

Binary Relation II

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2020-12-3



Adapted From:

Stanford CS103 Binary Relation
《数理逻辑与集合论》10.5,10.8



Review

- **Binary Relation Basics**
 - Subset of Cartesian Products
 - Representation: Relation matrix and Digraph
 - Operations: Union, composite, power, etc
- **Equivalence Relation and Partitions**
 - Reflexivity, Symmetry and Transitivity.
- **Compatible Relation and Covers**
 - Reflexivity and Symmetry

How we investigate computability?

《数理逻辑与集合论》 10.5, 10.8, 11

2.1 Discussion on Problems

Part1. Intro & Set theory(I) : Basics & Formal Language.

Part2. Set Theory(II): Axiom system & Cardinality.

Part3. Capture Structures: Binary Relation & Function

2.2 Discussion on Computation

Part1. Turing Machine Basics.

Part2. Variants of Turing Machine. Church-Turing Thesis.

2.3 Discussion on computability

Part1. The Language of Turing Machine. R & RE

Part2. Undecidability.

Order Relations

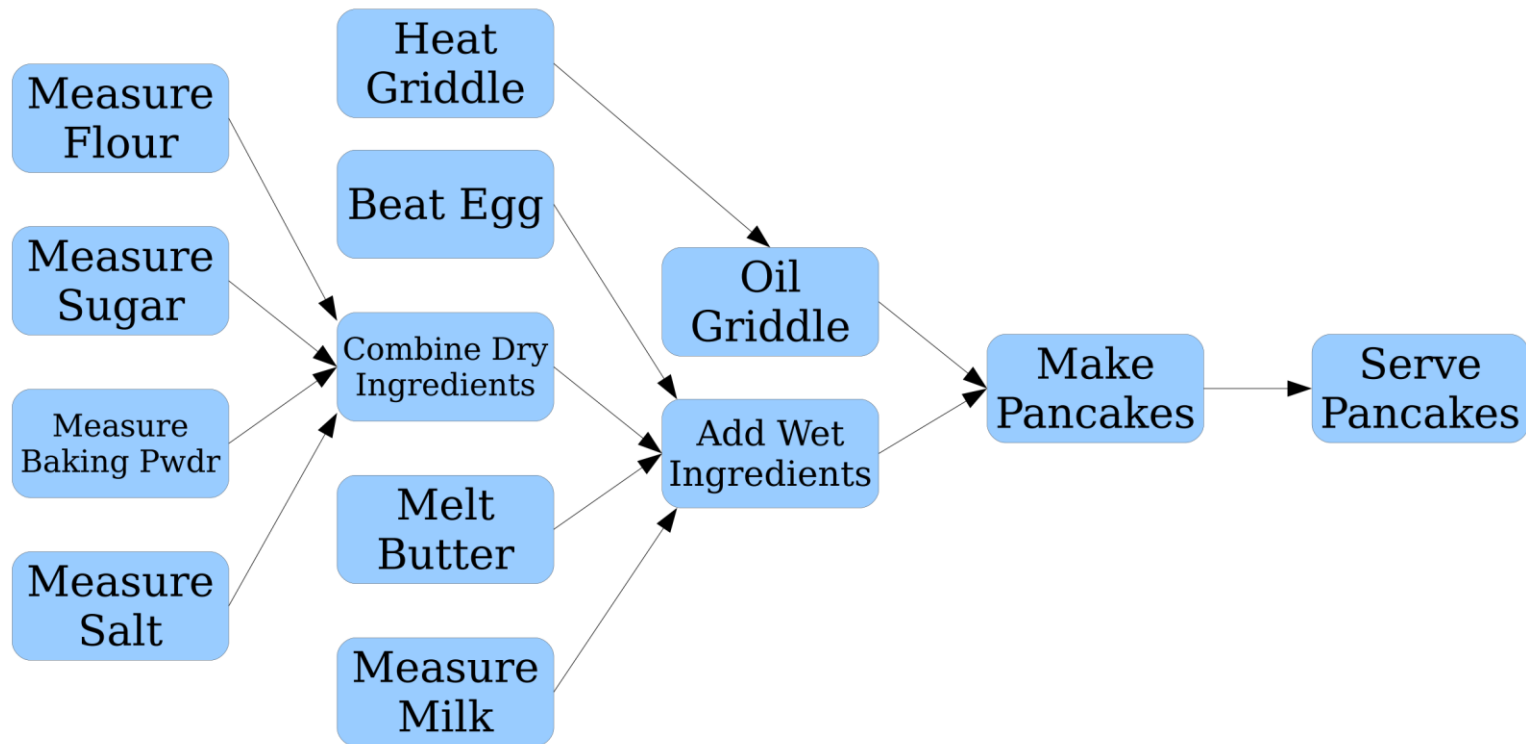
Ordered Objects

words in dictionary

a	bread	dog
about	bring	far
after	but	fly
an	buy	got
ask	cake	Hand
bear	call	it
bed	chair	letter

Ordered Objects

A recipe to make pancake



Ordered Objects

- Take $\leq$ on $\mathbb{R}$ as example. We know that:
 - $x \leq x$ for any $x \in \mathbb{R}$
 - If $x \leq y$ and $y \leq x$, then $x = y$
 - If $x \leq y$ and $y \leq z$, then $x \leq z$

Ordered Objects

- Take $\leq$ on $\mathbb{R}$ as example. We know that:

- $x \leq x$ for any $x \in \mathbb{R}$

Reflexivity

- If $x \leq y$ and $y \leq x$, then $x = y$

?

- If $x \leq y$ and $y \leq z$, then $x \leq z$

Transitivity

Anti-symmetry(反对称性)

- Some relation is symmetric only in its diagonal.
- Examples:
 - If $x \leq y$ and $y \leq x$, then $x = y$
 - If $A \subseteq B$ and $B \subseteq A$, then $A = B$
- Relations of this sort are called antisymmetric.

$$R \text{ on } A \text{ is antisymmetric} \Leftrightarrow (\forall a)(\forall b)((a \in A \wedge b \in B \wedge aRb \wedge bRa) \rightarrow a = b)$$

Anti-symmetry : Example

- I_A and N_A
- E_A when $|A| > 1$
- $R = \{\langle 1,1 \rangle, \langle 1,2 \rangle, \langle 2,1 \rangle, \langle 2,3 \rangle, \langle 3,3 \rangle\}$ on $\{1,2,3\}$

Anti-symmetry : Example

- I_A and N_A 😊
- E_A when $|A| > 1$ 😞
- $R = \{\langle 1,1 \rangle, \langle 1,2 \rangle, \langle 2,1 \rangle, \langle 2,3 \rangle, \langle 3,3 \rangle\}$ on $\{1,2,3\}$ 😞
 - $1R2$ and $2R1$

Partial-order Relation(偏序关系)

- An **partial-order relation** is a relation that is **reflexive, anti-symmetric and transitive**.
- Some example:
 - $x \leq y$
 - $x \subseteq y$
 - x can be divided by y (on $\mathbb{N}^+$)
- A set A together with a partial ordering R is called a partially ordered set, or poset(偏序集), and is denoted by $\langle A, R \rangle$.
 - $\langle \mathbb{N}, \leq \rangle, \langle \mathcal{P}(A), \subseteq \rangle$ are both poset.

Ordered Objects

- Take $<$ on $\mathbb{R}$ as example. We know that:
 - $x \not< x$ for any $x \in \mathbb{R}$
 - If $x < y$ and $y < z$, then $x < z$

Ordered Objects

- Take $<$ on $\mathbb{R}$ as example. We know that:
 - $x \not< x$ for any $x \in \mathbb{R}$?
 - If $x < y$ and $y < z$, then $x < z$ *Transitivity*

Anti-reflexivity

- Some relation never holds from any element to itself
- Examples:
 - $A \not\subset A$ for any set A
 - $x \not\prec x$ for any x
- Relations of this sort are called anti-reflexive or irreflexive:

R on A is anti-reflexive $\Leftrightarrow (\forall a)(a \in A \rightarrow a \not R a)$

Anti-reflexivity : Example

- I_A and E_A
- N_A
- $R = \{\langle 1,2 \rangle, \langle 2,1 \rangle, \langle 2,3 \rangle, \langle 3,3 \rangle\}$ on $\{1,2,3\}$

Anti-reflexivity : Example

- I_A and E_A 😞
- N_A 😊
- $R = \{\langle 1,2 \rangle, \langle 2,1 \rangle, \langle 2,3 \rangle, \langle 3,3 \rangle\}$ on $\{1,2,3\}$ 😞
 - $3R3$

Reflexivity and Anti-reflexivity

- Reflexivity and anti-reflexivity are not negations of one another!
- Reflexivity:

$$(\forall a)(a \in A \rightarrow aRa)$$

- Negation of Reflexivity(Non-reflexivity):

$$(\exists a)(a \in A \rightarrow a \not R a)$$

- Anti-reflexivity:

$$(\forall a)(a \in A \rightarrow a \not R a)$$

Quasi-order Relation(拟序关系)

- An **quasi-order relation, or strict order relation** is a relation that is **anti-reflexive, transitive**.
- Some example:
 - $x < y$
 - $x \subset y$
 - x is taller than y

Quasi-order Relation

Quasi-order relation is anti-symmetric.

Quasi-order Relation

Quasi-order relation is anti-symmetric.

*Anti-reflexivity
Transitivity* $\Rightarrow$ *Anti-symmetric*

Quasi-order Relation

Quasi-order relation is anti-symmetric.

Anti-reflexivity
Transitivity $\Rightarrow$ *Anti-symmetric*

Proof:

For a quasi-order relation R on A , assume that R is not anti-symmetric, then there exists x, y such that $xRy \wedge yRx \wedge x \neq y$.

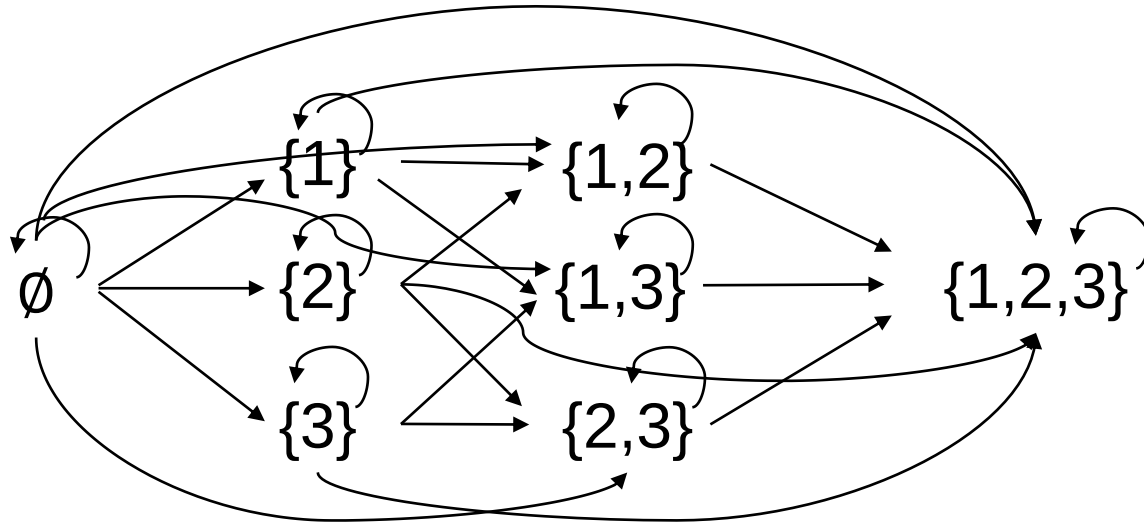
From transitivity and $xRy \wedge yRx$ we have xRx , but $x \not R x$ as R is anti-reflexivity.

