Computer Science and Mathematics

Part I:
Introduction to Computer Science

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1. Basic definitions

1.1 Sets

A *set* is a collection of different objects, which are called the *elements* of the set.
The order in which the elements are listed does not matter.
A set can have a finite or an infinite number of elements. We speak of finite and infinite sets.

Examples:
The set of all human beings on earth (finite)
The set of all prime numbers (infinite)

Sets are usually designated by upper-case letters, their elements by lower-case letters.

$a \in M$	*a* is element of the set *M*
$a \notin M$	*a* is *not* element of the set *M*

Two notations for sets:

- Listing of all elements, delimited by commas (or semicolons) and put in braces:
  $A = \{ 1; 2; 3; 4; 5 \}$

- Usage of a variable symbol and specification of a proposition (containing the variable) which has to be fulfilled by the elements:
  $A = \{ x \mid x \text{ is a positive integer smaller than } 6 \}$
  (the vertical line is read: "... for which holds: ...")

  alternative notation for the last one:
  $A = \{ x \in \mathbb{N} \mid x < 6 \}$

($\mathbb{N}$ is the set of positive integer numbers, not including 0.)

Number of elements of a set M (also called *cardinality* of M): $|M|$

example: $|\{ x \in \mathbb{N} \mid x < 12 \wedge x \text{ is even} \}| = 5$

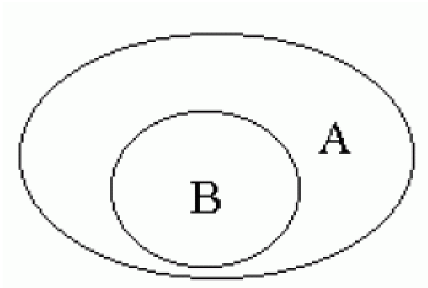
A special set: The *empty set*
Notation: $\emptyset$
For the empty set, we have $|\emptyset| = 0$.

Subsets and supersets

If *A* contains all elements of *B* (and possibly some more), *B* is called a *subset* of *A* (and *A* a *superset* of *B*).

Notation: $B \subseteq A$ (or, equivalently, $A \supseteq B$)

Visualization by a so-called *Venn diagram*:



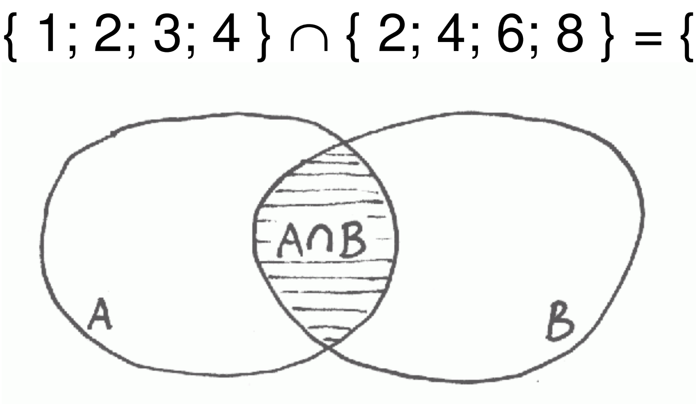
It holds: $A \subseteq B \;\wedge\; B \subseteq A \;\Leftrightarrow\; A = B$.

Intersection

The *intersection* of the sets *A* and *B* is the set of all elements which are elements of *A* *and* of *B*.
Operator symbol: $\cap$

$A \cap B = \{\, x \mid x \in A \text{ and } x \in B \,\}$.

Example:
$\{ 1; 2; 3; 4 \} \cap \{ 2; 4; 6; 8 \} = \{ 2; 4 \}$.



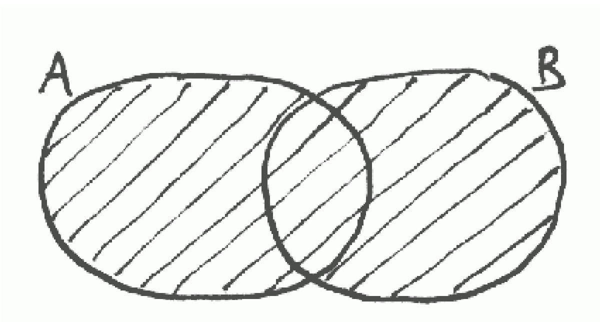
Two sets A and B are called disjoint if $A \cap B = \emptyset$.

