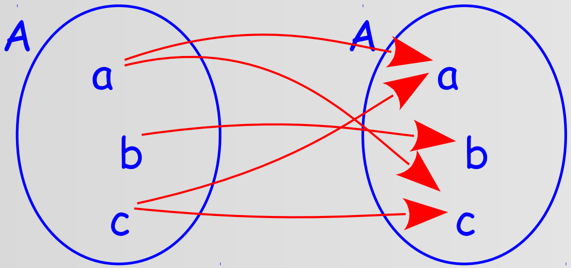
EDAA40

Discrete Structures in Computer Science



2: Relations

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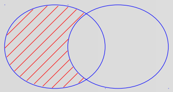
$R = \{x : x \notin x\}$

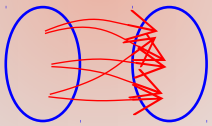
sets



$\supset$

$\heartsuit \subseteq P \times Q$

relations



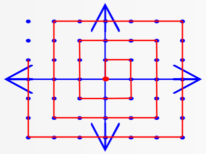
$\supset$

$f : A \longrightarrow B$

functions

$A \hookrightarrow B$

$\xrightarrow{\text{investigate}}$



infinity

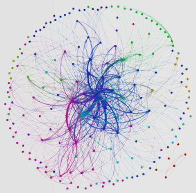
working with infinite
(or arbitrarily large) stuff

$\downarrow$

definition, construction,
recursion, induction
(also: proofs, logic)

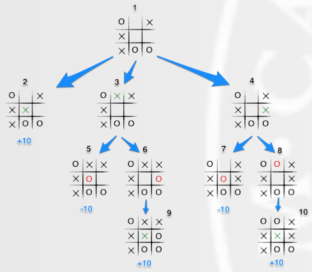
$\cup$

graphs



$\supset$

trees



relations

Mathematical *relations* are about connections between objects.

relations between numbers

a divides b, a is greater than b, a and b are prime to each other

relations between sets

subset of, same size as, smaller than

relations between people

customer/client, parent/child, spouse, employer/employee

We will focus on relations between two things. Often, they have distinct *roles* in a relation (superset/subset, parent/child, …), i.e. we cannot model them simply as unordered pairs {a, b}.

In order to properly model relations, we first need to introduce *ordered pairs*.

ordered pairs, tuples

ordered pair (a, b)

$$(a, b) = (x, y) \text{ iff } a = x \text{ and } b = y$$

corollary:

$$(a, b) \neq (b, a) \text{ if } a \neq b$$

n-tuple $(a_1, ..., a_n)$

$$(a_1, ..., a_n) = (b_1, ..., b_n) \text{ iff } a_i = b_i \text{ for } i = 1, ..., n$$

cartesian product

The *(cartesian) product* of a pair of sets, or more generally a finite family of sets, is the set of all ordered pairs or n-tuples.

$$A_1 \times ... \times A_n = \{(a_1, ..., a_n) : a_1 \in A_1, ..., a_n \in A_n\}$$

When the sets are the same, we also write

$$A \times A = A^2$$

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

If A and B are different, then

$$A \times B \neq B \times A$$

Occasionally, to avoid fussiness, the following are treated as equal:

$$A \times (B \times C) = (A \times B) \times C = A \times B \times C$$

cartesian product

Examples:

$$\{a, b\} \times \{1, 2, 3\} = \{(a, 1), (a, 2), (a, 3), (b, 1), (b, 2), (b, 3)\}$$
$$\mathbb{N}^+ \times \mathbb{N}^+ = \{(1, 1), (1, 2), (1, 3), ..., (2, 1), (2, 2), (2, 3), ...\}$$

Note: $\#(A \times B) = \#(A)\#(B)$

relations

A (binary, dyadic) relation R from A to B
(or *over A x B*)
is a subset of the cartesian product:

$$R \subseteq A \times B$$

If A and B are the same, i.e. $R \subseteq A \times A$, we also say that R is a binary relation *over A.*

Of course, this generalizes to...