Contradiction.

Partial Order and Quasi Order

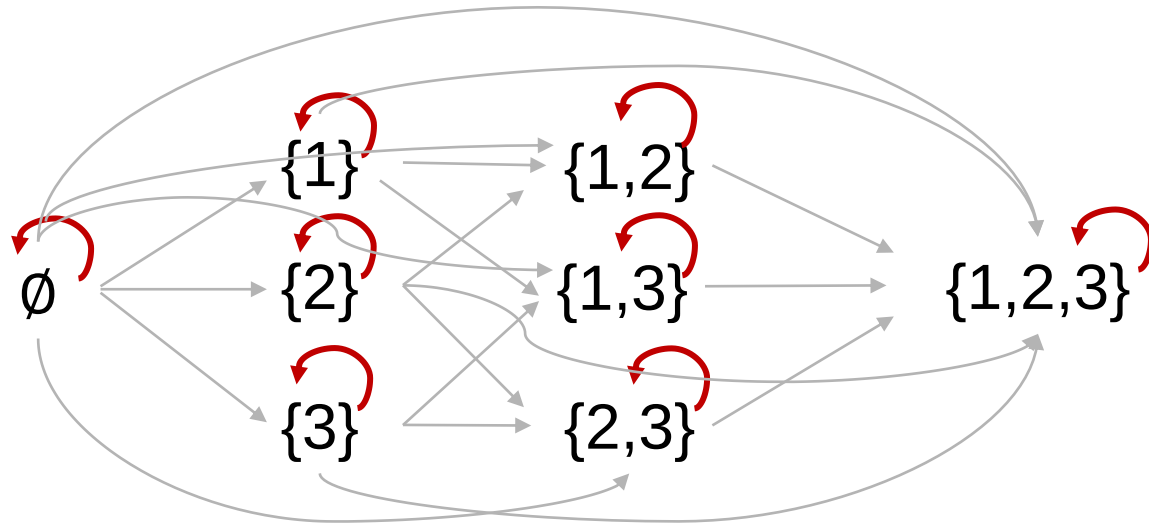
- Often denote as $\leq$ and $<$
 - Not necessarily mean numerical operation.
- Quasi order R on A , $R \cup R_0$ is a partial order
" $<$ " + " $=$ " $\rightarrow$ " $\leq$ "
- Partial order R on A , $R - R_0$ is a quasi order
" $\leq$ " - " $=$ " $\rightarrow$ " $<$ "

$\langle \mathcal{P}(A), \subseteq \rangle, A=\{1,2,3\}$



Too complicated!!!

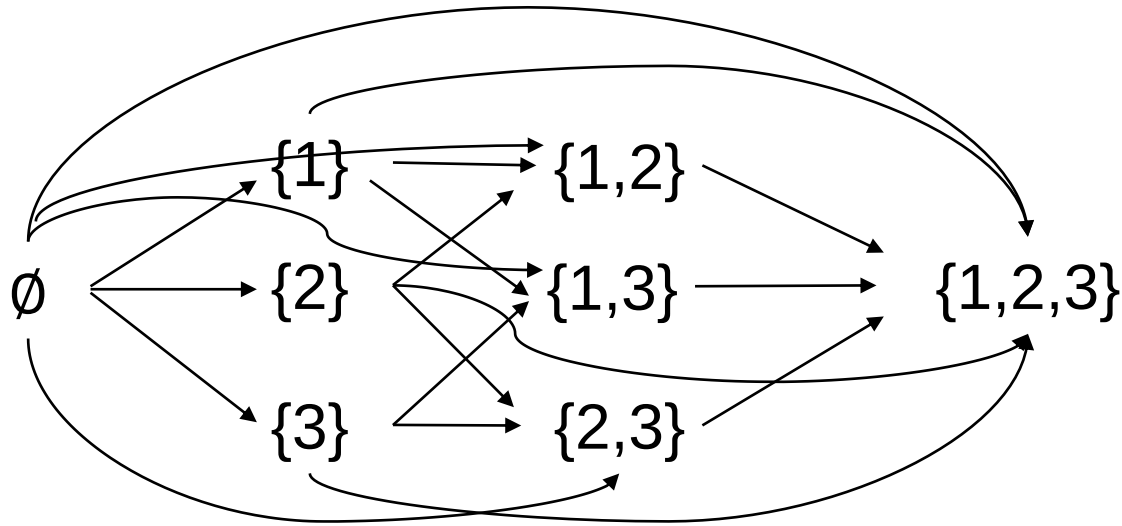
$$\langle \mathcal{P}(A), \subseteq \rangle, A = \{1, 2, 3\}$$



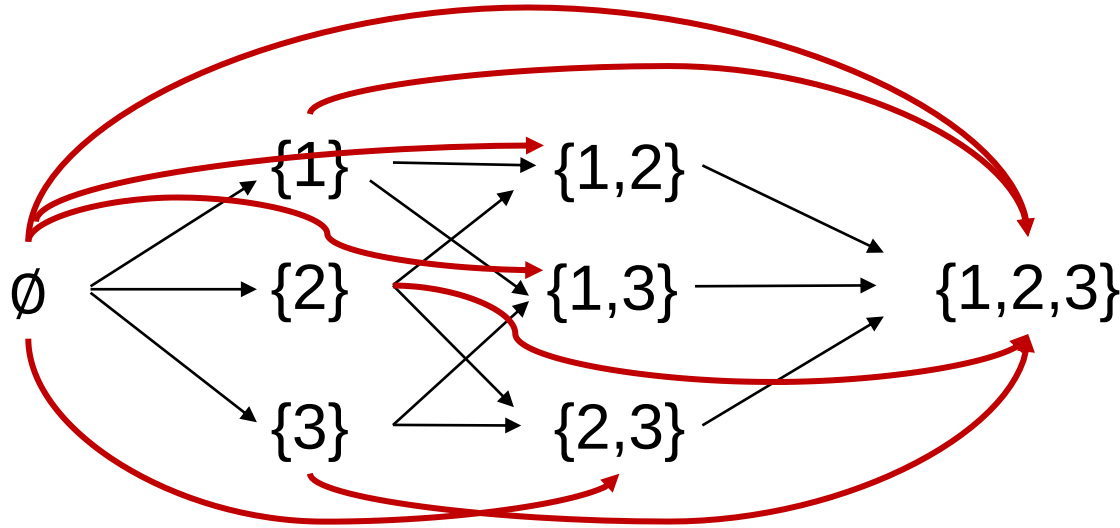
Reflexivity: Every object has a self-circle.

Drop it.

$\langle \mathcal{P}(A), \subseteq \rangle, A=\{1,2,3\}$



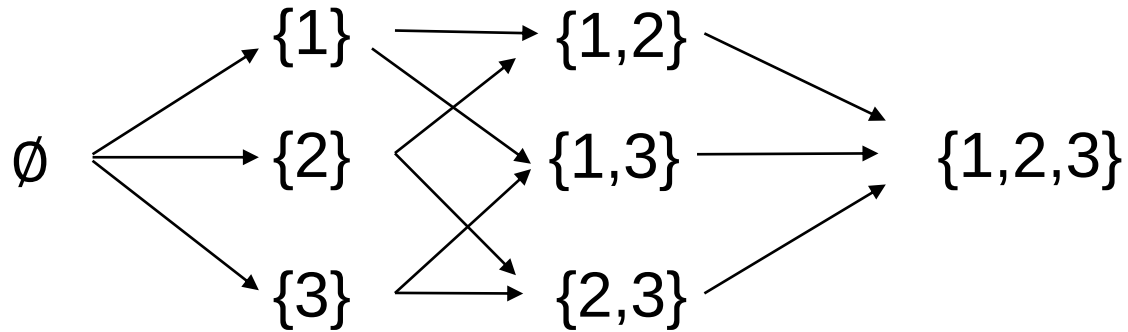
$$\langle \mathcal{P}(A), \subseteq \rangle, A = \{1, 2, 3\}$$



Transitivity: Some relation can be derived from “smaller” relation

Drop it.

$\langle \mathcal{P}(A), \subseteq \rangle, A = \{1, 2, 3\}$



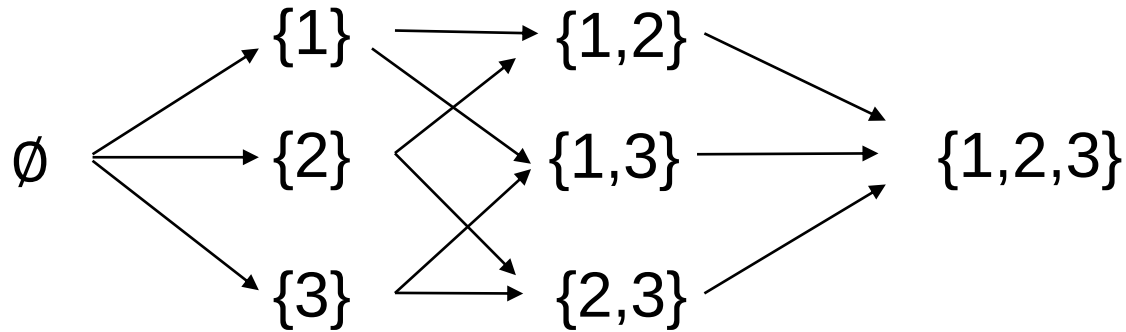
Cover Relation

- For poset $\langle A, \leq \rangle$, if $x, y \in A$, $x \leq y$, $x \neq y$, and there doesn't exist $z \in A$ such that $x \leq z$ and $z \leq y$, we call that **y covers x** .
- y covers x means that y is exactly greater than x and there's no elements between them.
- We can define a **cover relation** on A :

$$\text{cov}(A) = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge (y \text{ covers } x)\}$$

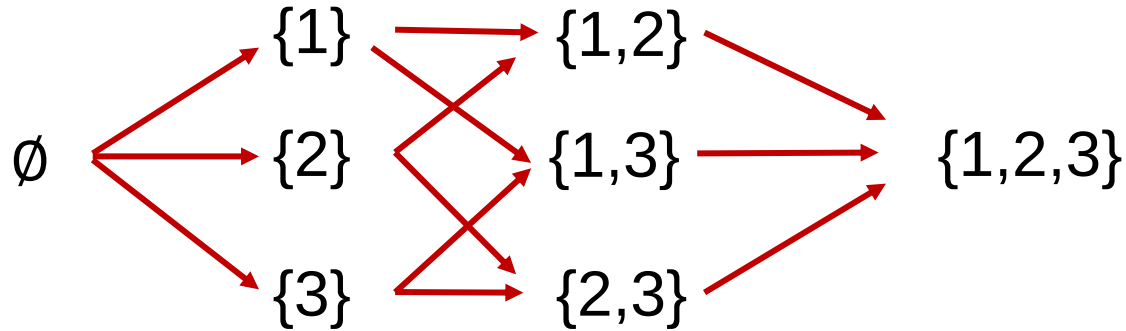
$\langle \mathcal{P}(A), \subseteq \rangle, A = \{1, 2, 3\}$