Union

The *union* of the sets A and B is the set of all elements which are element of A *or* of B.
Operator symbol: $\cup$ ($\cup$ = **U**nion)

$A \cup B = \{ x \mid x \in A \text{ or } x \in B \}$.

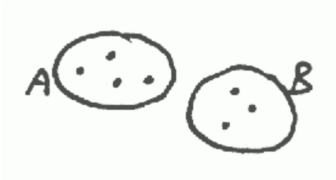
Example:
$\{ 1; 2; 3; 4 \} \cup \{ 2; 4; 6; 8 \} = \{ 1; 2; 3; 4; 6; 8 \}$.



What is the number of elements $| A \cup B |$?

If A and B are disjoint, we have:

$$| A \cup B | = |A| + |B|$$



Generalization:
If $A_1, A_2, ..., A_n$ are all pairwise disjoint, then
$| A_1 \cup A_2 \cup ... \cup A_n | = | A_1| + ... + | A_n |$.

Remarks:
(1) $(A \cup B) \cup C = A \cup (B \cup C)$ ("associativity"),

so we can omit the parentheses
(the same holds for + and for $\cap$).

(2) Short notations for iterated operations:

for n sets $A_1, A_2, ..., A_n$:

$$\bigcup_{i=1}^{n} A_i = A_1 \cup \ldots \cup A_n$$

for n numbers $x_1, x_2, ..., x_n$:

$$\sum_{i=1}^{n} x_i = x_1 + \ldots + x_n$$

$$\prod_{i=1}^{n} x_i = x_1 \cdot \ldots \cdot x_n$$

(3) The formula $|A \cup B| = |A| + |B|$ does not hold if A and B are not disjoint. In the general case, we have:

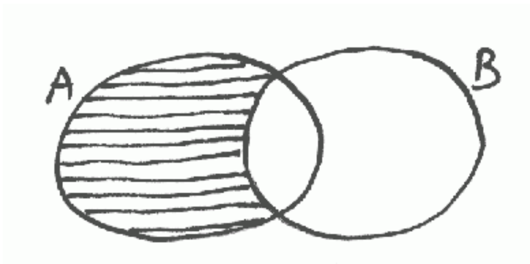
$$|A \cup B| = |A| + |B| - |A \cap B|.$$

Difference of sets

The *difference set* of the sets A and B is the set of all elements which are element of A *but not* of B. ("*A without B*")
Operator symbol: – (sometimes also used: \ ).

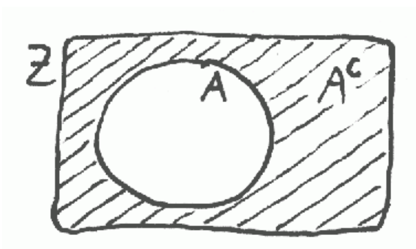
$A - B = \{ x \mid x \in A \text{ and } x \notin B \}.$

Example:
$\{ 1; 2; 3; 4 \} - \{ 2; 4; 6; 8 \} = \{ 1; 3 \}.$



Complement

If all considered sets are subsets of a given basic set Z, the difference $Z-A$ is often called the *complement* of A and is denoted A^C.
$A^C = \{ x \in Z \mid x \notin A \}.$



The power set

The set of all subsets of a given set S is called the *power set* of S and is denoted $\mathrm{P}(S)$.

$$\mathrm{P}(S) = \{ A \mid A \subseteq S \}$$

Example:

$S = \{ 1; 2; 3 \}$
$\mathrm{P}(S) = \{ \emptyset; \{1\}; \{2\}; \{3\}; \{1; 2\}; \{1; 3\}; \{2; 3\}; \{1; 2; 3\} \}$

For the number of its elements, we have always:

$| \mathrm{P}(S) | = 2^{|S|}$

Cartesian products of sets

The *cartesian product* of two sets A and B, denoted $A \times B$, is the set of all possible *ordered pairs* where the first component is an element of A and the second component an element of B.

$$A \times B = \{ (a, b) \mid a \in A \text{ and } b \in B \}$$

Remark: In an ordered pair, the order of the components is fixed. If $a \neq b$, then $(a, b) \neq (b, a)$.

