determine for any given object x whether or not x belongs to the set X .

A set X is **well-defined (ちゃんと定義になっている)**, meaning that if X is a set and x is some object, then either x is definitely in X , denoted by $x \in X$, or x is definitely not in X , denoted by $x \notin X$.

Thus, we should never say, “Consider the set S of some positive integers,” , because it is **not definite** whether $2 \in S$ or $2 \notin S$.

On the other hand, we can consider the set of all **even** positive integers, because every positive integer is definitely either even or odd. Thus $2 \in S$ and $3 \notin S$.

A set is usually specified by

(1) listing all of its elements inside a pair of braces

$$X = \{x_1, x_2, \dots, x_n\}$$

for a set containing elements x_1, x_2, \dots, x_n ;

(2) stating the characterizing property that determines whether or not an object x belongs to the set

$$X = \{x \mid x \text{ satisfies } P(x)\} \quad \text{or} \quad X = \{x : x \text{ satisfies } P(x)\}$$

if each x in X satisfies a certain property $P(x)$.

The notation $X = \{x \mid x \text{ satisfies } P(x)\}$ is often called "set-builder notation"

If S is the set of even positive integers, we can describe S by writing either

$$S = \{2, 4, 6, \dots\} \text{ or } S = \{x \mid x \text{ is an even integer and } x > 0\}$$

We write $2 \in S$ when we want to say that 2 is in the set S , and $3 \notin S$ to say that 3 is not in the set S .

- Some of the more **important sets** that we will consider are the following:

$$\mathbb{N} = \{n \mid n \text{ is a natural number}\} = \{1, 2, 3, \dots\}$$

$$\mathbb{Z} = \{z \mid z \text{ is an integer}\} = \{\dots, -2, -1, 0, 1, 2, \dots\}$$

$$\mathbb{Q} = \{r \mid r \text{ is a rational number}\} = \{p/q \mid p, q \in \mathbb{Z} \text{ where } q \neq 0\}$$

$$\mathbb{R} = \{x \mid x \text{ is a real number}\}$$

$$\mathbb{C} = \{z \mid z \text{ is a complex number}\}$$

A set A is said to be a **subset** (部分集合) of a set S if every element of A is an element of S . In this case, we write $A \subseteq S$ and say that A is contained in S .

If $A \subseteq S$, but $A \neq S$, then we write $A \subset S$ and say that A is properly contained in S . Or we say A is a **proper subset** (真部分集合) of S .

As an example, we have $\{1, 2, 3\} \subseteq \{1, 2, 3\}$ and $\{1, 2\} \subset \{1, 2, 3\}$.

If every element of A is a element of B and every element of B is a element of A , then we say that A and B are the same or equal.

In this case, we write $A = B$.

Then, we can easily have the following theorem

Theorem 1.1

Let A and B be sets. Then $A = B$ if and only if $A \subseteq B$ and $B \subseteq A$.

The **empty set** (空集合) or **null set** is the set with no elements.

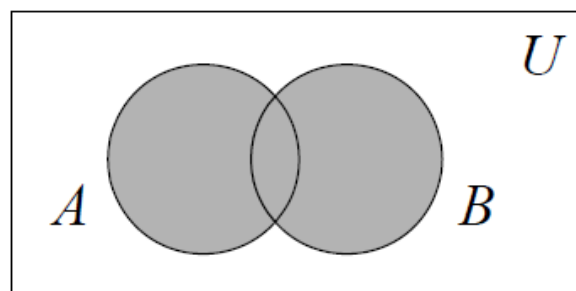
- We usually denote the empty set by \emptyset .
- For any set A , we have $\emptyset \subseteq A$.

Definition 1.1

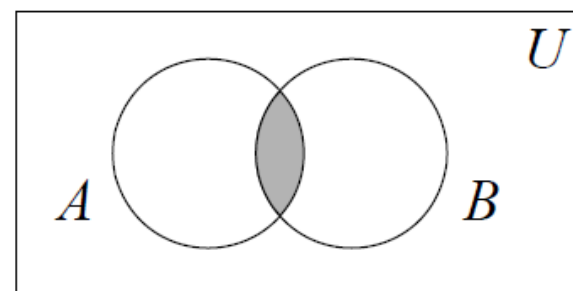
The **union** (和集合) of two sets A and B , written $A \cup B$, is defined to be the set $A \cup B = \{x \mid x \in A \text{ or } x \in B\}$.