An n-place relation R over
A_1 x ... x A_n
is a subset of that product:

$$R \subseteq A_1 \times ... \times A_n$$

notation, examples

For binary relations $R \subseteq A \times B$, these are equivalent:

$$(a, b) \in R \qquad\qquad aRb$$

$$C = \{F, E, B, D, NL, CH, I, GB, IRL\}$$

$$\begin{aligned} \bowtie \; = \{&(F,E),(E,F),(F,B),(B,F),(F,D),(D,F),\\ &(F,CH),(CH,F),(F,I),(I,F),(B,NL),(NL,B),\\ &(B,D),(D,B),(D,NL),(NL,D),(D,CH),(CH,D),\\ &(CH,I),(I,CH),(GB,IRL),(IRL,GB)\} \end{aligned}$$

Therefore: $F \bowtie CH$ but $E \not\bowtie I$

examples

$$< \quad \subseteq \mathbb{N}^+ \times \mathbb{N}^+$$

$$< \quad = \{(1,2),(1,3),....,(1,1557),....,(2,3),(2,4),....\}$$

$$(4,7) \in < \ \text{ but } \ (2,2) \notin < \ \text{ and } \ (7,1) \notin <$$

Suppose $\{M_i : i \in \mathbb{N}\}$ with $M_i = \{ik : k \in \mathbb{N}^+\}$

Let's define the relation

$$| = \{(a,b) \in \mathbb{N}^+ \times \mathbb{N}^+ : b \in M_a\}$$

What does this relation signify?

When is $a \mid b$?

terminology: source, target, domain, range

For binary relations $R \subseteq A \times B$:

A is a *source*. B is a *target*.

Note that for any R, source and target are *not uniquely determined*:

$$R \subseteq A \times B$$

For any $A' \supseteq A$ and $B' \supseteq B$, we have $A \times B \subseteq A' \times B'$.

$$R \subseteq A \times B \subseteq A' \times B'$$

By contrast, these *are* uniquely determined:

the *domain* of R: $\mathrm{dom}(R) = \{a : (a, b) \in R \text{ for some } b\}$

the *range* of R: $\mathrm{range}(R) = \{b : (a, b) \in R \text{ for some } a\}$

For any relation $R \subseteq A \times B$ it is always the case that

$\mathrm{dom}(R) \subseteq A$ and $\mathrm{range}(R) \subseteq B$

example

$R_{\text{Charlie}} = \{\text{Violet}, \text{LRHG}, \text{Peggy}\}$, $R_{\text{Linus}} = \{\text{Sally}, \text{Mrs. Othmar}, \text{Lydia}\}$,
$R_{\text{Lucy}} = \{\text{Schroeder}\}$, $R_{\text{Patty}} = \{\text{Charlie}\}$, $R_{\text{Sally}} = \{\text{Linus}\}$
$P = \{\text{Charlie}, \text{Linus}, \text{Lucy}, \text{Patty}, \text{Sally}, \text{Violet}, \text{Peggy}, \text{Lydia}, \text{Schroeder}\}$
$Q = \{\text{Charlie}, \text{Linus}, \text{Lucy}, \text{Patty}, \text{Sally}, \text{Violet}, \text{Peggy}, \text{Lydia}, \text{Schroeder}, \text{LRHG}, \text{Mrs. Othmar}\}$

We can represent the same information as a relation from P to Q:

$\heartsuit \subseteq P \times Q$

$$\begin{aligned}\heartsuit = \{&(\text{Charlie}, \text{Violet}), (\text{Charlie}, \text{LRHG}), (\text{Charlie}, \text{Peggy}),\\ &(\text{Linus}, \text{Sally}), (\text{Linus}, \text{Mrs. Othmar}), (\text{Linus}, \text{Lydia}),\\ &(\text{Lucy}, \text{Schroeder}), (\text{Patty}, \text{Charlie}), (\text{Sally}, \text{Linus}),\\ &(\text{Violet}, \text{Violet}), (\text{Peggy}, \text{Charlie})\}\end{aligned}$$

So that $\text{Sally} \heartsuit \text{Linus}$ but $\text{Sally} \not\heartsuit \text{Schroeder}$.

relations as tables

$\heartsuit$	Charlie	Linus	Lucy	Patty	Sally	Violet	Peggy	Lydia	Schroeder	LRHG	Mrs Othmar
Charlie	0	0	0	0	0	1	1	0	0	1	0
Linus	0	0	0	0	1	0	0	1	0	0	1
Lucy	0	0	0	0	0	0	0	0	1	0	0
Patty	1	0	0	0	0	0	0	0	0	0	0
Sally	0	1	0	0	0	0	0	0	0	0	0
Violet	0	0	0	0	0	1	0	0	0	0	0
Peggy	1	0	0	0	0	0	0	0	0	0	0
Lydia	0	0	0	0	0	0	0	0	0	0	0
Schroeder	0	0	0	0	0	0	0	0	0	0	0