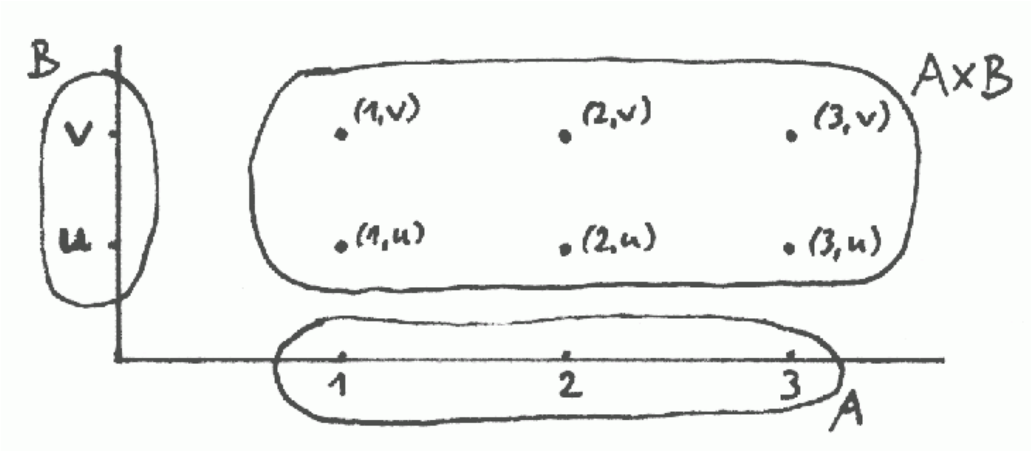
Example: $A = \{ 1; 2; 3 \}$, $B = \{ \mathrm{u}, \mathrm{v} \}$:

$A \times B = \{ (1, \mathrm{u}); (2, \mathrm{u}); (3, \mathrm{u}); (1, \mathrm{v}); (2, \mathrm{v}); (3, \mathrm{v}) \}$.

Attention: Usually it is $A \times B \neq B \times A$!

Number of elements: $|A \times B| = |A| \cdot |B|$.

Visualization of $A \times B$ in a coordinate system:



If A and B are subsets of the set IR of real numbers, we can use the well-known cartesian coordinate system.

Products of more than two sets

The elements of $(A \times B) \times C$ are "nested pairs" $((a,b),c)$;
we identify them with the <u>triples (a,b,c)</u> and write $A \times B \times C$.
Analogously for quadruples, etc.

$$A_1 \times A_2 \times \ldots \times A_n = \{ (a_1, a_2, \ldots, a_n) \mid a_1 \in A_1 \wedge a_2 \in A_2 \wedge \ldots \wedge a_n \in A_n \}$$

If $A_1 = A_2 = \ldots = A_n$, we write:

$$A^n = \underbrace{A \times A \times \ldots \times A}_{n \text{ times}}$$

= set of all <u>n-tuples</u> with components from A.

Example:

$B = \{x; y\} \quad \Rightarrow$

$B^3 = \{ (x,x,x); (x,x,y); (x,y,x); (x,y,y);$
$(y,x,x); (y,x,y); (y,y,x); (y,y,y) \}$

If the components are letters, the parentheses and commas are often omitted: $B^3 = \{ xxx; xxy; xyx; \ldots; yyy \}$ set of <u>words</u> of length 3

Set of arbitrary words (strings) over a set:

$$A^* = A^0 \cup A^1 \cup A^2 \cup A^3 \cup \ldots$$

with $A^0 := \{ \varepsilon \}$, where ε is the <u>empty word</u>.

Example: $\{x; y\}^* = \{ \varepsilon; x; y; xx; xy; yx; yy; xxx; \ldots \}$

$A^+ = A^1 \cup A^2 \cup A^3 \cup \ldots$ does not contain the empty word.

The cartesian product in the description of datasets

Frequently, informations regarding a measurement are put together in an n-tuple. Example:

S = set of time values
T = set of temperature values
U = set of laboratory identifiers
V = set of measurement values

A measurement is then represented by a 4-tuple

$$(s, t, u, v) \in S \times T \times U \times V$$

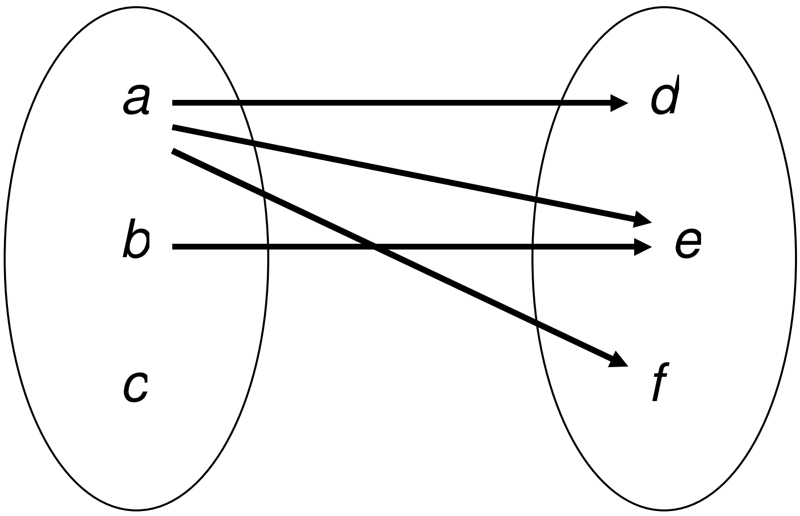
s: time of measurement; t: current temperature; u: lab id; v: measured value