Definition 1.2

The **intersection** (積集合, 共通部分) of two sets A and B , written $A \cap B$, is defined to be the set $A \cap B = \{x \mid x \in A \text{ and } x \in B\}$.



$A \cup B$



$A \cap B$

Example 1.1

Let A be the set $\{1, 2, 3, 4\}$ and B be the set $\{3, 4, 5, 6\}$.

Then $A \cup B = \{1, 2, 3, 4, 5, 6\}$ and $A \cap B = \{3, 4\}$

If C is the set $\{5, 6\}$, then $A \cup C = \{1, 2, 3, 4, 5, 6\}$ while $A \cap C = \emptyset$.

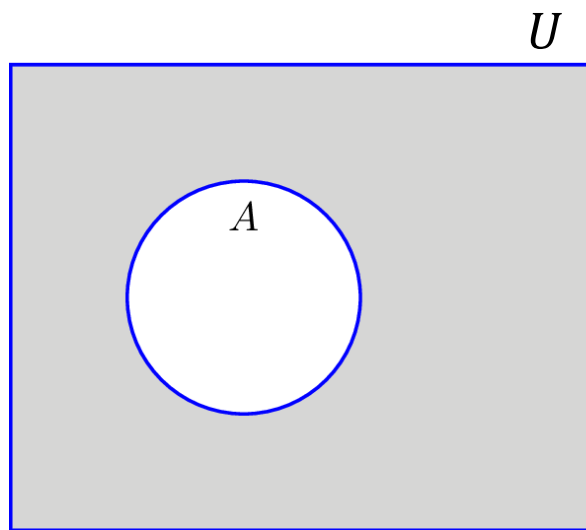
Notice:

Two sets A and B are called **disjoint** (2つの集合が交わりを持たない
あるいは互いに素) exactly when $A \cap B = \emptyset$.

Definition 1.3

For any set $A \subset U$, where U is **universal set (全体集合)**, we define the **complement (補集合)** of A , denoted by A' , to be the set

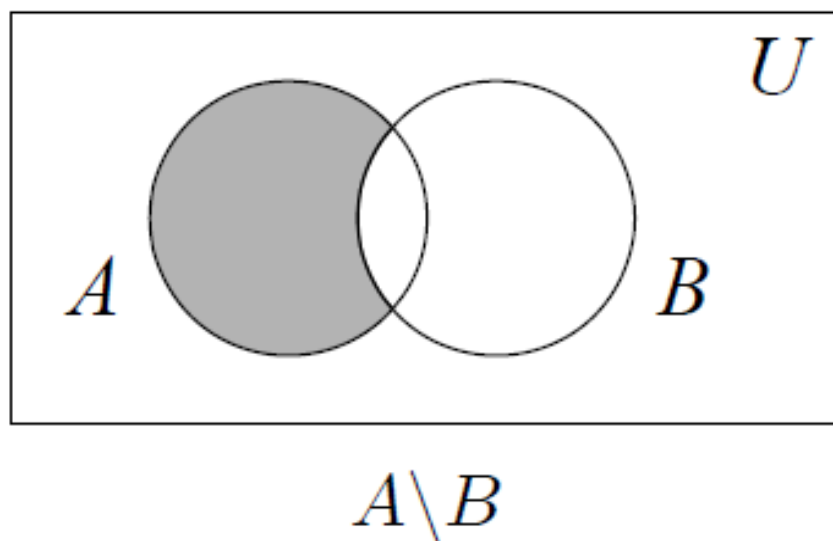
$$A' = \{x \mid x \in U \text{ and } x \notin A\}.$$



Definition 1.4

Given two sets A and B , the **relative complement** of B in A , denoted by *the set difference* $A \setminus B$, is the set

$$A \setminus B = A \cap B' = \{x \mid x \in A, \text{ but } x \notin B\}.$$



Example 1.2

Let $A = \{1, 2, 3, 4\}$ and $B = \{3, 4, 5, 6\}$. Then $A \setminus B = \{1, 2\}$

1.1 Sets (集合)

Remark

Let P and Q be statements.

Throughout the class, we will encounter questions in which we will be asked to show that P if and only if Q ;

that is, show that statement P is true if and only if statement Q is true.