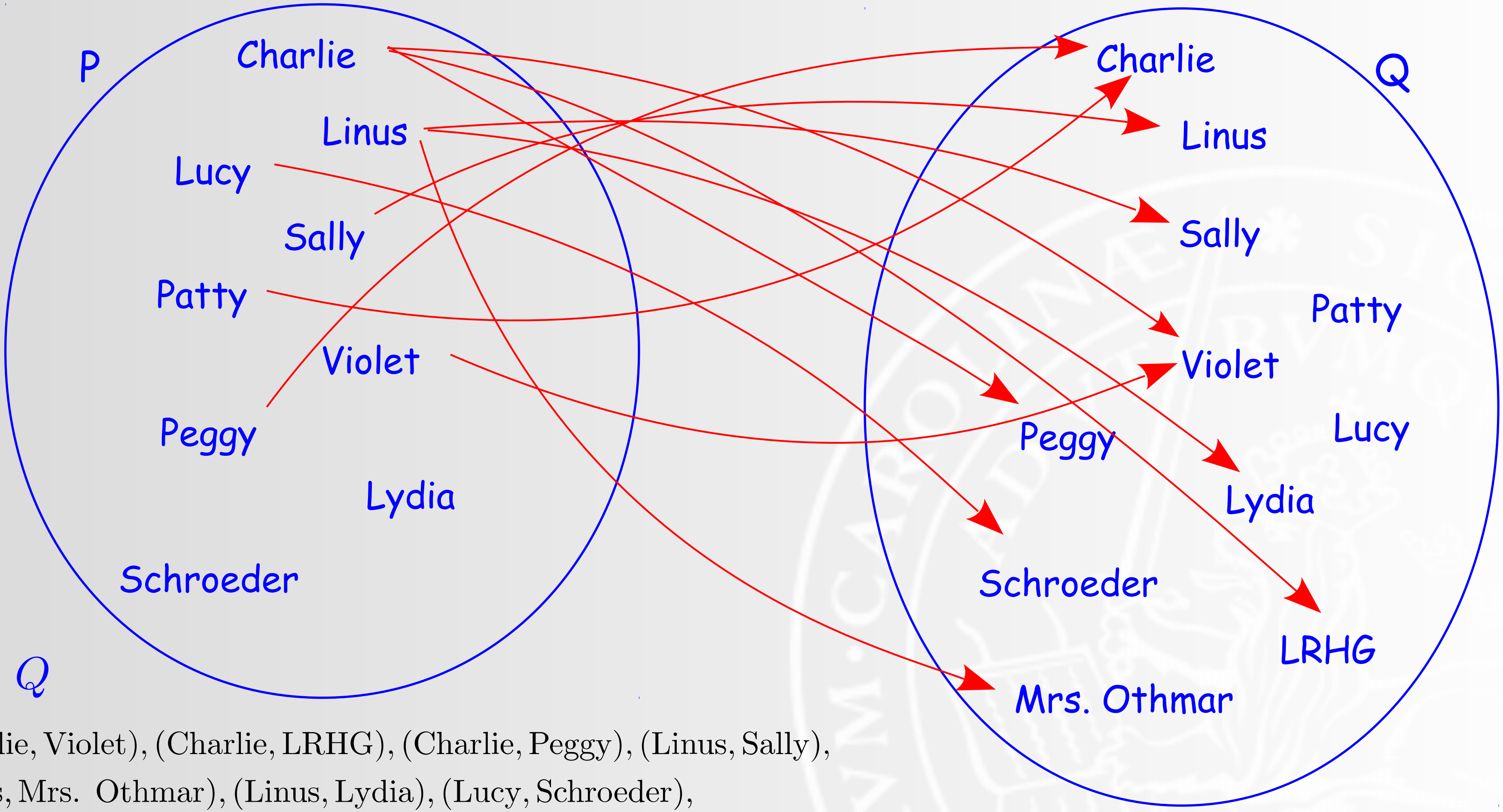
← Q

↑ P

$$\heartsuit \subseteq P \times Q$$

$$\heartsuit = \{(\text{Charlie}, \text{Violet}), (\text{Charlie}, \text{LRHG}), (\text{Charlie}, \text{Peggy}), (\text{Linus}, \text{Sally}), (\text{Linus}, \text{Mrs. Othmar}), (\text{Linus}, \text{Lydia}), (\text{Lucy}, \text{Schroeder}), (\text{Patty}, \text{Charlie}), (\text{Sally}, \text{Linus}), (\text{Violet}, \text{Violet}), (\text{Peggy}, \text{Charlie})\}$$