$\text{cover}(\mathcal{P}(A))$



$\langle \mathcal{P}(A), \subseteq \rangle, A = \{1, 2, 3\}$

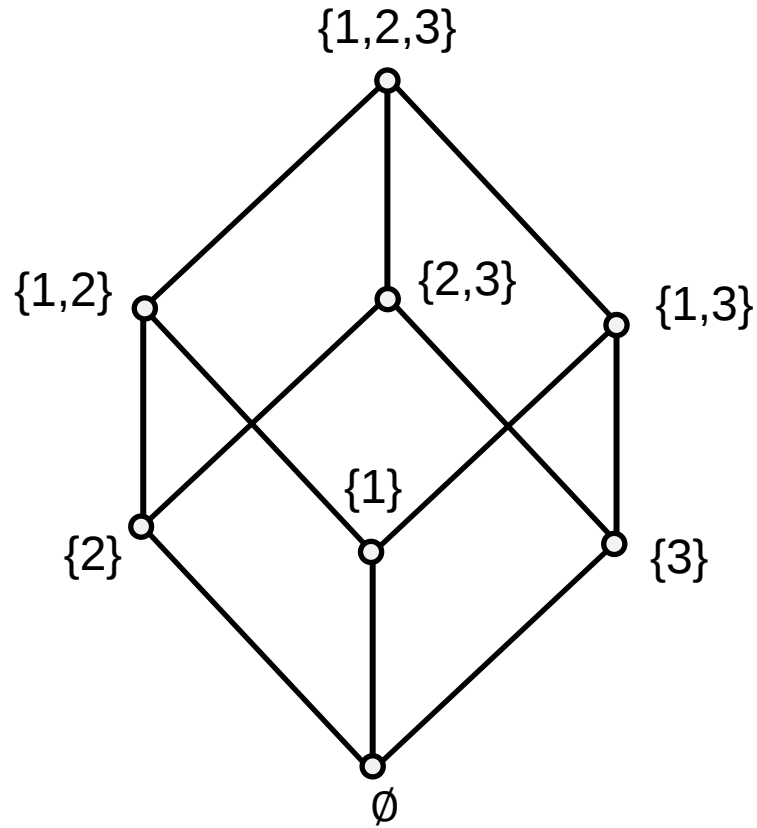
$\text{cover}(\mathcal{P}(A))$



All directed edge are
towards the same way

*Choose a direction as
increased direction.*

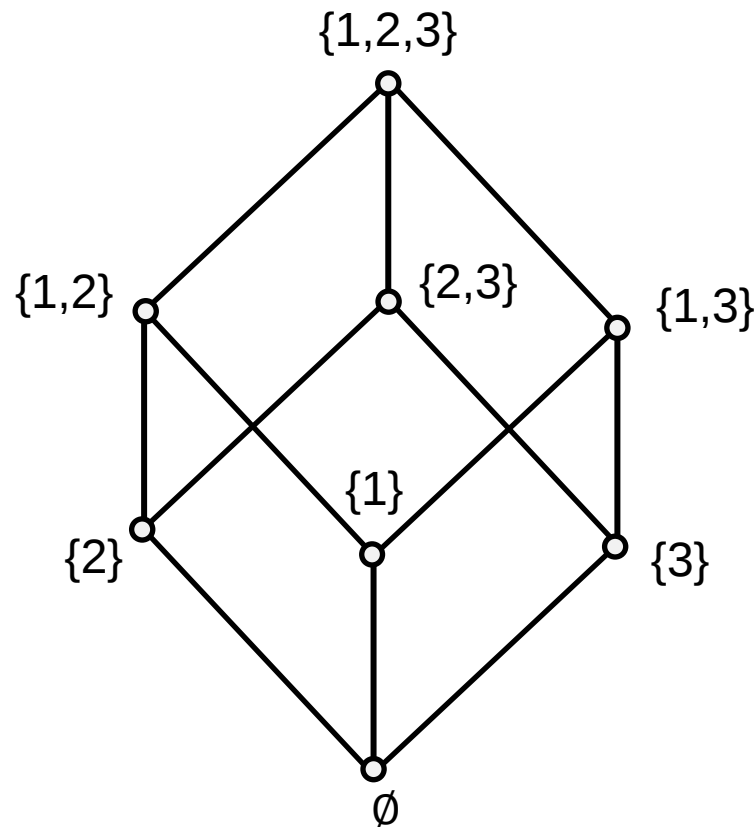
$\langle \mathcal{P}(A), \subseteq \rangle, A=\{1,2,3\}$
 $cover(\mathcal{P}(A))$



↑
Increased
Direction

Hasse Diagram(哈斯图)

- For poset $\langle A, \leq \rangle$:
 - Every vertex is an element
 - If $x \leq y \wedge x \neq y$, then vertex y is above vertex x
 - If $\langle x, y \rangle \in \text{cov}(A)$, then there's an undirected edge between x and y



Hasse Diagram

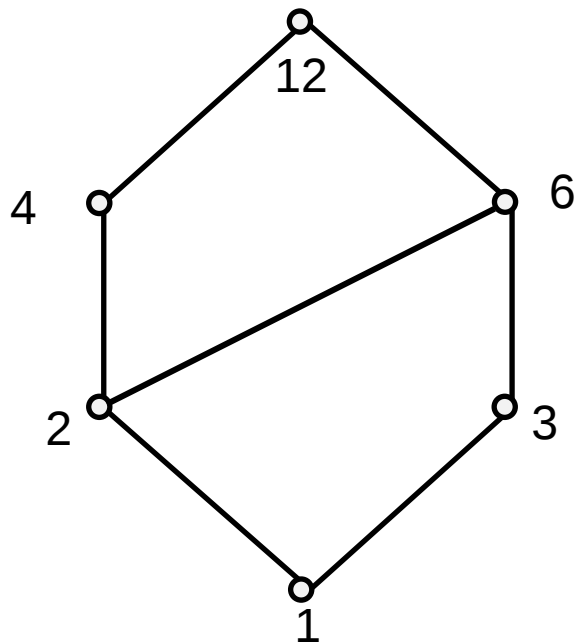
- Define the divisibility relation on $A = \{1,2,3,4,6,12\}$:

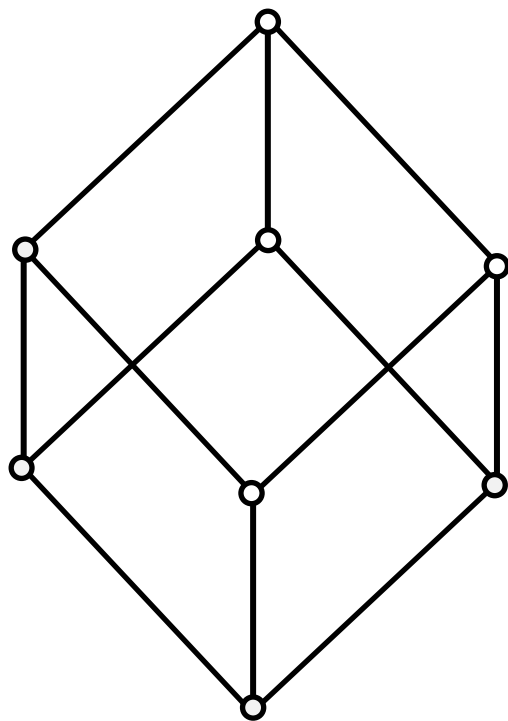
$$R = \{\langle x, y \rangle | x \in A \wedge y \in A \wedge x|y\}$$

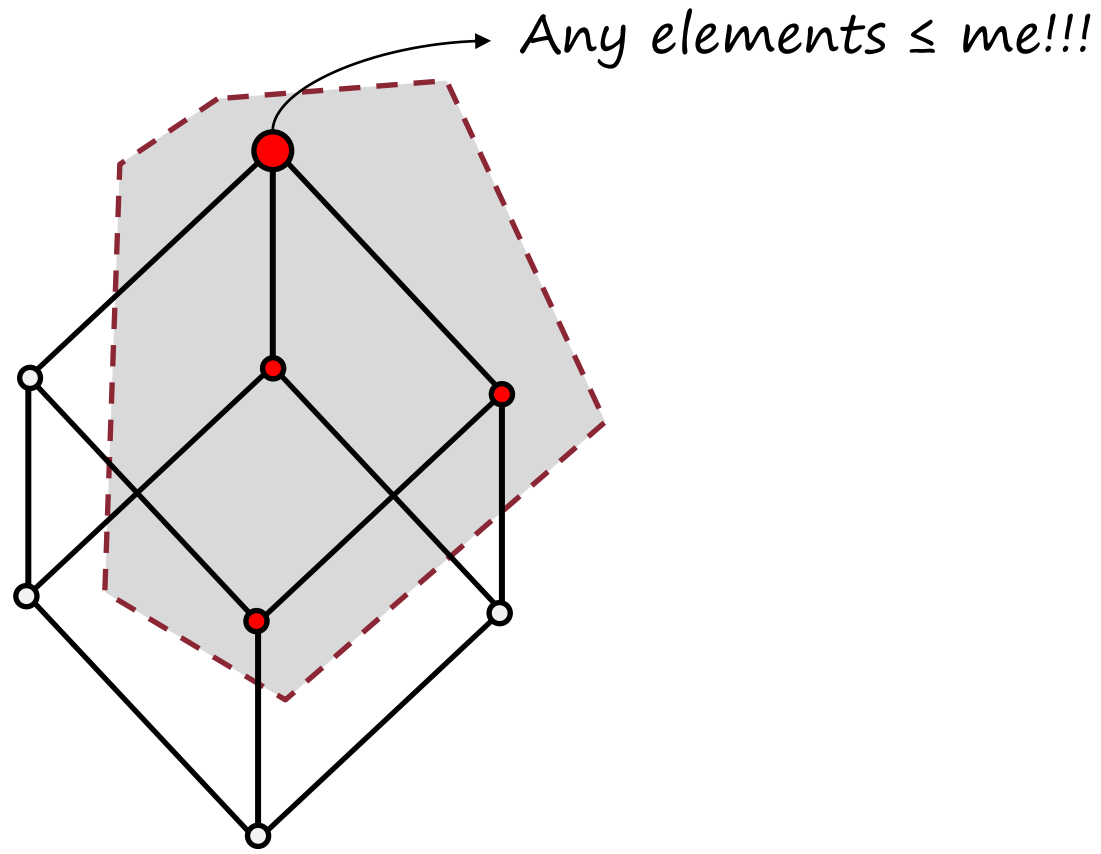
Hasse Diagram

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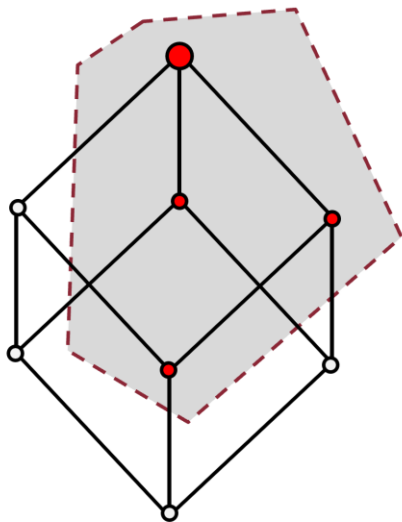