In situations like this,

- we first assume that statement P is true and show that statement Q is true.
- Then we assume that statement Q is true and show that statement P is true.

The statement P if and only if Q is also equivalent to the statement: if P , then Q , and if Q , then P .

1.2 Relation (関係), Mapping (写像) and Permutation (置換)

Definition 1.5

Let A and B be nonempty sets (空でない集合) and $x \in A, y \in B$. The **Cartesian cross product** (Cartesian product, 直積集合) of A and B , written $A \times B$, is defined to be the set

$$A \times B = \{(x, y) \mid x \in A, y \in B\}.$$

where (x, y) is called the **ordered pair** (順序対).

Example 1.3

If $A = \{x, y\}$, $B = \{1, 2, 3\}$, and $C = \emptyset$,
then $A \times B = \{(x, 1), (x, 2), (x, 3), (y, 1), (y, 2), (y, 3)\}$.
and $A \times C = \emptyset$

We define the **Cartesian product** of n sets to be

$$A_1 \times \cdots \times A_n = \{(a_1, \dots, a_n) \mid a_i \in A_i \text{ for } i = 1, \dots, n\}.$$


$$a_1 \in A_1, a_2 \in A_2, \dots, \text{ and } a_n \in A_n$$

If $A_1 = A_2 = \cdots = A_n$, we often write A^n for $A \times \cdots \times A$ (where A would be written n times).

For example, the set $\mathbb{R}^3 = \mathbb{R} \times \mathbb{R} \times \mathbb{R}$ consists of all of 3-tuples of real numbers.

Definition 1.6

A **binary relation** (二項関係) or simply a **relation** \mathcal{R} from a set A to a set B is a **subset** of $A \times B$.

Let \mathcal{R} be a relation from a set A into a set B .

If $(x, y) \in \mathcal{R}$, we write $x\mathcal{R}y$ or $\mathcal{R}(x) = y$.

If $x\mathcal{R}y$, then sometimes we say that x is related to y (or y is in relation with x) with respect to \mathcal{R} or simply x is related to y .

Definition 1.7

Let A and B be nonempty sets. A special type of relation $f \subset A \times B$ from A into B is called a **function** (関数) (or **mapping** (写像)) from A into B if

- (i) $\mathcal{D}(f) = A$, i.e. the *domain* (定義域) of f is the set A ;
- (ii) for all $(x, y), (x', y') \in f$, we have that $x = x'$ implies $y = y'$.

When (ii) is satisfied by a relation f , we say that f is **well defined** or **single-valued**.

We can also say that for every element in A , f assigns a unique element in B . We usually write $f: A \rightarrow B$ or $A \xrightarrow{f} B$.

Instead of writing down ordered pairs $(a, b) \in A \times B$, we write $f(a) = b$ or $f: a \mapsto b$.

The set A is called the *domain* (定義域) of f , denote by $\mathcal{D}(f) = A$. The set $f(A)$ is called the *range* (値域) or *image* of f , defined by

$$f(A) = \{f(a) \mid a \in A\} \subset B.$$

Notice that here $f(A)$ is a subset of B .

We can think of the elements in the function's domain as input values and the elements in the function's range as output values.