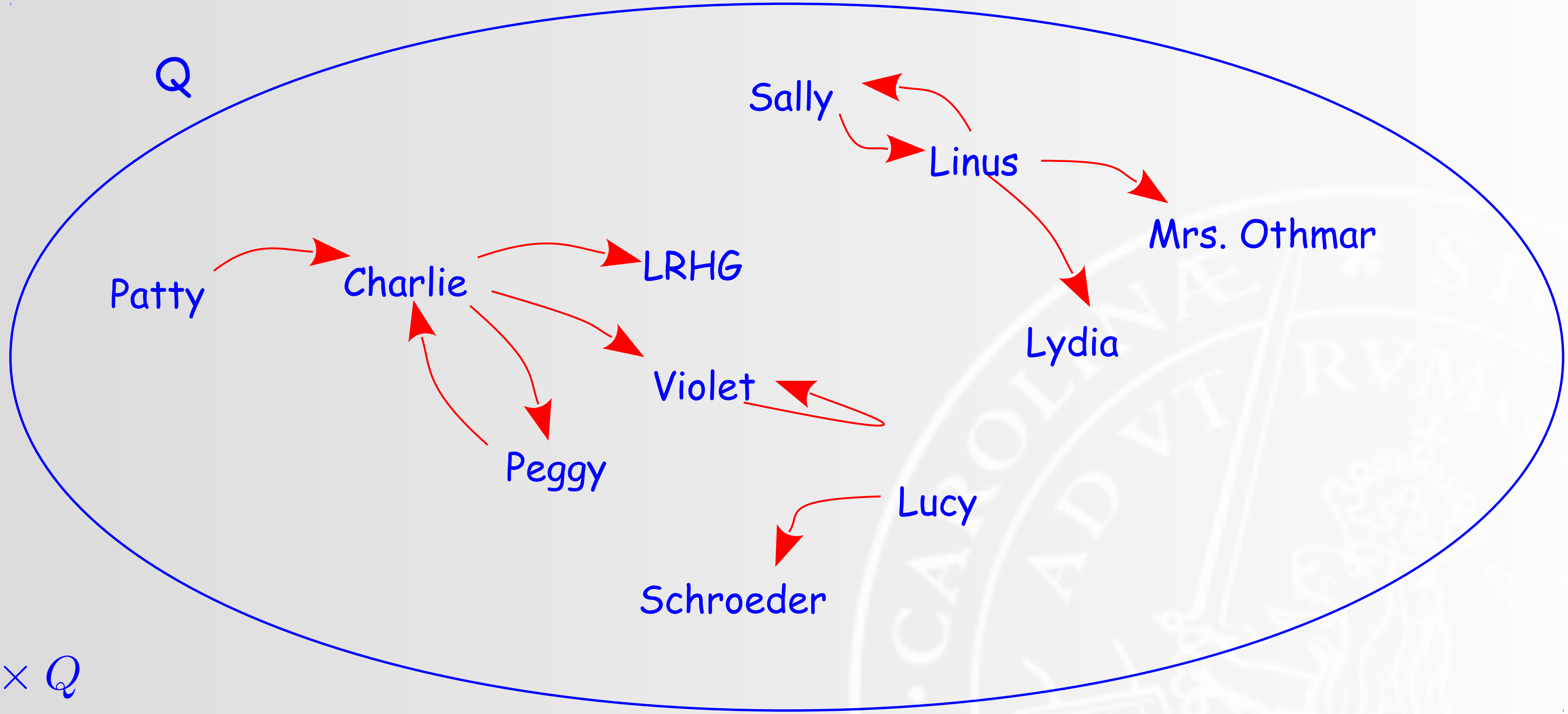
drawing relations: digraphs



$\heartsuit \subseteq P \times Q$

$\heartsuit = \{$(Charlie, Violet), (Charlie, LRHG), (Charlie, Peggy), (Linus, Sally), (Linus, Mrs. Othmar), (Linus, Lydia), (Lucy, Schroeder), (Patty, Charlie), (Sally, Linus), (Violet, Violet), (Peggy, Charlie)$\}$