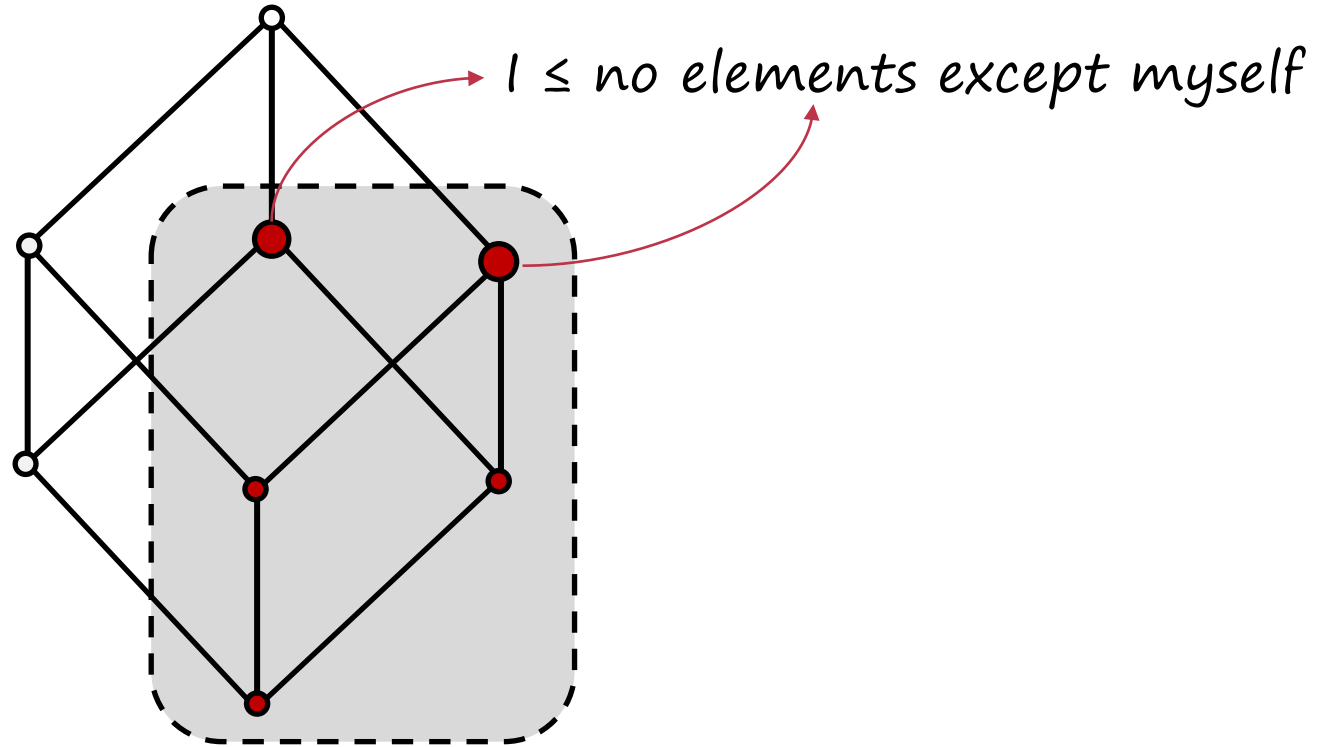


Maximum Elements(最大元)

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
- If there exists $y \in B$ such that $\forall x \in B, x \leq y$, we call y the **maximum** elements of B

$$y \text{ is maximum} \Leftrightarrow y \in B \wedge (\forall x)(x \in B \rightarrow x \leq y)$$

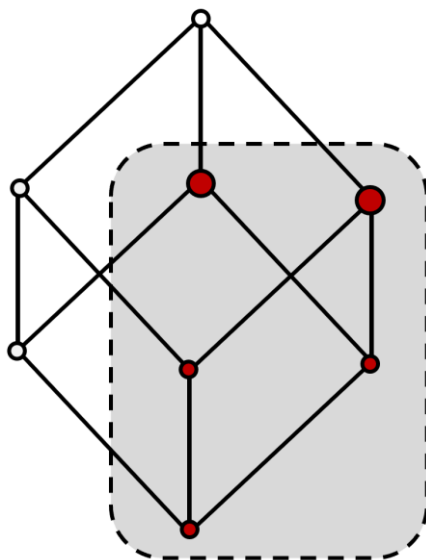




Maximal Elements(极大元)

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
- If there exists $y \in B$ such that $\forall x \in B$, if $y \leq x$, then $x = y$. We call y the **maximal** elements of B

$$y \text{ is maximal} \Leftrightarrow y \in B \wedge (\forall x)((x \in B \wedge y \leq x) \rightarrow x = y)$$



Maximal and Maximum Elements

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - If there exists $y \in B$ such that $\forall x \in B, x \leq y$, we call y the **maximum** elements(最大元) of B

$$y \text{ is maximum} \Leftrightarrow y \in B \wedge (\forall x)(x \in B \rightarrow x \leq y)$$

- If there exists $y \in B$ such that $\forall x \in B$, if $y \leq x$, then $x = y$. We call y the **maximal** elements(极大元) of B

$$y \text{ is maximal} \Leftrightarrow y \in B \wedge (\forall x)((x \in B \wedge y \leq x) \rightarrow x = y)$$

Maximal and Maximum Elements

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:

I beat every one.

- If there exists $y \in B$ such that $\forall x \in B, x \leq y$, we call y the **maximum** elements(最大元) of B

$$y \text{ is maximum} \Leftrightarrow y \in B \wedge (\forall x)(x \in B \rightarrow x \leq y)$$

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$$y \text{ is maximal} \Leftrightarrow y \in B \wedge (\forall x)((x \in B \wedge y \leq x) \rightarrow x = y)$$

No one can beat me except myself.

Minimum(最小) and Minimal(极小) Elements

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - If there exists $x \in B$ such that $\forall y \in B, x \leq y$, we call x the **minimum** elements(最小元) of B

$$x \text{ is minimum} \Leftrightarrow x \in B \wedge (\forall y)(y \in B \rightarrow x \leq y)$$

- If there exists $x \in B$ such that $\forall y \in B$, if $y \leq x$, then $x = y$. We call x the **minimal** elements(极小元) of B

$$x \text{ is minimal} \Leftrightarrow x \in B \wedge (\forall y)((y \in B \wedge y \leq x) \rightarrow x = y)$$

Minimum(最小) and Minimal(极小) Elements

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:

Everyone beats me.

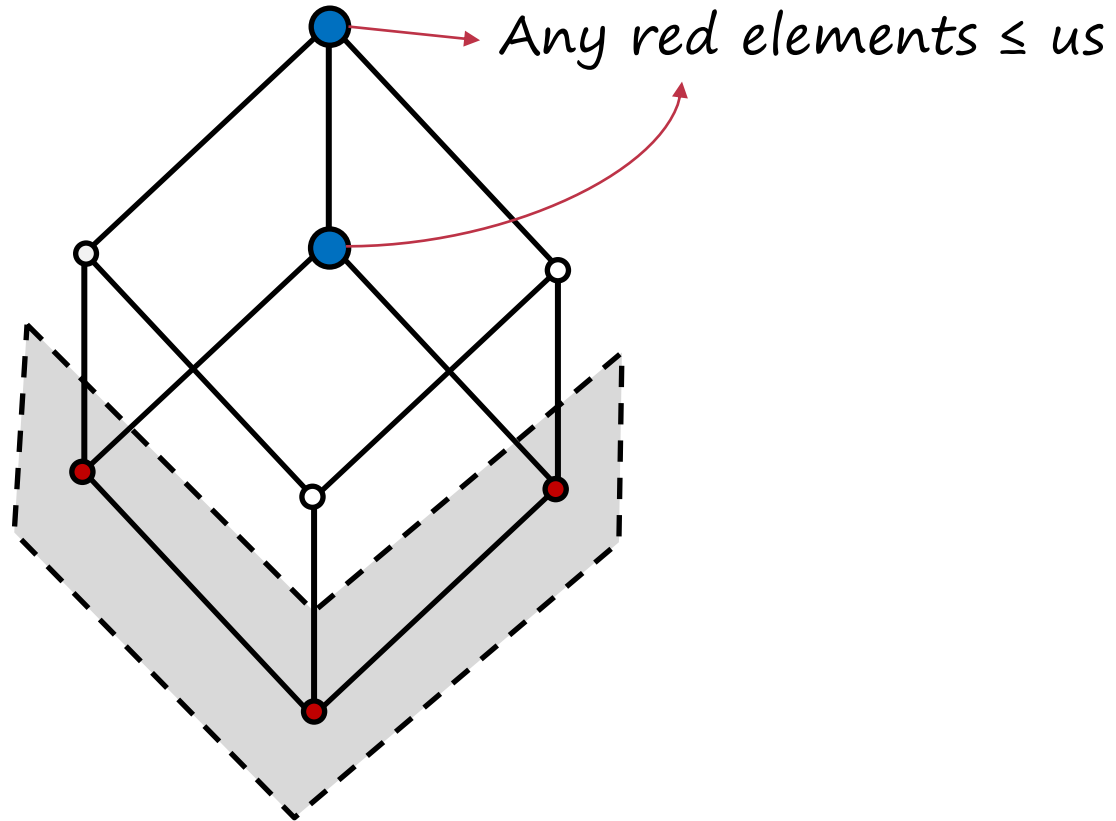
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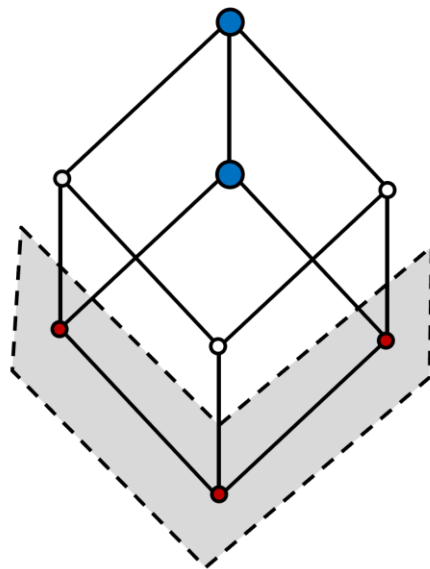
I can beats no one except myself.