1.2 Relation, Mapping and Permutation

Domain & Range

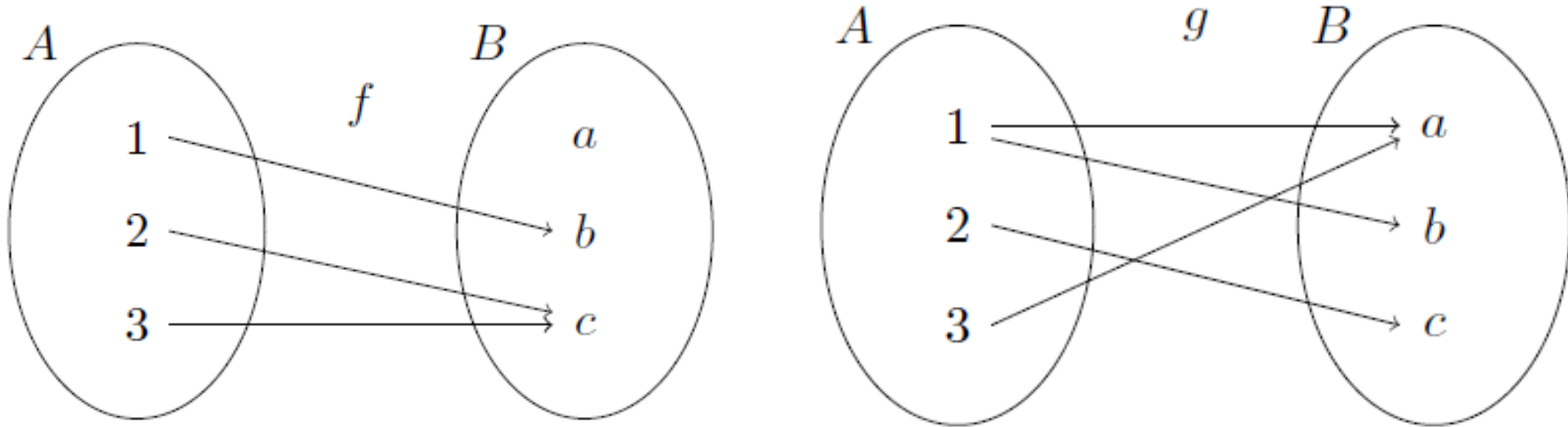


Figure 1.1 Mappings and relations

Example 1.4

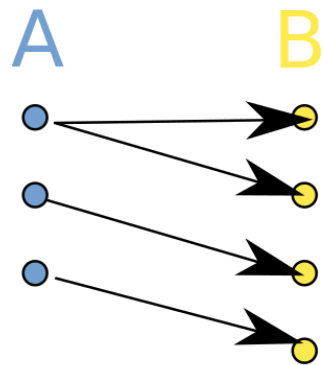
Suppose $A = \{1, 2, 3\}$, and $B = \{a, b, c\}$. In Figure 1.1 we define relations f and g from A to B . The relation f is a mapping, but g is not, because $1 \in A$ is not assigned to a unique element in B ; that is, $g(1) = a$ and $g(1) = b$.

Definition 1.8

Let f be a function from a set A to a set B . Then

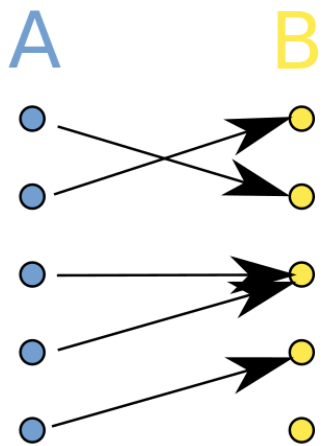
- (i) f is called *one-to-one* (一対一) or *injective* (単射) if for all $x, x' \in A$, we have that $f(x) = f(x')$ implies $x = x'$.
- (ii) f is called *onto* or *surjective* (全射) B (or f maps A onto B) if $f(A) = B$.
- (iii) A map is called *bijective* (全単射、あるいは双射) if both *one-to-one* and *onto*.

1.2 Relation, Mapping and Permutation



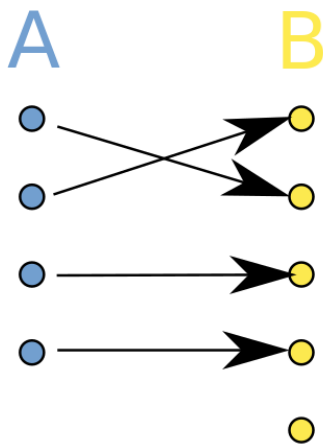
NOT a
Function

A has many B



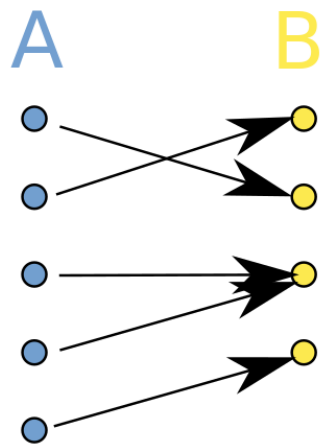
General
Function

B can have many A



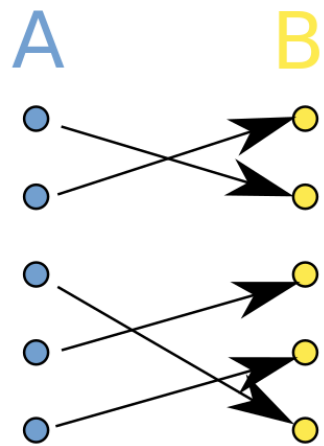
Injective
(not surjective)