1.2 Relations

A (binary) relation R between two sets A and B is a subset of $A \times B$.
That means, a relation is represented by a set R of ordered pairs (a, b) with $a \in A$ and $b \in B$.
If $(a, b) \in R$ we write also $a\ R\ b$ (infix notation).

Graphical representation (if A and B are finite):

If $(a, b) \in R$, connect a and b by an arrow



The converse relation R^{-1} of R:

$$(b, a) \in R^{-1} \Leftrightarrow (a, b) \in R$$

R^{-1} is a subset of $B \times A$.

In the graphical representation, switch the directions of all arrows to obtain the converse relation!

If $A = B$, we have a relation *in* a set A.

Example: A = IR (set of real numbers), R = < relation "smaller as". R consists of all number pairs (x, y) with $x < y$.

Generalization: n-ary relation:
any subset of $A_1 \times A_2 \times \ldots \times A_n$.

1.3 Graphs

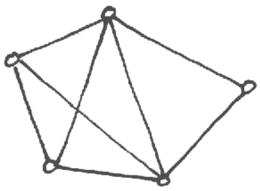
A graph consists of a set V of vertices and a set E of edges. Each edge connects two vertices.

Different variants of graphs differ in the way how the edges are defined and what edges are allowed:

- Undirected graphs:

  The edges are (unordered) 2-element subsets of V.

  Visualization by undirected arcs:

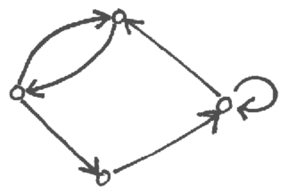


- Directed graphs:

  The edges are ordered pairs, i.e., $E \subseteq V \times V$

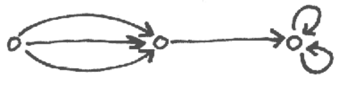
  (E is a relation in V)

  Visualization by directed arcs. "Loops" are allowed, multiple arcs between the same vertices are not allowed:



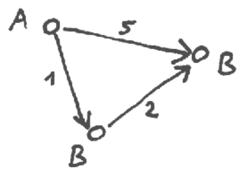
- Multigraphs:

  Multiple directed edges are allowed



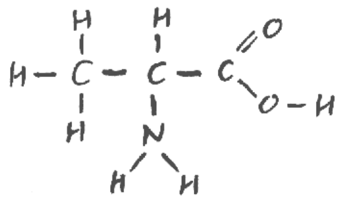
- Labelled graphs:

  Vertices and/or edges have labels from a set of vertex/edge labels (names, numbers, ...)



Examples:

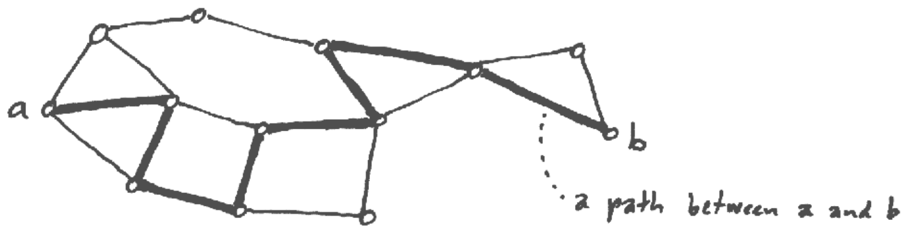
- transport networks
- metabolic networks
- food webs
- class diagrams in software engineering
- genealogical trees
- structural formulae in chemistry



vertex-labelled multigraph

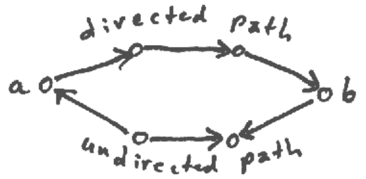
Paths in graphs

A <u>path</u> is a sequence of edges where two consecutive edges have one vertex in common:

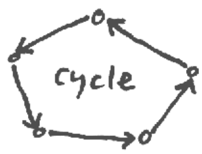


A path where start- and end vertex coincide is called a <u>circle</u>.