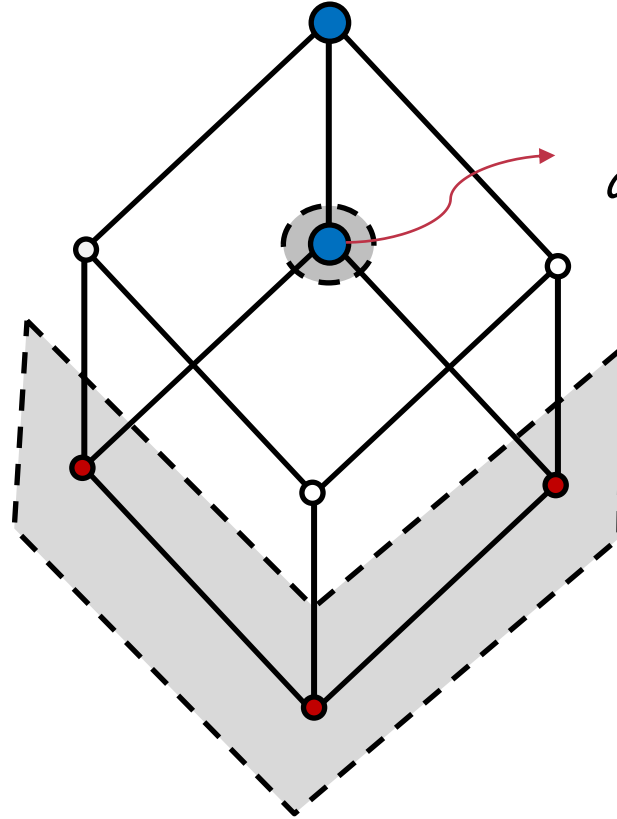


Upper Bound(上界)

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - If there exists $y \in A$ such that $\forall x \in B, x \leq y$, we call y the **upper bound** of B

y is upper bound $\Leftrightarrow y \in A \wedge (\forall x)(x \in B \rightarrow x \leq y)$

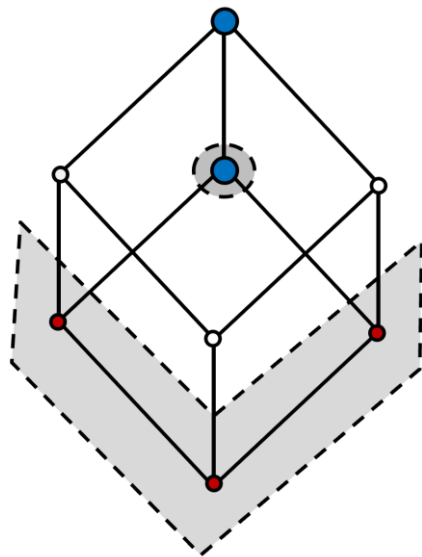




Any red elements $\leq m_e$
and $1 \leq$ any blue elements.

Supremum(上确界)

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - Let $C = \{y \mid y \text{ is the upper bound of } B\}$, then the minimum elements in C is the **supremum** of B .



Upper Bound and Supremum

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - If there exists $y \in A$ such that $\forall x \in B, x \leq y$, we call y the **upper bound (上界)** of B
$$y \text{ is upper bound} \Leftrightarrow y \in A \wedge (\forall x)(x \in B \rightarrow x \leq y)$$
 - Let $C = \{y \mid y \text{ is the upper bound of } B\}$, then the minimum elements in C is the **supremum (上确界)** of B .

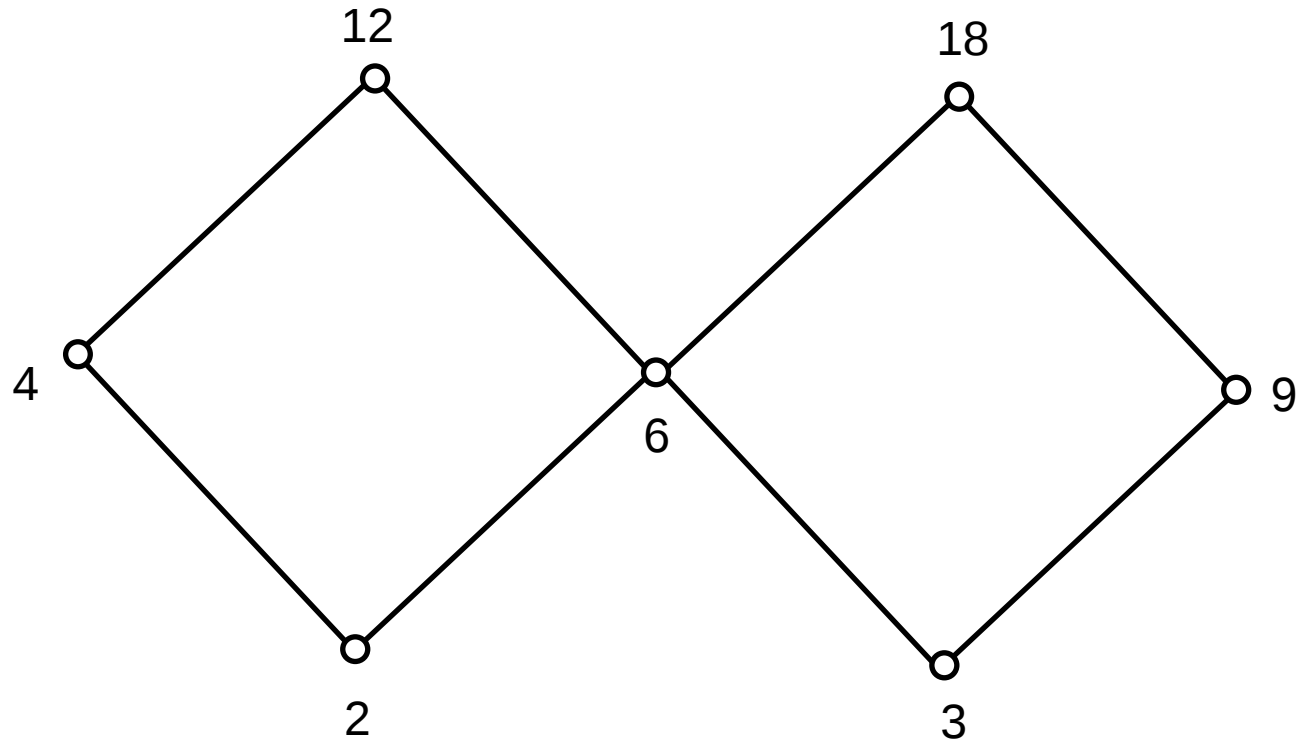
Lower Bound(下界) and Infimum(下确界)

- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - If there exists $x \in A$ such that $\forall y \in B, x \leq y$, we call x the **lower bound (下界)** of B
$$x \text{ is lower bound} \Leftrightarrow x \in A \wedge (\forall y)(y \in B \rightarrow x \leq y)$$
 - Let $C = \{x \mid x \text{ is the lower bound of } B\}$, then the maximum elements in C is the **infimum (下确界)** of B .

Bound

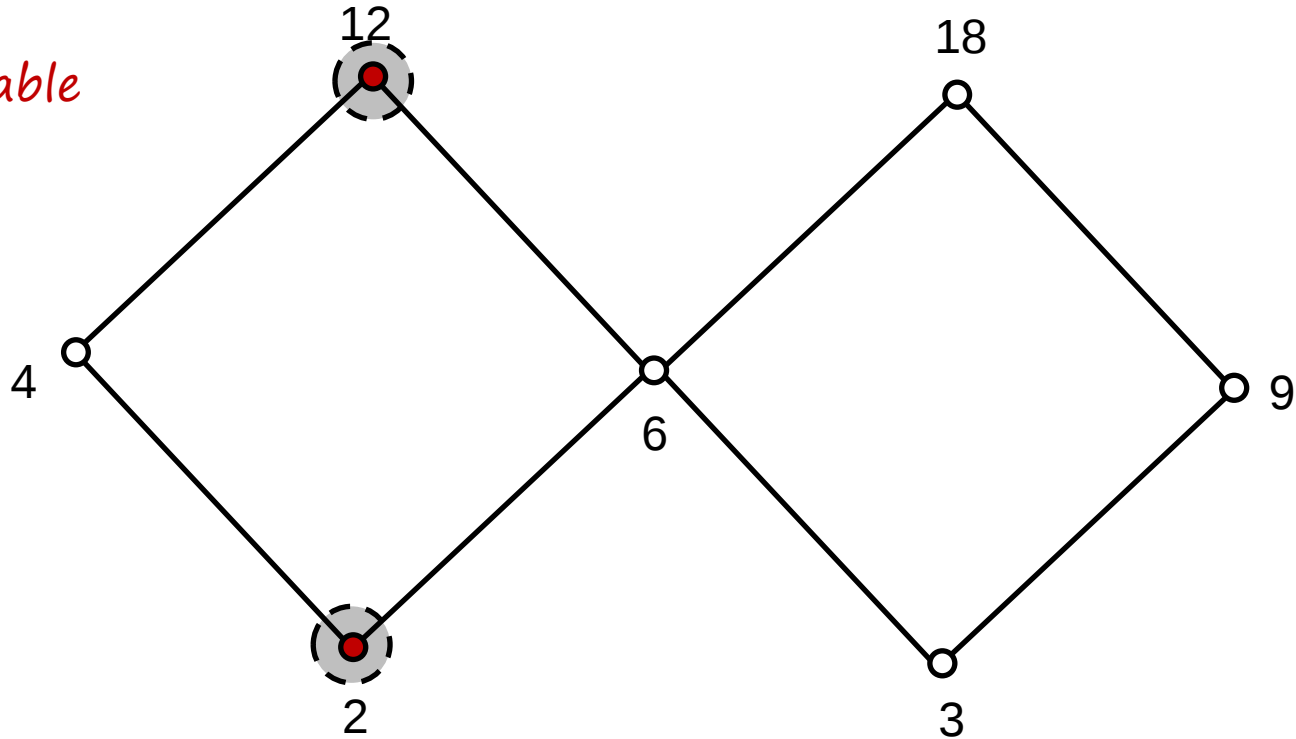
- For a poset $\langle A, \leq \rangle$, and $B \subseteq A$:
 - The upper (lower) bounds or supremum (infimum) of B may in or not in B .
 - The upper (lower) bounds of B may not exist, and may be not unique.
 - The supremum (infimum) of B may not exist, but it must be unique if exists.

$$A = \{2, 3, 4, 6, 9, 12, 18\}$$
$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$



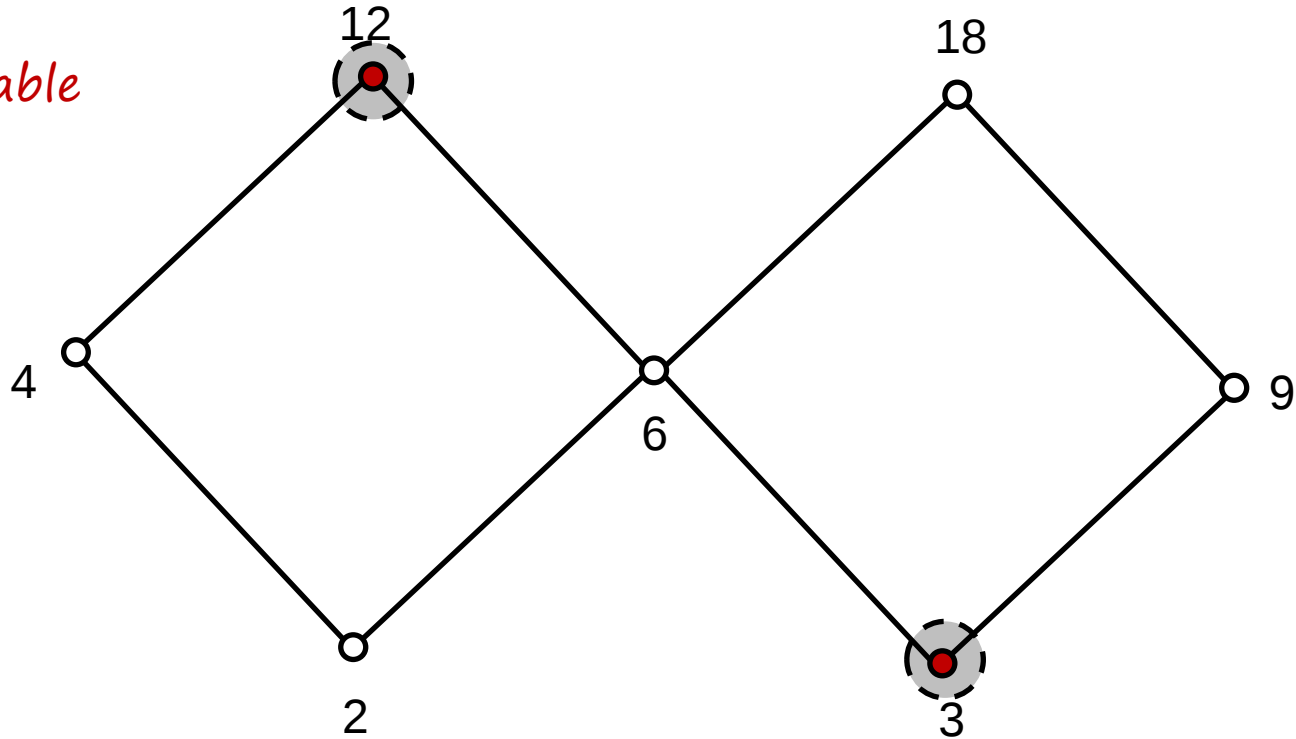
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Comparable