B can't have many A



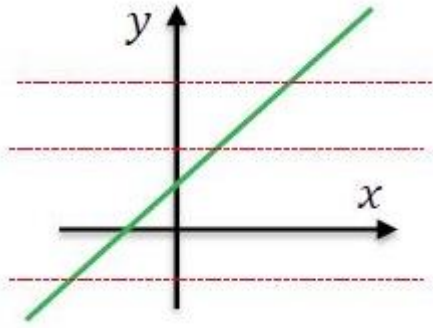
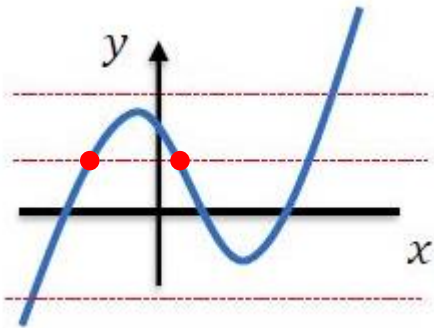
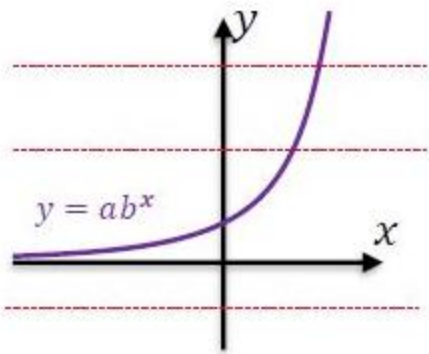
Surjective
(not injective)

Every B has some A



Bijjective
(injective, surjective)

A to B, perfectly



Negative y is not used
Applied Algebra (応用代数)

1.2 Relation, Mapping and Permutation

Example 1.5

Let $A = \{1, 2, 3\}$, $B = \{2, 4, 6\}$. For the following relation between A and B given as a subset of $A \times B$, decide whether it is a function mapping A into B . If it is a function, decide whether it is *one-to-one* and whether it is *onto* B .

	is function	is <i>one-to-one</i>	is <i>onto</i> B
(a) $\{(1,4),(2,4),(3,6)\}$	Yes	No	No
(b) $\{(1,4),(2,6),(3,2)\}$	Yes	Yes	Yes
(c) $\{(1,4),(1,6),(2,2)\}$	No		

Given two functions, we can construct a new function by using the range of the first function as the domain of the second function.

Definition 1.9

Let $f: A \rightarrow B$ and $g: B \rightarrow C$ be mappings.
Define the *composition of mapping* (合成写像) of f and g from A to C , by $(g \circ f)(x) = g(f(x))$.