drawing relations: digraphs



$\heartsuit \subseteq Q \times Q$

$$\heartsuit = \{(\text{Charlie}, \text{Violet}), (\text{Charlie}, \text{LRHG}), (\text{Charlie}, \text{Peggy}), (\text{Linus}, \text{Sally}), (\text{Linus}, \text{Mrs. Othmar}), (\text{Linus}, \text{Lydia}), (\text{Lucy}, \text{Schroeder}), (\text{Patty}, \text{Charlie}), (\text{Sally}, \text{Linus}), (\text{Violet}, \text{Violet}), (\text{Peggy}, \text{Charlie})\}$$

converse, complement

For a binary relation $R \subseteq A \times B$
its *converse* (*inverse*) is the relation $R^{-1} = \{(b,a) : aRb\}$

some properties:

$$R^{-1} \subseteq B \times A$$
$$(R^{-1})^{-1} = R$$
$$(R \cup S)^{-1} = R^{-1} \cup S^{-1} \qquad (R \cap S)^{-1} = R^{-1} \cap S^{-1}$$

For a binary relation $R \subseteq A \times B$
its *complement* is the relation $\overline{R} = -_{A \times B} R = A \times B \setminus R$

some properties:

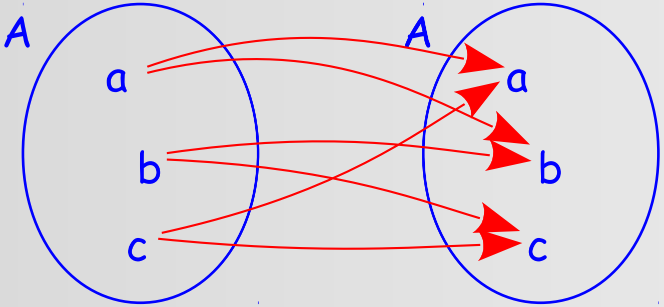
$$\overline{R} \subseteq A \times B \qquad \overline{\overline{R}} = R$$
$$\overline{R \cup S} = \overline{R} \cap \overline{S} \qquad \overline{R \cap S} = \overline{R} \cup \overline{S}$$

Notation: There is no firm standard for denoting converse or complement.
When using symbols such as $\prec$ or $\bowtie$, the complement is often indicated
by striking through the symbol, i.e. $\not\prec$ or $\not\bowtie$, while the converse is denoted
by reversing the symbol $\succ$.

converse vs complement

Especially when source and target are the same, converse and complement seem to have a lot in common. Hence the importance of understanding the differences.

$$R = \{(a,a),(a,b),(b,b),(b,c),(c,a),(c,c)\}$$

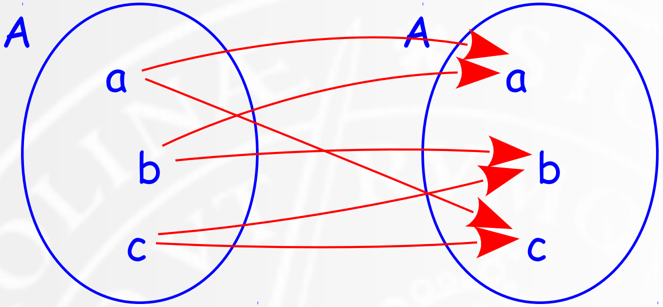


converse: invert the arrows
complement: absent arrows

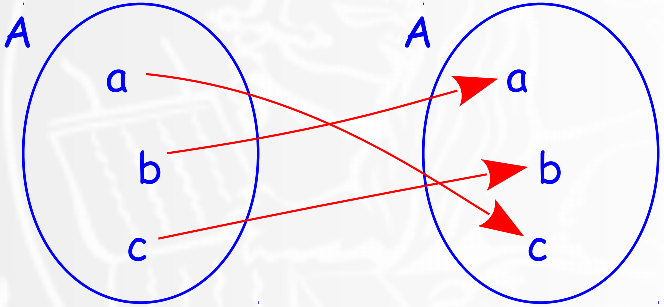
For finite A, B, given $R \subseteq A \times B$

What are $\#(R^{-1})$ and $\#(\overline{R})$?