In directed graphs, we distinguish between directed and undirected paths.

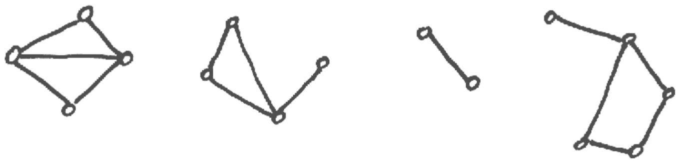


A directed circle is called a <u>cycle</u>.



Connectedness

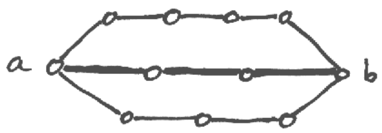
If for every pair of vertices (a, b) in a graph, there is a path between a and b, the graph is called <u>connected</u>.
Every unconnected graph can be decomposed in <u>connected components</u>.



a graph with 4 connected components

Graph-theoretical distance

The <u>distance</u> between two vertices a and b in a graph is the length, i.e., the number of edges, of the shortest path between a and b — if such a path exists. Otherwise, the distance is undefined.

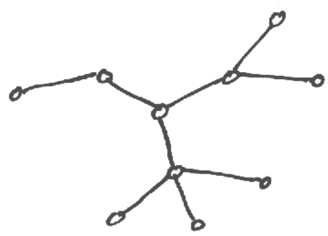


$\text{dist}(a,b) = 3$

Trees

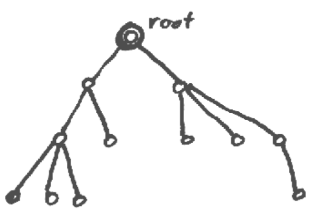
A <u>tree</u> is a graph without circles.

A tree:

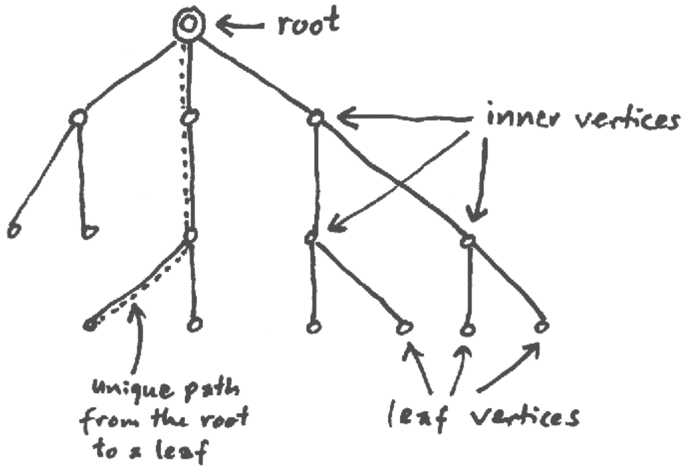


Example: phylogenetic trees,
describing genetic kinship between species

A <u>rooted tree</u> is a tree in which one vertex, the root, is distinguished.
The root is often drawn at the top:



Rooted trees are used to describe hierarchies, e.g., in biological systematics, in organizations or in nested directories of data.



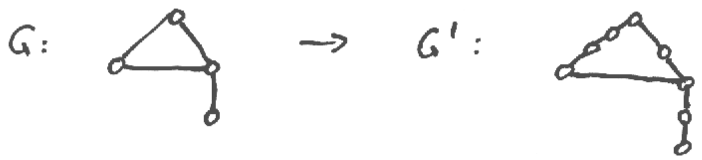
Degree

The number of edges to which a vertex belongs is called the <u>degree</u> of the vertex.

In directed graphs we distinguish between <u>indegree</u> and <u>outdegree</u> of a vertex.

Subdivision

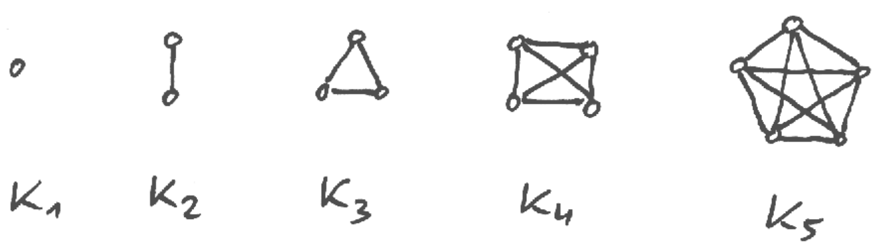
A <u>subdivision</u> G' of a graph G is obtained by inserting vertices of degree 2 in the edges of G.