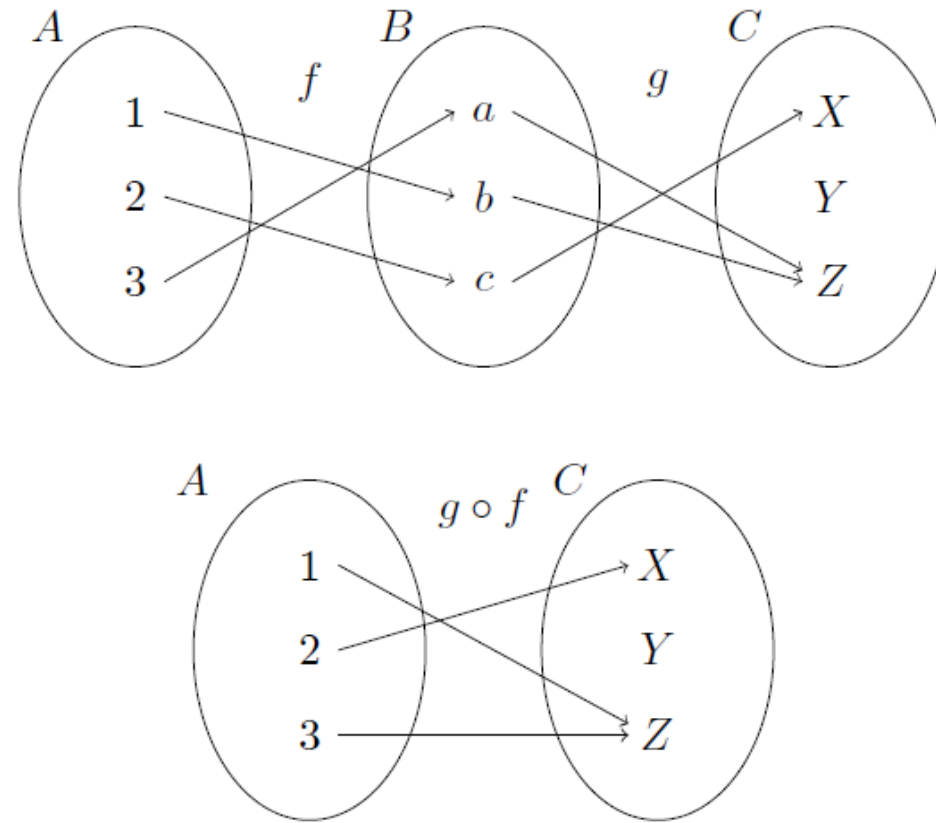


Figure 1.2 Composition of maps

Example 1.6 Consider the functions $f: A \rightarrow B$ and $g: B \rightarrow C$ that are defined in Figure 1.2 (top). The composition of these functions, $g \circ f: A \rightarrow C$, is defined in Figure 1.2 (bottom).

Example 1.7

Let $f(x) = x^2$ and $g(x) = 2x + 5$. Then

$$(f \circ g)(x) = f(g(x)) = (2x + 5)^2 = 4x^2 + 20x + 25$$

and

$$(g \circ f)(x) = g(f(x)) = 2x^2 + 5$$

In general, order (順序) makes a difference; that is, in most cases

$$f \circ g \neq g \circ f.$$

Example 1.8

Sometimes it has the case that $f \circ g = g \circ f$. Let $f(x) = x^3$ and $g(x) = \sqrt[3]{x}$. Then

$$(f \circ g)(x) = f(g(x)) = f(\sqrt[3]{x}) = (\sqrt[3]{x})^3 = x$$

and

$$(g \circ f)(x) = g(f(x)) = g(x^3) = \sqrt[3]{(x^3)} = x$$

Example 1.9

Suppose that $S = \{1, 2, 3\}$. Define a map $\pi: S \rightarrow S$ by $\pi(1) = 2, \pi(2) = 1, \pi(3) = 3$.

This is a *bijective* map. An alternative way to write π is

$$\begin{pmatrix} 1 & 2 & 3 \\ \pi(1) & \pi(2) & \pi(3) \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix}$$

*This notation is due to Cauchy and is called the **two-row notation**.

For any set S , a **one-to-one** and **onto** mapping $\pi: S \rightarrow S$ is called a **permutation** (置換) of S .

If S is any set, we will use id_S or id to denote the *identity mapping* (恒等写像) from S to itself. Define this map by $id_S(s) = s$ for all $s \in S$.

Definition 1.10

Let A and B be sets and $f: A \rightarrow B$.

(i) f is called **left invertible** (左可逆) if there exists $g: B \rightarrow A$ such that $g \circ f = id_A$.

(ii) f is called **right invertible** (右可逆) if there exists $h: B \rightarrow A$ such that $f \circ h = id_B$.

A function $f: A \rightarrow B$ is called **invertible** (可逆) if f is both left and right invertible.

Example 1.10

The function $f(x) = x^3$ has inverse $f^{-1}(x) = g(x) = \sqrt[3]{x}$.

Because left invertible

$$(g \circ f)(x) = g(f(x)) = g(x^3) = \sqrt[3]{(x^3)} = x = id_X$$

and right invertible

$$(f \circ g)(x) = f(g(x)) = f(\sqrt[3]{x}) = (\sqrt[3]{x})^3 = x = id_X$$

Theorem 1.2

A mapping is **invertible** (可逆) if and only if it is ***bijjective*** (全单射), i.e. both ***one-to-one*** and ***onto***.

1.3 Division (除法), Quotient (商), Remainder (剰余), Great Common Divisor (最大公約数)

Theorem 1.3 Division Algorithm

Let x and y be integers, with $y \neq 0$. Then there exist unique integers q and r such that $x = yq + r$ where $0 \leq r < |y|$.

The integer q is called the **quotient (商)** of x and y on dividing x by y and
the integer r is called the **remainder (剰余)** of x and y on dividing x by y .