$$R^{-1} = \{(a,a),(a,c)(b,a),(b,b),(c,b),(c,c)\}$$



$$\overline{R} = \{(a,c),(b,a),(c,b)\}$$



converse vs complement

$$R = \{(a,a),(a,b),(b,b),(b,c),(c,a),(c,c)\}$$

R	a	b	c
a	1	1	0
b	0	1	1
c	1	0	1

$$R^{-1} = \{(a,a),(a,c)(b,a),(b,b),(c,b),(c,c)\}$$

R	a	b	c
a	1	0	1
b	1	1	0
c	0	1	1

converse: mirror at the diagonal

$$\overline{R} = \{(a,c),(b,a),(c,b)\}$$

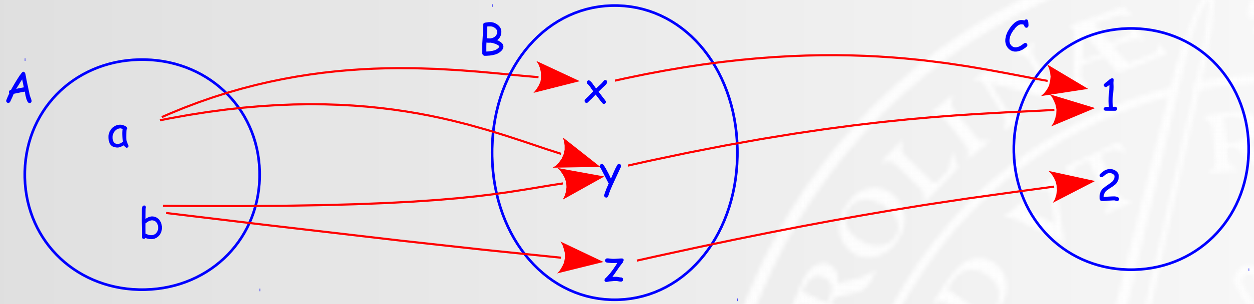
R	a	b	c
a	0	0	1
b	1	0	0
c	0	1	0

complement: flip zeros and ones

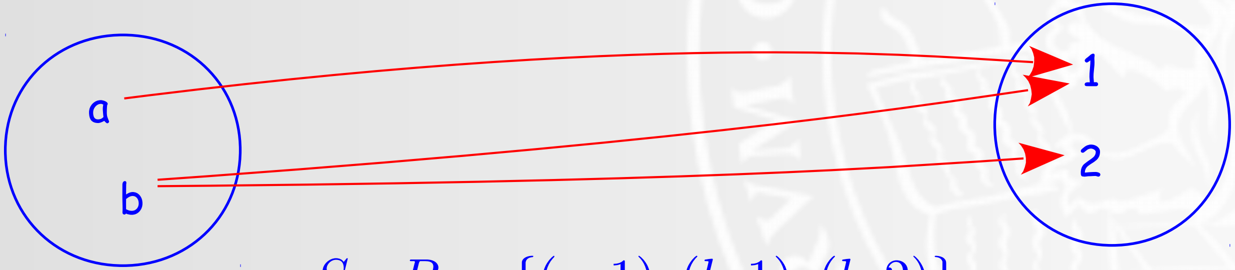
composition

Given two binary relations $R \subseteq A \times B$ and $S \subseteq B \times C$
their *composition* is a binary relation on $A \times C$

$$S \circ R = \{(a,c) : aRb \text{ and } bSc \text{ for some } b \in B\}$$



$R = \{(a,x),(a,y),(b,y),(b,z)\}$ $S = \{(x,1),(y,1),(z,2)\}$



$S \circ R = \{(a,1),(b,1),(b,2)\}$

composition

s i d e b a r

$$R = \{(a,x),(a,y),(b,y),(b,z)\}$$

R	x	y	z
a	1	1	0
b	0	1	1

$$S = \{(x,1),(y,1),(z,2)\}$$

S	1	2
x	1	0
y	1	0
z	0	1

$$S \circ R = \{(a,1),(b,1),(b,2)\}$$

SoR	1	2
a	1	0
b	1	1

What is the relationship between the tables for R and S, and their composition?

image

Given a binary relation $R \subseteq A \times B$ from A to B, for any $a \in A$
its *image under R*, written R(a), is defined as $R(a) = \{b \in B : aRb\}$

Can be "lifted" to subsets $X \subseteq A$: $R(X) = \{b \in B : aRb \text{ for some } a \in X\}$

Note: $R(X) = \bigcup_{a \in X} R(a)$

$$C = \{F, E, B, D, NL, CH, I, GB, IRL\}$$

$$\begin{aligned} \bowtie \; = \{&(F,E),(E,F),(F,B),(B,F),(F,D),(D,F),(F,CH),(CH,F),(F,I),\\ &(I,F),(B,NL),(NL,B),(B,D),(D,B),(D,NL),(NL,D),(D,CH),\\ &(CH,D),(CH,I),(I,CH),(GB,IRL),(IRL,GB)\} \end{aligned}$$