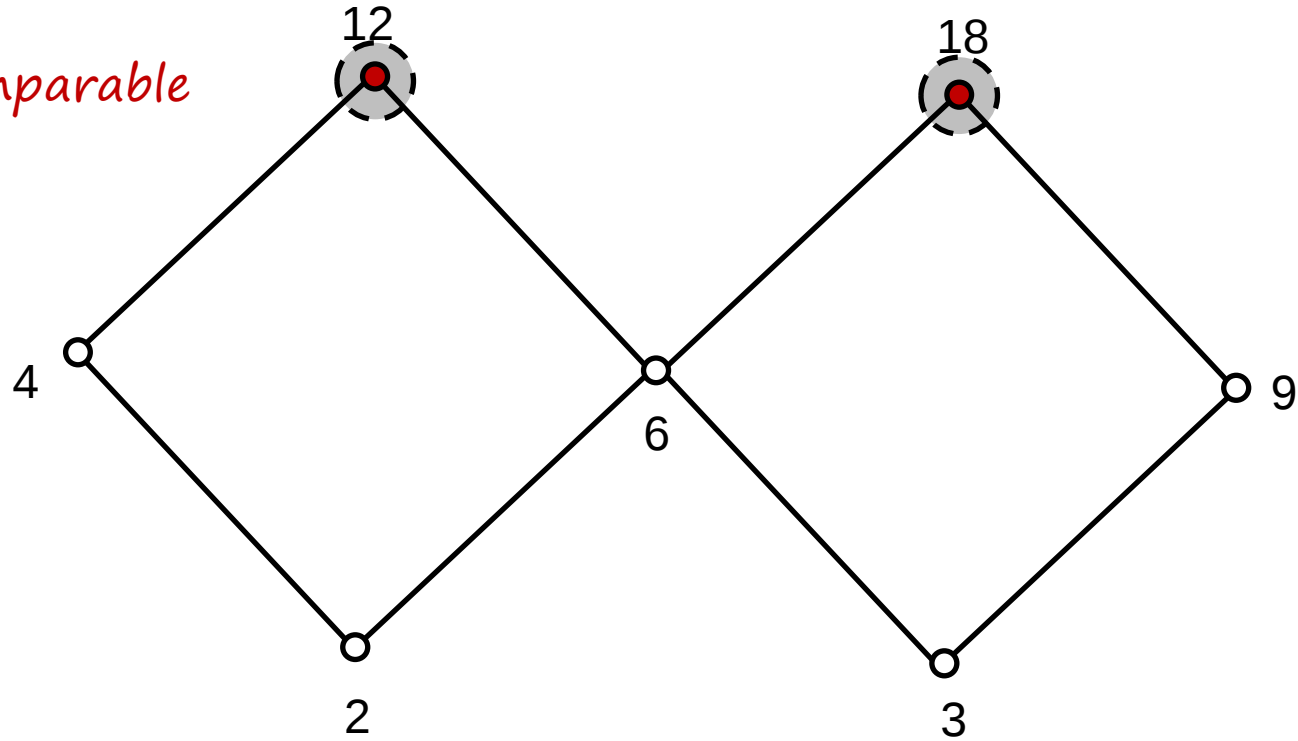
$$A = \{2, 3, 4, 6, 9, 12, 18\}$$
$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x|y\}$$

Comparable



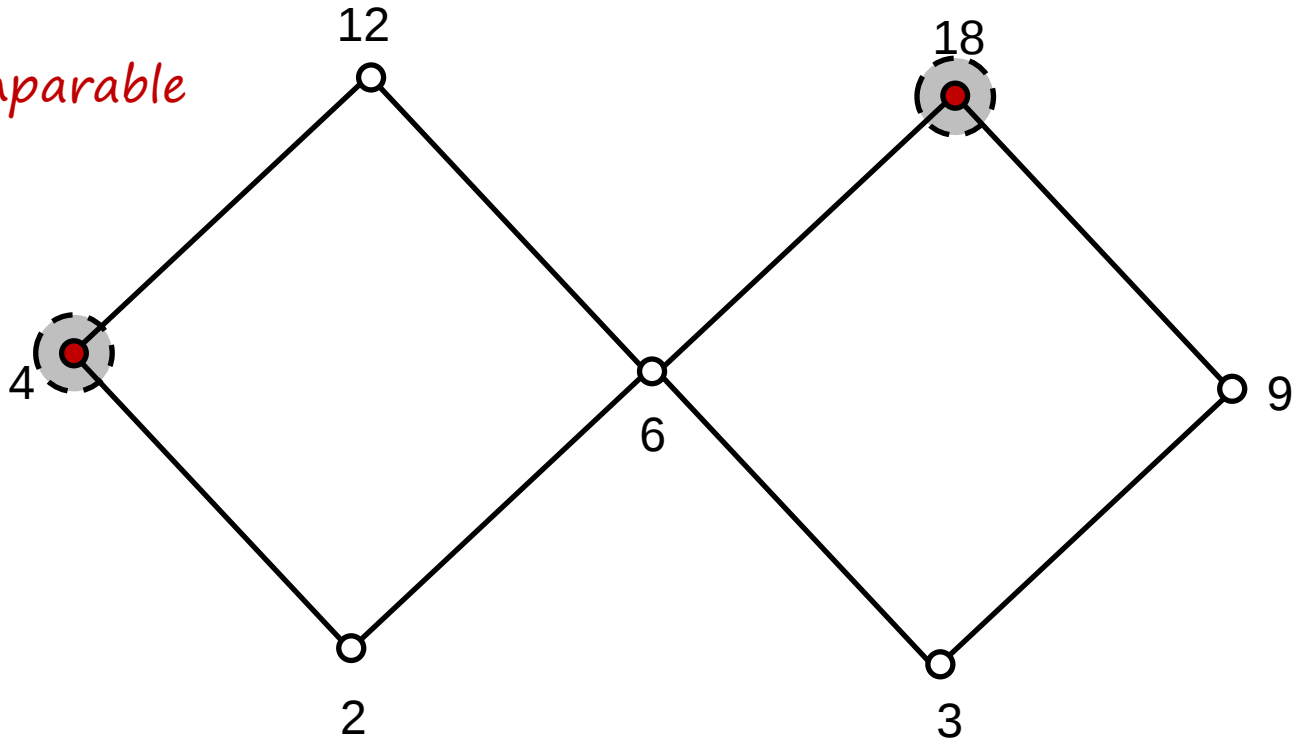
$$A = \{2, 3, 4, 6, 9, 12, 18\}$$
$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$

Not Comparable



$$A = \{2, 3, 4, 6, 9, 12, 18\}$$
$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$

Not Comparable



Total Order Relation(全序关系)

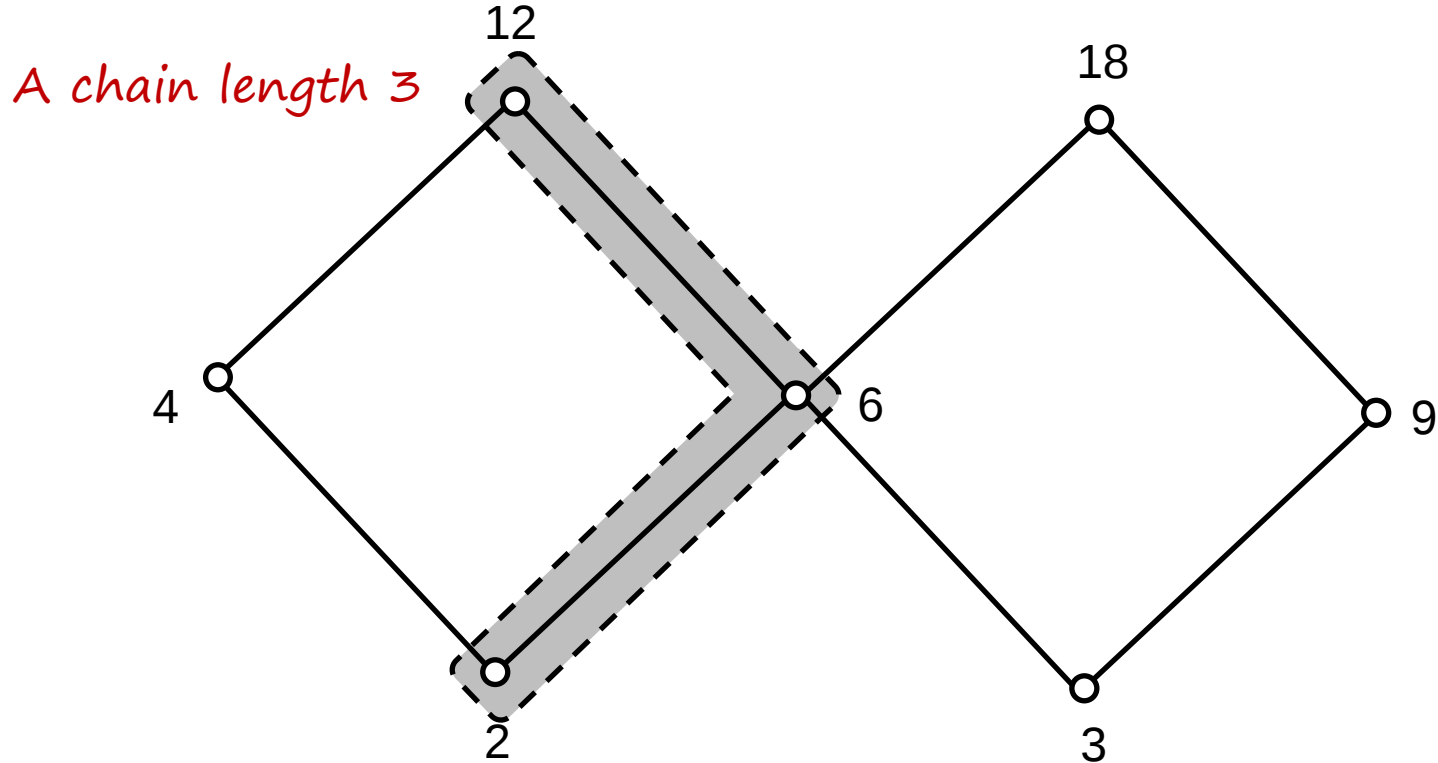
- For a poset $\langle A, \leq \rangle$:
 - For any $x \in A$ and $y \in A$, if $x \leq y$ or $y \leq x$, then we call x and y are comparable.
 - If for any $x \in A$ and $y \in A$, we have x and y are comparable, then we called $\leq$ is a **total order relation** on A , $\langle A, \leq \rangle$ is a total order set.
- $\langle \mathbb{N}, \leq \rangle$ is a total order set
- For a non-empty set A , $\langle \mathcal{P}(A), \subseteq \rangle$ is not a total order set.