Definition 1.11

Let $x, y \in \mathbb{Z}$ with $x \neq 0$. Then x is said to divide y or x is a **divisor** (約数) (or **factor** (因子)) of y , written $x|y$, provided there exists $q \in \mathbb{Z}$ such that $y = qx$. When x does not divide y , we sometimes write $x \nmid y$.

Definition 1.12

Let $x, y \in \mathbb{Z}$. A nonzero integer c is called a **common divisor** (公約数) of x and y if $c|x$ and $c|y$.

Definition 1.13

A nonzero integer d is called a **greatest common divisor** (gcd) (最大公約数) of the integers x and y if

- (i) $d|x$ and $d|y$,
- (ii) for all $c \in \mathbb{Z}$ if $c|x$ and $c|y$, then $c|d$.

Theorem 1.4

Let $x, y \in \mathbb{Z}$ with either $x \neq 0$ and $y \neq 0$. Then x and y have a positive greatest common divisor $\gcd(x, y) = d$. Moreover, there exist integers $s, t \in \mathbb{Z}$ such that

$$\gcd(x, y) = d = sx + ty.$$

Example 1.11

Consider the $\gcd(45, 126)$.

$$126 = 2 \cdot 45 + 36$$

$$45 = 1 \cdot 36 + 9$$

$$36 = 4 \cdot 9 + 0$$

$$\text{Thus, } \gcd(45, 126) = 9$$

Also,

$$9 = 45 - 1 \cdot 36$$

$$= 45 - 1 \cdot [126 - 2 \cdot 45]$$

$$= 3 \cdot 45 + (-1) \cdot 126.$$

Here $s = 3$ and $t = -1$.

Definition 1.14

- (i) An integer $p > 1$ is called **prime** (素数) if the only divisors of p are ± 1 and $\pm p$.
- (ii) Two integers x and y are called **relatively prime** (互いに素) if $\gcd(x, y) = 1$.

1.4 Equivalence Classes (同値類)

1.4 Equivalence Classes (同値類)

Definition 1.15

Let \mathcal{R} be a binary relation on a set X , i.e. $\mathcal{R} \subset X \times X$. Then \mathcal{R} is called

- (i) **reflexive** (反射的) if for all $x \in X$, $(x, x) \in \mathcal{R}$ (i.e. $x\mathcal{R}x$);
- (ii) **symmetric** (対称的) if for all $x, y \in X$, $(x, y) \in \mathcal{R}$ implies $(y, x) \in \mathcal{R}$ (i.e. $x\mathcal{R}y$ implies $y\mathcal{R}x$);
- (iii) **Transitive** (推移的) if for all $x, y, z \in X$, (x, y) and $(y, z) \in \mathcal{R}$ implies $(x, z) \in \mathcal{R}$ (i.e. $x\mathcal{R}y$ and $y\mathcal{R}z$ imply $x\mathcal{R}z$).

Definition 1.16

A binary relation \mathcal{R} on a set X is called an **equivalence relation** (同値関係) on X if \mathcal{R} is reflexive, symmetric, and transitive.

Definition 1.17

Let \mathcal{R} be an **equivalence relation** on a set A . For all $x \in A$, let $[x]$ denote the set

$$[x] = \{y \in A \mid y\mathcal{R}x\}.$$

The set $[x]$ is called the **equivalence class** (with respect to \mathcal{R}) of x .

Theorem 1.5

Let \mathcal{R} be an equivalence relation on the set A . Then

- (i) for all $x \in A$, $[x] \neq \emptyset$,
- (ii) if $y \in [x]$, then $[x] = [y]$, where $x, y \in A$,
- (iii) for all $x, y \in A$, either $[x] = [y]$ or $[x] \cap [y] = \emptyset$,
- (iv) $A = \bigcup_{x \in A} [x]$, i.e., A is the union of all equivalence classes with respect to \mathcal{R} .

1.4 Equivalence Classes (同値類)

Let r and s be two integers and suppose that $n \in \mathbb{N}$.

We say that r is *congruent* (合同) to s *modulo* (剰余演算) n , or r is **congruent** to $s \bmod n$, if $r - s$ is evenly divisible by n ; that is, $r - s = nk$ for some $k \in \mathbb{Z}$.

In this case we write $r \equiv s \pmod{n}$.