Complete graphs

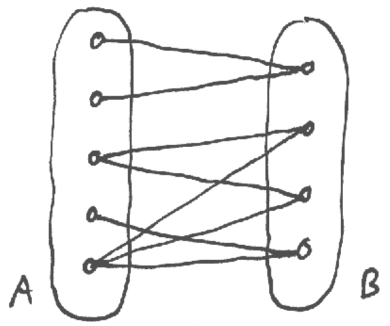
The <u>complete graph</u> K_n is the graph with n vertices where every pair of different vertices is connected by an edge.

(also called: <u>Clique</u>.)



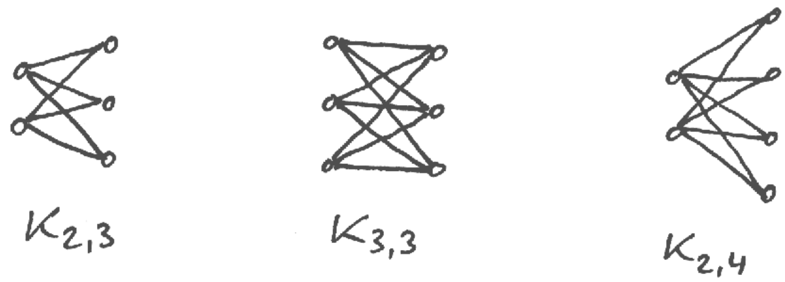
Bipartite graphs

A <u>bipartite graph</u> can be split into two disjoint sets of vertices, A and B, such that all edges go from a vertex from A to a vertex from B.



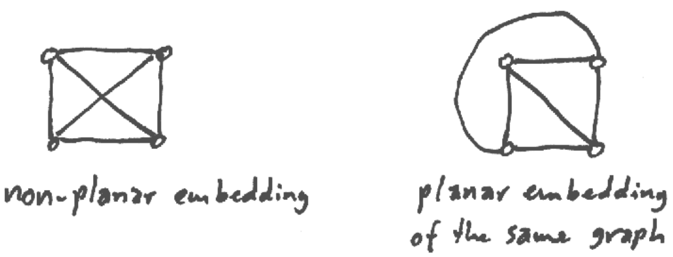
(The edges then form a relation between A and B.)

The <u>complete bipartite graph</u> $K_{m,n}$ is a bipartite graph with $|A| = m$, $|B| = n$, and edges go from every vertex of A to every vertex of B.



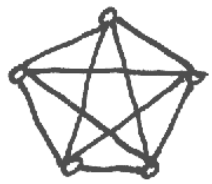
Planarity

A graph is <u>planar</u> if its vertices and edges can be embedded in the plane, with edges as arcs in the plane, such that no two different edges intersect in points different from their start- and end vertex.

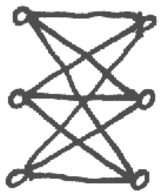


Kuratowski's theorem:

A graph is planar if and only if it does not contain any subdivision of K_5 or $K_{3,3}$.



K_5

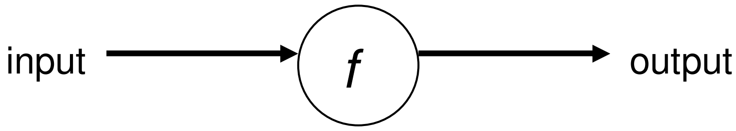


$K_{3,3}$

1.4 Functions

The *function* is a fundamental notion in mathematics. It is used to describe:

- a dependency between two variables (e.g., between measured sizes of the same objects)
- a transformation of data during some calculation or processing step



- a development of a variable in time or in space (e.g., heigth growth of a plant; magnetic field strength in space...)

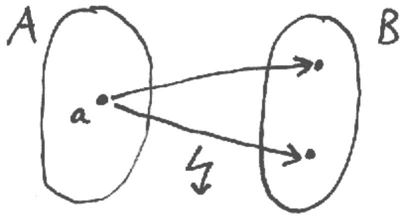
Frequently used synonyms for *function*:
mapping, *transformation*, *operator*

The precise definition of a function identifies it with the relation between "input" (argument(s)) and "output" (value), i.e., a function is defined as a special case of a relation:

A relation R between the sets A (= possible input values) and B (= possible values) is a *function* if for every $a \in A$ there is exactly one $b \in B$ with $a\ R\ b$.
We write then f instead of R and use frequently the notation $f(a) = b$.
Further typical notations:

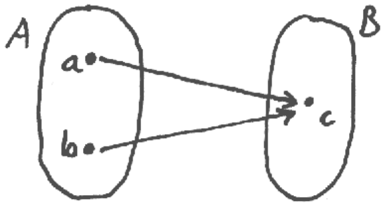
$$f: A \to B, \quad a \mapsto b\ .$$

The following situation is thus excluded for functions, because a would have two different "images" in B :



f(a) must be **unique**.