Chain(链) and Anti-chain(反链)

- For a poset $\langle A, \leq \rangle$, $B \subseteq A$:
 - For any $x \in B$ and $y \in B$, if x and y are **comparable**, we call B is a **chain** on A , $|B|$ is the length of this chain.
 - For any $x \in B$ and $y \in B$, if x and y are **not comparable**, we call B is an **anti-chain** on A , $|B|$ is the length of this anti-chain.

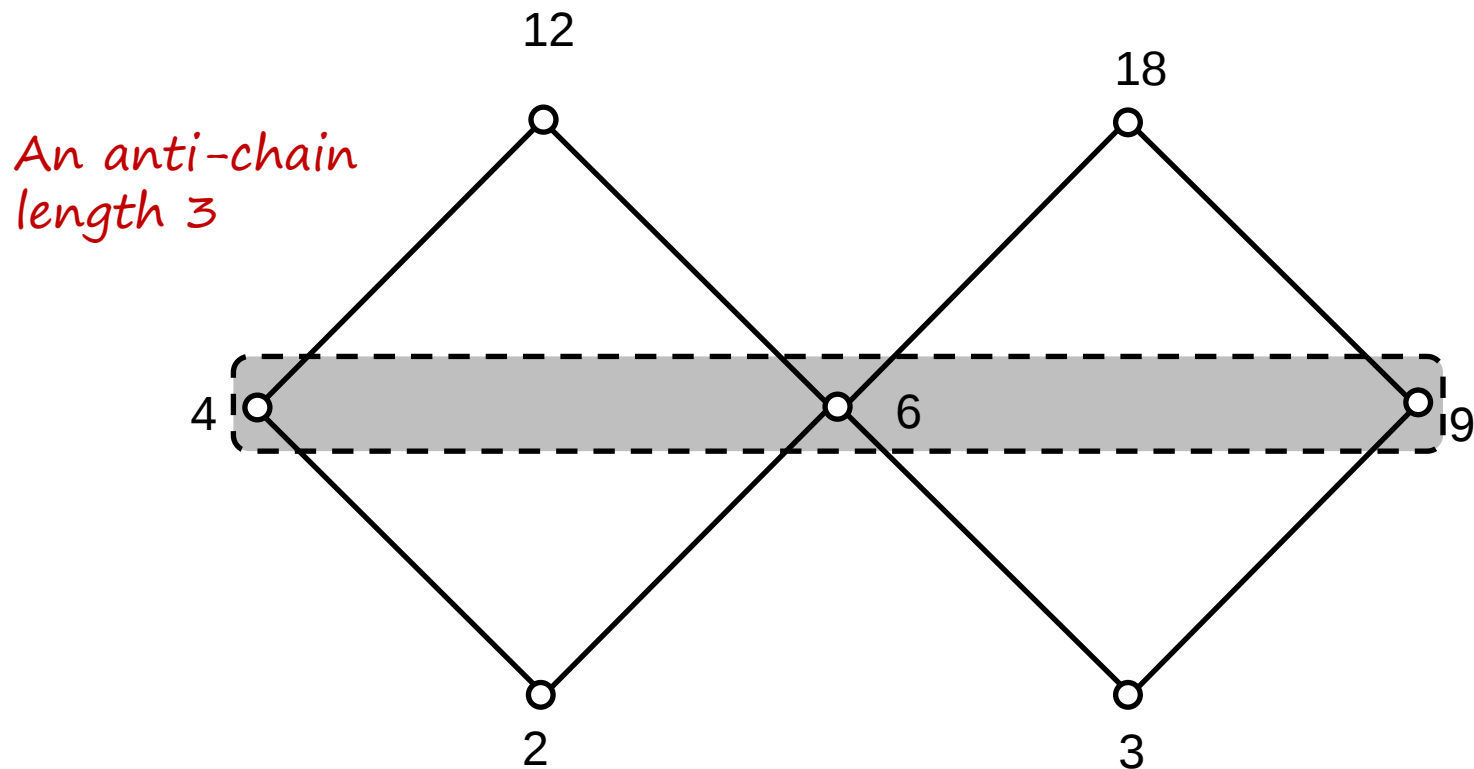
$$A = \{2,3,4,6,9,12,18\}$$

$$R = \{\langle x, y \rangle | x \in A \wedge y \in A \wedge x|y\}$$



$$A = \{2, 3, 4, 6, 9, 12, 18\}$$

$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$

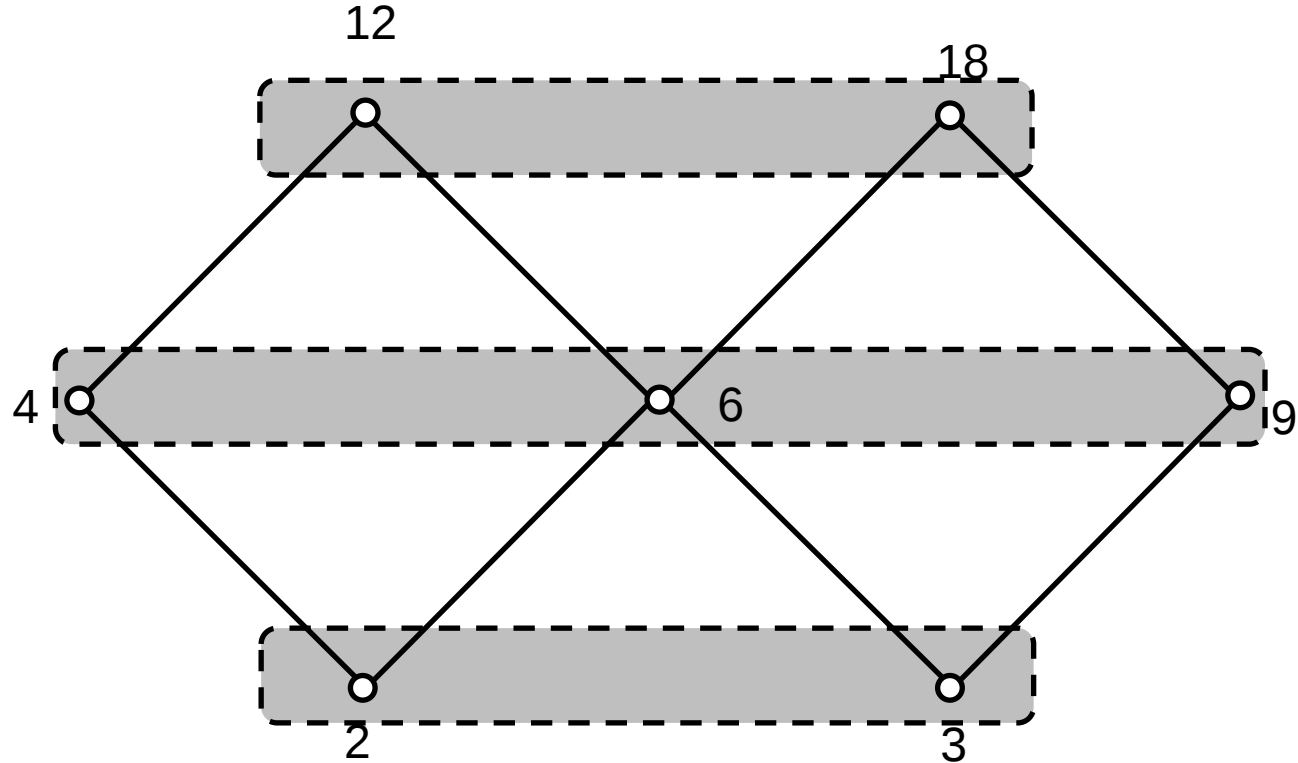


Decompose Poset

- For a poset $\langle A, \leq \rangle$, we can decompose A into non-disjoint anti-chain.

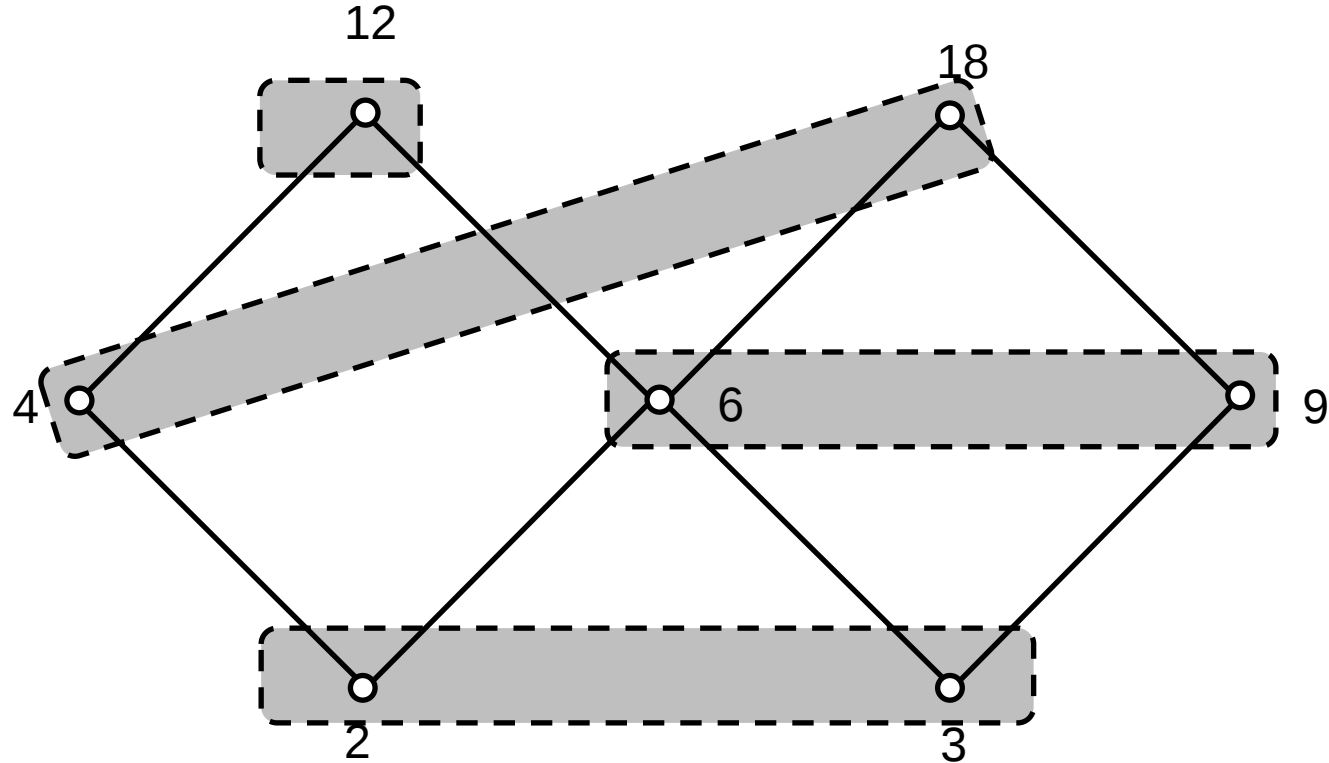
$$A = \{2,3,4,6,9,12,18\}$$

$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$



$$A = \{2, 3, 4, 6, 9, 12, 18\}$$

$$R = \{\langle x, y \rangle \mid x \in A \wedge y \in A \wedge x \mid y\}$$



Decompose Poset

- For a poset $\langle A, \leq \rangle$, we can decompose A into non-disjoint anti-chain.