1. What is $\bowtie (F)$?
2. What does it mean?

properties: reflexivity

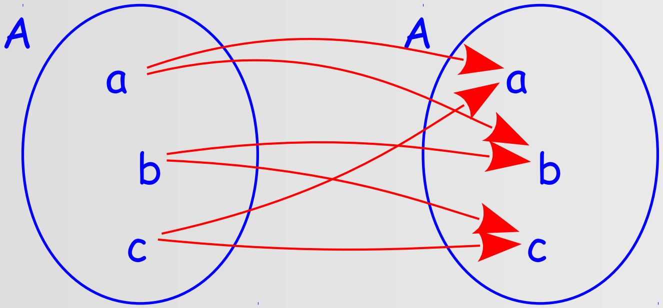
A binary relation $R \subseteq A \times A$ is *reflexive* iff for all $a \in A$

$$aRa$$

A binary relation $R \subseteq A \times A$ is *irreflexive* iff there is no $a \in A$ such that

$$aRa$$

$$R = \{(a,a),(a,b),(b,b),(b,c),(c,a),(c,c)\}$$



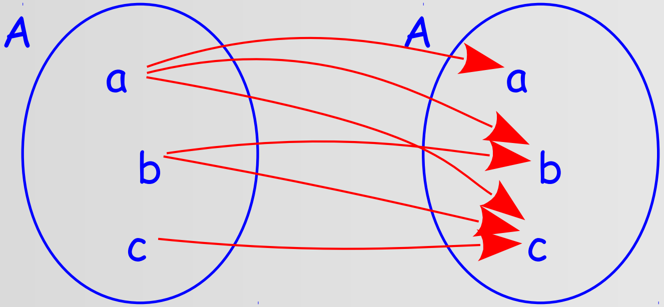
R	a	b	c
a	1	1	0
b	0	1	1
c	1	0	1

Other examples?
What is the difference between irreflexive and not reflexive?

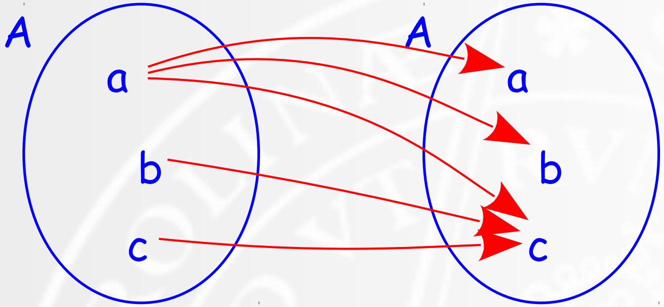
properties: transitivity

A binary relation $R \subseteq A \times A$ is *transitive* iff for all $a, b, c \in A$

$$\text{if } aRb \text{ and } bRc \text{ then } aRc$$



R	a	b	c
a	1	1	1
b	0	1	1
c	0	0	1



R	a	b	c
a	1	1	1
b	0	0	1
c	0	0	1

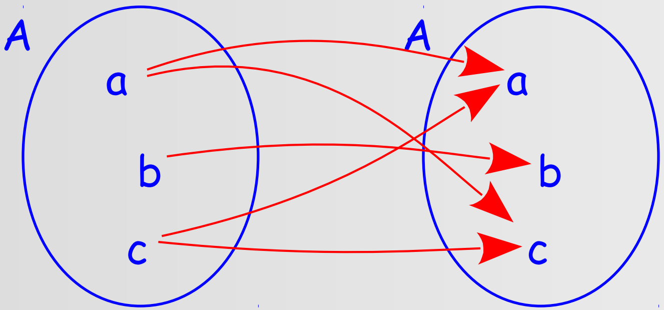
Other examples?

properties: symmetry

A binary relation $R \subseteq A \times A$ is *symmetric* iff for all $a, b \in A$

$$\text{if } aRb \text{ then } bRa$$

$$R = \{(a,a),(a,c),(b,b),(c,a),(c,c)\}$$



R	a	b	c
a	1	0	1
b	0	1	0
c	1	0	1

Other examples?

properties: a(nti)symmetry

Consider $\leq$ and $<$ on the natural numbers. Neither is symmetric, but in slightly different ways.
For $<$, it is **never** the case that $a < b$ and $b < a$.
This is called **asymmetry**.

For $\leq$, it sometimes is, but only when $a = b$.
This is called **antisymmetry**.

Both relations are antisymmetric. Only $<$ is asymmetric.