Allowed is :



$f(a) = c$
$f(b) = c$

written as set: $f = \{(a,c); (b,c)\} \subseteq A \times B$

We say: "f maps a to c", "c is an image of a under f".

f is the function, f(a) is a special value.

a is called the **argument** of f.

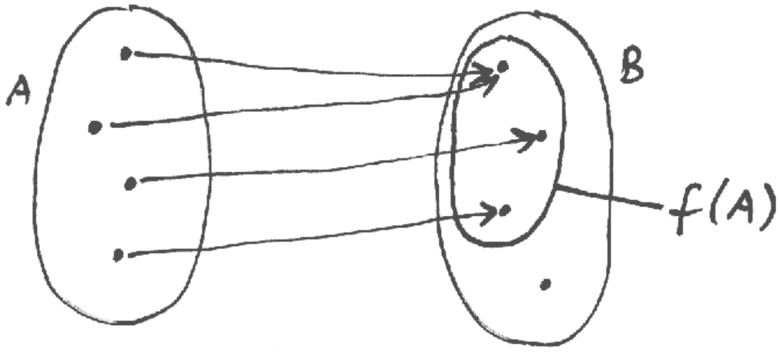
Different notations:

$f(a)$ or fa — prefix notation

af — postfix notation

Domain and image of a function

$f: A \to B$



A is called the <u>domain</u> of f

$f(A)$ is called the <u>image</u> of A under f,

sometimes also <u>range</u> of f

Multivariate functions

Functions can have several arguments:

$f: A \times B \to C$

$(a, b) \mapsto f(a, b) = c \in C$

$a \in A \quad b \in B$

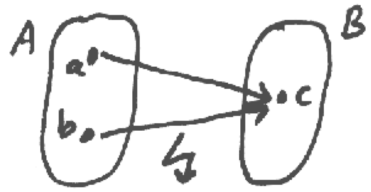
$f: A_1 \times \ldots \times A_n \ni (a_1, \ldots, a_n) \mapsto f(a_1, \ldots, a_n) \in C$

Injective, surjective, bijective functions

Injectivity

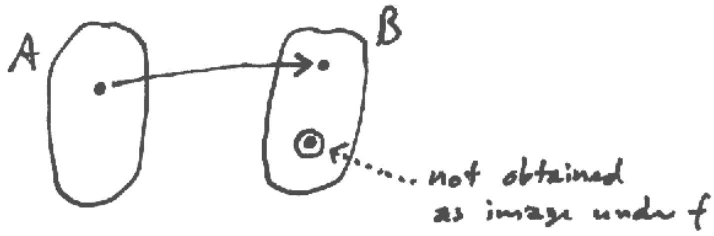
A function $f: A \to B$ is called <u>injective</u> if
$\forall a, b \in A: \quad a \neq b \Rightarrow f(a) \neq f(b)$.

That means, two distinct elements of A have always distinct images. Not allowed is:



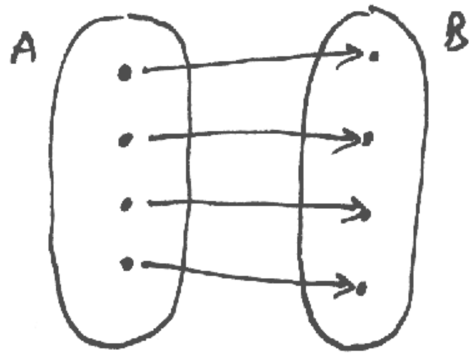
Surjectivity

A function $f: A \to B$ is called <u>surjective</u> if
$\forall b \in B \; \exists a \in A: f(a) = b$. All elements of B are images of elements of A. Not allowed is:



Bijectivity

$f: A \to B$ is called <u>bijective</u> if it is injective and surjective.



Bijective functions can be <u>inverted</u>,

i.e., the converse relation $f^{-1}: B \to A$ is again a function.