For a poset $\langle A, \leq \rangle$, if the maximal length of a chain is n , then the decomposition of A has at least n anti-chains.

Proof:

Consider the longest chain which has length n , the n elements of this chain must be in different anti-chains in the decomposition (as any of two are comparable, they can not in a same anti-chain). So there's at least n anti-chains.

Well Order Relation(良序关系)

- For a poset $\langle A, \leq \rangle$, if any non-empty subset of A has the minimal elements, then we call $\leq$ is a **well order relation**, $\langle A, \leq \rangle$ is a well order set.
- $\langle \mathbb{N}, \leq \rangle$ is a well order set. $\langle \mathbb{Z}, \leq \rangle$ is not a well order set.

Well Order Relation

A well order set is a total order set.

- For a well-order set $\langle A, \leq \rangle$, $\forall x, y \in A$, the subset $\{x, y\}$ has a minimal elements, so $x \leq y$ or $y \leq x$. $\langle A, \leq \rangle$ is a total order set.

A finite total order set is a well order set.

Properties of Relations

<i>Reflexivity</i>	$(\forall x)(x \in A \rightarrow xRx)$
<i>Anti-reflexivity</i>	$(\forall x)(x \in A \rightarrow \neg xRx)$
<i>Symmetry</i>	$(\forall x)(\forall y)((x \in A \wedge y \in A \wedge xRy) \rightarrow yRx)$
<i>Anti-symmetry</i>	$(\forall x)(\forall y)((x \in A \wedge y \in A \wedge xRy \wedge yRx) \rightarrow x = y)$
<i>Transitivity</i>	$(\forall x)(\forall y)(\forall z)$ $((x \in A \wedge y \in A \wedge z \in A \wedge xRy \wedge yRz) \rightarrow xRz)$

Some relation may not good enough
to have those relations

But we can help them!



Some relation may not good enough
to have those relations

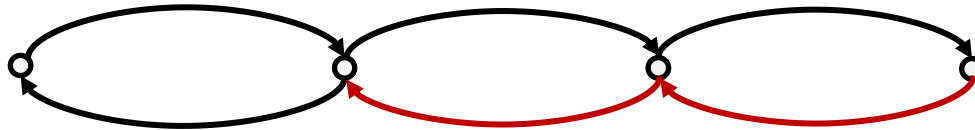
But we can help them!



Reflexivity

Some relation may not good enough
to have those relations

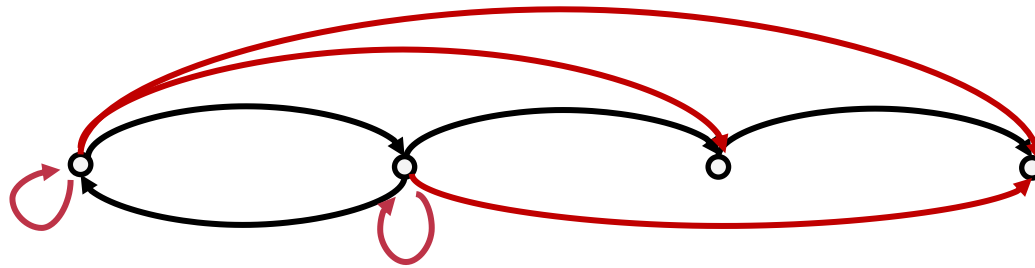
But we can help them!



Symmetry

Some relation may not good enough
to have those relations

But we can help them!



Transitivity

Reflexive Closure(自反闭包)

- For a relation R on non-empty set A , if there are another relation R' such that:

- R' is **reflexive**
- $R \subseteq R'$.
- For any **reflexive** relation R'' on A , $R \subseteq R'' \rightarrow R' \subseteq R''$.

R' is generated based on R

R' is the “smallest” relation to make R reflexive

Reflexive Closure(自反闭包)

- For a relation R on non-empty set A , if there are another relation R' such that:
 - R' is **reflexive**
 - $R \subseteq R'$.
 - For any **reflexive** relation R'' on A , $R \subseteq R'' \rightarrow R' \subseteq R''$.
- We call that R' is the **reflexive** closure of R , donated by $r(R)$

Symmetric Closure(对称闭包)

- For a relation R on non-empty set A , if there are another relation R' such that:
 - R' is **symmetric**
 - $R \subseteq R'$.
 - For any **symmetric** relation R'' on A , $R \subseteq R'' \rightarrow R' \subseteq R''$.
- We call that R' is the **symmetric** closure of R , donated by $s(R)$

Transitive Closure(传递闭包)

- For a relation R on non-empty set A , if there are another relation R' such that:
 - R' is **transitive**
 - $R \subseteq R'$.
 - For any **transitive** relation R'' on A , $R \subseteq R'' \rightarrow R' \subseteq R''$.
- We call that R' is the **transitive** closure of R , donated by $t(R)$

Closure

- For a relation R on non-empty set A
 - R is reflexive $\Leftrightarrow r(R) = R$
 - R is symmetric $\Leftrightarrow s(R) = R$
 - R is transitive $\Leftrightarrow t(R) = R$

Constructing Closure

For a relation R on non-empty set A , $r(R) = R \cup R^0$

- $R \cup R^0$ is reflexive as $\forall x \in A, \langle x, x \rangle \in R^0$
- Assume that R'' is reflexive and $R \subseteq R''$.
 - Because R'' is reflexive, $R^0 = I_A \subseteq R''$
 - $R \subseteq R'' \wedge R^0 \subseteq R'' \Rightarrow R \cup R^0 \subseteq R''$

Constructing Closure

For a relation R on non-empty set A , $s(R) = R \cup R^{-1}$

- $\langle x, y \rangle \in R \cup R^{-1} \Leftrightarrow \langle x, y \rangle \in R \vee \langle x, y \rangle \in R^{-1}$
 $\Rightarrow \langle y, x \rangle \in R^{-1} \vee \langle y, x \rangle \in R \Leftrightarrow \langle y, x \rangle \in R \cup R^{-1}$
- Assume that R'' is symmetric and $R \subseteq R''$.

$$\begin{array}{lcl} \langle x, y \rangle \in R \cup R^{-1} & \begin{array}{l} \nearrow \langle x, y \rangle \in R \Rightarrow \langle x, y \rangle \in R'' \\ \searrow \langle x, y \rangle \in R^{-1} \Rightarrow \langle y, x \rangle \in R \\ \quad \Rightarrow \langle y, x \rangle \in R'' \Rightarrow \langle x, y \rangle \in R'' \end{array} & \Rightarrow \langle x, y \rangle \in R'' \end{array}$$

So $R \cup R^{-1} \subseteq R''$

Constructing Closure

For a relation R on non-empty set A , $|A| = n$,

$$t(R) = R \cup R^2 \dots \cup R^n$$

Lemma

Let R be a relation on a set A . There is a path of length n ($n \in \mathbb{N}^+$) from a to b if and only if $\langle a, b \rangle \in R^n$

Proof:

By definition, there is a path from a to b of length 1 if and only if $\langle a, b \rangle \in R$, so the lemma is true when $n = 1$.

Assume that the lemma is true when $n = k$ ($k \in \mathbb{N}^+$). For $n = k + 1$

There is a path of length $k + 1$ from a to b

$\Leftrightarrow$ There exists c such that there's a path of length 1 from a to c and a path of length k from c to b

$\Leftrightarrow (\exists c) (\langle a, c \rangle \in R \wedge \langle c, b \rangle \in R^k) \Leftrightarrow \langle a, b \rangle \in R^{k+1}$

So the lemma is true when $n = k + 1$. Q.E.D

Connectivity Relation(连接关系)

- Let R be a relation on a set A . The **connectivity relation** R^+ consists of the pairs $\langle a, b \rangle$ such that there is a path of length at least one from a to b in R .
- By definition:

$$R^+ = R \cup R^2 \cup R^3 \cup \dots$$

- But we only need to consider the path of length as most $|A|$, assume that $|A| = n$

$$R^+ = R \cup R^2 \cup R^3 \cup \dots \cup R^n$$

Constructing Closure

For a relation R on non-empty set A , $|A| = n$,

$$t(R) = R^+ = R \cup R^2 \dots \cup R^n$$

Proof:

- $R \subseteq R^+$ by definition.
- **R^+ is transitive:** For $\langle x, y \rangle \in R^+$ and $\langle y, z \rangle \in R^+$, it means there are paths from x to y and y to z , so there's a path from x to z . Then $\langle x, z \rangle \in R^+$.
- Assume R'' is transitive and $R \subseteq R''$.
 - For any $\langle x, y \rangle \in R^+$, it means that there's a path of length k ($k \in \mathbb{N}^+$) from x to y ,
 - Let the path be $x, p_1, \dots, p_{k-1}, y$, so $\langle x, p_1 \rangle, \langle p_1, p_2 \rangle \dots \langle p_{k-1}, y \rangle \in R$.
 - Because $R \subseteq R''$, $\langle x, p_1 \rangle, \langle p_1, p_2 \rangle \dots \langle p_{k-1}, y \rangle \in R''$.
 - According to the transitivity of R'' , we have $\langle x, y \rangle \in R''$.
 - So $R^+ \subseteq R''$.

Exercise

- $A = \{a, b, c\}$, $R = \{\langle a, b \rangle, \langle b, c \rangle, \langle c, a \rangle\}$, find $r(R)$, $s(R)$ and $t(R)$.

Exercise

- $A = \{a, b, c\}$, $R = \{\langle a, b \rangle, \langle b, c \rangle, \langle c, a \rangle\}$, find $r(R)$, $s(R)$ and $t(R)$.
- Answer:
 - $r(R) = R \cup R^0 = \{\langle a, a \rangle, \langle a, b \rangle, \langle b, b \rangle, \langle b, c \rangle, \langle c, a \rangle, \langle c, c \rangle\}$
 - $s(R) = R \cup R^{-1} = \{\langle a, b \rangle, \langle a, c \rangle, \langle b, a \rangle, \langle b, c \rangle, \langle c, a \rangle, \langle c, b \rangle\}$
 - $R^2 = \{\langle a, c \rangle, \langle b, a \rangle, \langle c, b \rangle\}$,
 - $R^3 = \{\langle a, a \rangle, \langle b, b \rangle, \langle c, c \rangle\}$
 - So $t(R) = R \cup R^2 \cup R^3 =$
 $\{\langle a, a \rangle, \langle a, b \rangle, \langle a, c \rangle, \langle b, a \rangle, \langle b, b \rangle, \langle b, c \rangle, \langle c, a \rangle, \langle c, b \rangle, \langle c, c \rangle\}$



Next

Capture the structure of a problem (continued)

- Warshall Algorithm

Other fundamental tools.

- Functions