A binary relation $R \subseteq A \times A$ is *asymmetric* iff for all $a, b \in A$

$$\text{if } aRb \text{ then not } bRa$$

A binary relation $R \subseteq A \times A$ is *antisymmetric* iff for all $a, b \in A$

$$\text{if } aRb \text{ and } bRa \text{ then } a = b$$

equivalence relations

A binary relation $\approx \subseteq A \times A$ is an *equivalence relation* iff it is

1. reflexive
2. symmetric
3. transitive

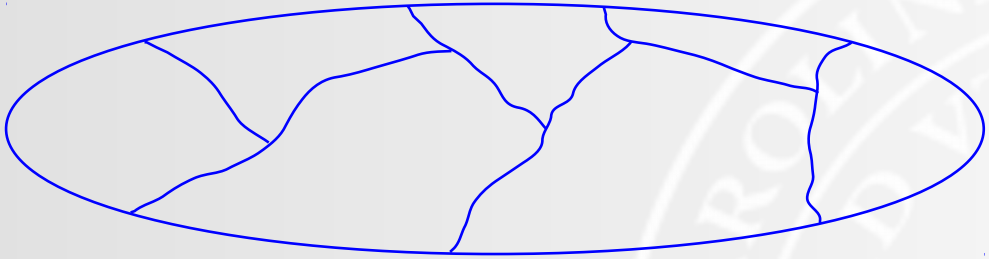
What about these:

- equality
- having the same number of elements: $A \sim B \text{ iff } \#(A) = \#(B)$
- divides: $m \mid n \text{ iff there is } k \geq 1 : km = n$
- relatively prime: $m \perp n \text{ iff there is no } k \geq 2 : k \mid m \text{ and } k \mid n$

partitions

Given a set A, a *partition of A* is a set of pairwise disjoint sets $\{B_i : i \in I\}$, such that

$$A = \bigcup_{i \in I} B_i$$



A: EU citizens, I: EU member states, B_i: citizens of country i

A: atoms, I: elements, B_i: atoms of element i

A: natural numbers, I: primes, B_i: multiples of i (excluding i)

order relation, poset

A binary relation $\preceq \subseteq A \times A$ is an (*inclusive* or *non-strict*) (*partial*) *order* iff it is

1. reflexive 2. antisymmetric 3. transitive

What about these:

- divides: $m \mid n$ iff there is $k \geq 1 : km = n$
- set inclusion: $\subseteq$
- on numbers: $\leq$ and $<$
- proper set inclusion: $\subset$

A pair $(A, \preceq)$ where A is a set and $\preceq \subseteq A \times A$ a partial order on A is called a *partially ordered set* or *poset*.

Examples: $(\mathbb{N}^+, |)$

$(\mathcal{P}(A), \subseteq)$

strict (partial) order

A binary relation $\prec \subseteq A \times A$ is a *strict* (*partial*) *order* iff it is

1. irreflexive
2. transitive

Note: Irreflexivity and transitivity imply asymmetry.

How?

irreflexivity:	$a \not\prec a$
transitivity:	if $a \prec b$ and $b \prec c$ then $a \prec c$
asymmetry:	if $a \prec b$ then $b \not\prec a$

total (or linear) order

A binary relation $\preceq \subseteq A \times A$ is a (*non-strict*) *total (or linear) order* iff it is

1. reflexive
2. antisymmetric
3. transitive
4. total (complete): $a \preceq b \text{ or } b \preceq a$

What about these:

- divides: $m \mid n \text{ iff there is } k \geq 1 : km = n$
- set inclusion: $\subseteq$
- on numbers: $\leq$ and $<$

transitive closure

The *transitive closure* R^* of a binary relation $R \subseteq A \times A$ is defined as follows:

$$R^* = \bigcup_{i \in \mathbb{N}} R_i \text{ with}$$

$$R_0 = R$$

$$R_{n+1} = R_n \cup \{(a,c) : \text{if } aRb \text{ and } bRc \text{ for some } b \in A\}$$

R^+
alternative syntax

$$\bowtie \;= \{(F,E),(E,F),(F,B),(B,F),(F,D),(D,F),(F,CH),(CH,F),(F,I),(I,F),(B,NL),(NL,B),(B,D),(D,B),(D,NL),(NL,D),(D,CH),(CH,D),(CH,I),(I,CH),(GB,IRL),(IRL,GB)\}$$

What is the meaning of $\bowtie^*$?
What are its properties?