Example 1.12

$41 \equiv 17 \pmod{8}$ since $41 - 17 = 24$ is divisible by 8.

We claim that congruence modulo n forms an **equivalence relation** of \mathbb{Z} .

Certainly any integer r is equivalent to itself since $r - r = 0$ is divisible by n .

1.4 Equivalence Classes (同値類)

We will now show that the relation is symmetric. If $r \equiv s \pmod{n}$, then $r - s = -(s - r)$ is divisible by n . So $s - r$ is divisible by n and $s \equiv r \pmod{n}$. Now suppose that $r \equiv s \pmod{n}$ and $s \equiv t \pmod{n}$. Then there exist integers k and m such that $r - s = kn$ and $s - t = mn$.

To show transitivity, it is necessary to prove that $r - t$ is divisible by n . However,

$$r - t = r - s + s - t = kn + mn = (k + l)n$$

and so $r - t$ is divisible by n .

1.4 Equivalence Classes (同値類)

If we consider the equivalence relation established by the integers modulo 3, then

$$[0] = \{\dots, -3, 0, 3, 6, \dots\}$$

$$[1] = \{\dots, -2, 1, 4, 7, \dots\}$$

$$[2] = \{\dots, -1, 2, 5, 8, \dots\}$$

Notice that $[0] \cup [1] \cup [2] = \mathbb{Z}$ and also that these sets are **disjoint**. The sets $[0]$, $[1]$, and $[2]$ form a **partition** (分割) of the integers.

Notice:

The **integers modulo n** are a very important example in the study of abstract algebra and will become quite useful in our investigation of various algebraic structures such as **groups** and **rings**.

Review for Lecture 1

- Sets
- Relation, Mapping
- Invertible
- Quotient, Remainder, Greatest Common Divisor
- Equivalence Classes
- Modulo

Assignment

Please Check <https://github.com/uoaworks/Applied-Algebra>

References

- [1] Thomas W. Judson etc. Abstract Algebra Theory and Applications, 2018
- [2] D. S. Malik, John N. Mordeson, M.K. Sen, Introduction to Abstract Algebra, 2007
- [3] (おすすめ) 松本 眞, 代数系への入門, <http://www.math.sci.hiroshima-u.ac.jp/~m-mat/TEACH/daisu-nyumon2014.pdf>
- [4] Wikipedia
- [5] Materials from internet.

Appendix (付録)

Definition

The union of A_1, A_2, \dots, A_n , denoted by $\cup_{i=1}^n A_i$ or $A_1 \cup A_2 \cup \dots \cup A_n$, is the set of all elements x such that x is an element of some A_i , where $1 \leq i \leq n$.

The intersection of A_1, A_2, \dots, A_n , denoted by $\cap_{i=1}^n A_i$ or $A_1 \cap A_2 \cap \dots \cap A_n$, is the set of all elements x such that $x \in A_i$ for all $1 \leq i \leq n$.

Appendix (付録)

Definition

Let A be a set and \mathcal{P} be a collection of nonempty subsets of A . Then \mathcal{P} is called a **partition** (分割) of A if the following properties are satisfied:

- (i) for all $B, C \in \mathcal{P}$, either $B = C$ or $B \cap C = \emptyset$.
- (ii) $A = \bigcup_{B \in \mathcal{P}} B$.

Appendix (付録)

Definition

For any set X , the **power set of X** , written $\mathcal{P}(X)$, is defined to be the set $\{A \mid A \text{ is a subset of } X\}$.

Example

Let $X = \{1, 2, 3\}$. Then

$$\mathcal{P}(X) = \{\emptyset, \{1\}, \{2\}, \{3\}, \{1, 2\}, \{1, 3\}, \{2, 3\}, \{1, 2, 3\}\}.$$

Here $\mathcal{P}(X)$ has 2^3 elements.

Appendix (付録)

Theorem

Let $f: A \rightarrow B$, $g: B \rightarrow C$, and $h: C \rightarrow D$. Then

1. The composition of mappings is associative; that is, $(h \circ g) \circ f = h \circ (g \circ f)$;
2. If f and g are both *one-to-one*, then the mapping $g \circ f$ is *one-to-one*;
3. If f and g are both *onto*, then the mapping $g \circ f$ is *onto*;
4. If f and g are *bijective*, then so is $g \circ f$.