That means: $f^{-1}(b)$ is <u>unique</u> for every $b \in B$.

Example where this is not the case:

$f(x) = x^2 \qquad A = B = \mathbb{R}$

$\left.\begin{array}{l} f(2) = 4 \\ f(-2) = 4 \end{array}\right\} \Rightarrow f^{-1}(4)$ not unique, f^{-1} no function

f is not bijective on $\mathbb{R}$.

How to obtain the inverse function of a bijective real-valued function (with one argument):

- solve $f(x) = y$ for x, so you obtain $x = f^{-1}(y)$
- switch the names of the variables ($x \leftrightarrow y$)

2. Number systems

Question: How to represent numbers?
We consider first only positive integers.

Decimal number system: base 10; each digit represents a multiple of an exponent of 10. Digits 0..9.

Example: $123.456_{10} = 1 * 10^2 + 2 * 10^1 + 3 * 10^0 + 4 * 10^{-1} + 5 * 10^{-2} + 6 * 10^{-3}$.

Binary number system: base 2. Only two digits: 0 and 1.

Example: $1101.01_2 = 1 * 2^3 + 1 * 2^2 + 0 * 2^1 + 1 * 2^0 + 0 * 2^{-1} + 1 * 2^{-2} = 13.25_{10}$.

Hexadecimal system (better but unhistorical name: sedecimal number system): Base 16, digits 0..9,A..F. One digit for four bits. Examples: $A2.8_{16} = 162.5_{10}, FF_{16} = 255_{10}$.

The additional digits in the hexadecimal system:
$A = 10$, $B = 11$, $C = 12$, $D = 13$, $E = 14$, $F = 15$.

Transformation from one number system to the other:

- Special case (easy): from binary to hexadecimal

Every 4 binary digits correspond directly to a hexadecimal digit

Example: <u>0000</u> <u>0010</u> <u>1100</u> <u>0110</u>
$\rightarrow$ 0 2 C 6

- from arbitrary system to decimal:
  Horner scheme

Input: $z_{n-1}\ z_{n-2}$ ... z_0 to base b
start with $h_{n-1} = z_{n-1}$
calculate for $k = n-1, n-2, ..., 1$:

$$h_{k-1} = h_k * b + z_{k-1}$$

Output: $z = h_0$

Example:
Input: binary number 1010 ($n = 4$, $b = 2$)
Start: $h_{n-1} = h_3 = z_3 = 1$
$k = n-1 = 3$: $h_2 = h_3 * 2 + z_2 = 1*2 + 0 = 2$
$k = 2$: $h_1 = h_2 * 2 + z_1 = 2*2 + 1 = 5$
$k = 1$: $h_0 = h_1 * 2 + z_0 = 2*5 + 0 = \mathbf{10} = z$

- from decimal to arbitrary:
  Inverse Horner scheme

start with $h_0 = z$ (= input)
calculate for $k = 1, 2, 3, ...$:

$$z_{k-1} = h_{k-1} \bmod b,$$
$$h_k = h_{k-1} \operatorname{div} b$$

(mod: rest when dividing by b, div: integral part from dividing by b)

Output: $z_{n-1}\ z_{n-2}$ ... z_0 to base b

Example:
Input: decimal number 34, transform in ternary system ($b = 3$)

Start: $h_0 = 34$

$k = 1$: $z_0 = h_0 \bmod 3 = 34 \bmod 3 = 1$,
$h_1 = h_0 \operatorname{div} 3 = 34 \operatorname{div} 3 = 11$

$k = 2$: $z_1 = h_1 \bmod 3 = 11 \bmod 3 = 2$,
$h_2 = h_1 \operatorname{div} 3 = 11 \operatorname{div} 3 = 3$

$k = 3$: $z_2 = h_2 \bmod 3 = 3 \bmod 3 = 0$,
$h_3 = h_2 \operatorname{div} 3 = 3 \operatorname{div} 3 = 1$,

$k = 4$: $z_3 = h_3 \bmod 3 = 1 \bmod 3 = 1$,
$h_4 = h_3 \operatorname{div} 3 = 1 \operatorname{div} 3 = 0$ (Stop)

$\Rightarrow\ z = 1021$

Remark:
Arbitrary real numbers can also be represented using an arbitrary integer $b > 1$ as base.
Digits after the dot are interpreted as coefficients of b^{-n} ($n = 1, 2, 3, \ldots$).

Example:
0.111_2 (base b=2) = 1/2 + 1/4 + 1/8 = 7/8
$= 0.875_{10}$