Discrete Mathematics in Computer Science

B6. Equivalence and Order Relations

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B6.1 Equivalence Relations

Relations: Recap

- A relation over sets $S_1, \dots, S_n$ is a set $R \subseteq S_1 \times \dots \times S_n$.
- Possible properties of homogeneous relations R over S:
  - reflexive: $(x, x) \in R$ for all $x \in S$
  - irreflexive: $(x, x) \notin R$ for all $x \in S$
  - symmetric: $(x, y) \in R$ iff $(y, x) \in R$
  - asymmetric: if $(x, y) \in R$ then $(y, x) \notin R$
  - antisymmetric: if $(x, y) \in R$ then $(y, x) \notin R$ or $x = y$
  - transitive: if $(x, y) \in R$ and $(y, z) \in R$ then $(x, z) \in R$

Motivation

- Think of any attribute that two objects can have in common, e. g. their color.
- We could place the objects into distinct “buckets”, e. g. one bucket for each color.
- We also can define a relation $\sim$ such that $x \sim y$ iff x and y share the attribute, e. g.have the same color.
- Would this relation be
  - reflexive?
  - irreflexive?
  - symmetric?
  - asymmetric?
  - antisymmetric?
  - transitive?

Equivalence Relation

Definition (Equivalence Relation)
A binary relation $\sim$ over set S is an equivalence relation if $\sim$ is reflexive, symmetric and transitive.

Examples:

- $\{(x, y) \mid x \text{ and } y \text{ have the same place of origin}\}$ over the set of all Swiss citizens
- $\{(x, y) \mid x \text{ and } y \text{ have the same parity}\}$ over $\mathbb{N}_0$
- $\{(1,1),(1,4),(1,5),(4,1),(4,4),(4,5),(5,1),(5,4),(5,5),$ $(2,2),(2,3),(3,2),(3,3)\}$ over $\{1,2,\dots,5\}$

Is this definition indeed what we want?
Does it allow us to partition the objects into buckets (e. g. one “bucket” for all objects that share a specific color)?

Equivalence Classes

Definition (equivalence class)
Let $\sim$ be an equivalence relation over set S.
For any $x \in S$, the equivalence class of x is the set

$$[x]_\sim = \{y \in S \mid x \sim y\}.$$

Consider
$\sim = \{(1,1),(1,4),(1,5),(4,1),(4,4),(4,5),(5,1),(5,4),(5,5),$ $(2,2),(2,3),(3,2),(3,3)\}$
over set $\{1,2,\dots,5\}$.

$[4]_\sim =$

Equivalence Classes: Properties

Let $\sim$ be an equivalence relation over set S and $E = \{[x]_\sim \mid x \in S\}$ the set of all equivalence classes.

- Every element of S is in some equivalence class in E.
- Every element of S is in at most one equivalence class in E.
  $\rightsquigarrow$ homework assignment

$\Rightarrow$ Equivalence relations induce partitions (not covered in this course).

B6.2 Order Relations

Order Relations

- We now consider other combinations of properties, that allow us to describe a consistent order of the objects.
- "Number x is not larger than number y."
  "Set S is a subset of set T."
  "Jerry runs at least as fast as Tom."
  "Pasta tastes better than Potatoes."

Partial Orders

- We begin with partial orders.
- Example partial order relations are $\leq$ over $\mathbb{N}_0$ or $\subseteq$ for sets.
- Are these relations
  - reflexive?
  - irreflexive?
  - symmetric?
  - asymmetric?
  - antisymmetric?
  - transitive?

Partial Orders – Definition

Definition (Partial order)

A binary relation $\preceq$ over set S is a partial order if $\preceq$ is reflexive, antisymmetric and transitive.

Which of these relations are partial orders?

- strict subset relation $\subset$ for sets
- not-less-than relation $\geq$ over $\mathbb{N}_0$
- $R = \{(a, a), (a, b), (b, b), (b, c), (c, c)\}$ over $\{a, b, c\}$

Least and Greatest Element

Definition (Least and greatest element)

Let $\preceq$ be a partial order over set S.

An element $x \in S$ is the least element of S if for all $y \in S$ it holds that $x \preceq y$.

It is the greatest element of S if for all $y \in S$, $y \preceq x$.

- Is there a least/greatest element? Which one?
  - $S = \{1, 2, 3\}$ and $\preceq\ = \{(x, y) \mid x, y \in S \text{ and } x \leq y\}$
  - relation $\leq$ over $\mathbb{N}_0$
  - relation $\leq$ over $\mathbb{Z}$
- Why can we say the least element instead of a least element?

Uniqueness of Least Element

Theorem

Let $\preceq$ be a partial order over set S.
If S contains a least element, it contains exactly one least element.

Proof.

By contradiction: Assume x, y are least elements of S with $x \neq y$.
Since x is a least element, $x \preceq y$ is true.
Since y is a least element, $y \preceq x$ is true.
As a partial order is antisymmetric, this implies that $x = y$. ↯ □

Analogously: If there is a greatest element then is unique.

Minimal and Maximal Elements

Definition (Minimal/Maximal element of a set)

Let $\preceq$ be a partial order over set S.
An element $x \in S$ is a minimal element of S if there is no $y \in S$ with $y \preceq x$ and $x \neq y$.

An element $x \in S$ is a maximal element of S if there is no $y \in S$ with $x \preceq y$ and $x \neq y$.

A set can have several minimal elements and no least element.
Example?

Total Orders

- Relations $\leq$ over $\mathbb{N}_0$ and $\subseteq$ for sets are partial orders.
- Can we compare every object against every object?
  - For all $x, y \in \mathbb{N}_0$ it holds that $x \leq y$ or that $y \leq x$ (or both).
  - $\{1, 2\} \not\subseteq \{2, 3\}$ and $\{2, 3\} \not\subseteq \{1, 2\}$
- Relation $\leq$ is a total order, relation $\subseteq$ is not.

Total Order – Definition

Definition (Total relation)
A binary relation R over set S is total (or connex)
if for all $x, y \in S$ at least one of xRy or yRx is true.

Definition (Total order)
A binary relation is a total order if it is total and a partial order.

Strict Orders

- A partial order is reflexive, antisymmetric and transitive.
- We now consider strict orders.
- Example strict order relations are $<$ over $\mathbb{N}_0$ or $\subset$ for sets.
- Are these relations
  - reflexive?
  - irreflexive?
  - symmetric?
  - asymmetric?
  - antisymmetric?
  - transitive?

Strict Orders – Definition

Definition (Strict order)
A binary relation $\prec$ over set S is a strict order
if $\prec$ is irreflexive, asymmetric and transitive.

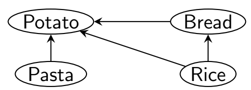
Which of these relations are strict orders?

- subset relation $\subseteq$ for sets
- strict superset relation $\supset$ for sets

Can a relation be both, a partial order and a strict order?

Strict Total Orders

- As partial orders, a strict order does not automatically allow us to rank arbitrary two objects against each other.
- Example 1 (personal preferences):
  - "Pasta tastes better than potato."
  - "Rice tastes better than bread."
  - "Bread tastes better than potato."
  - "Rice tastes better than potato."



  - This definition of "tastes better than" is a strict order.
  - No ranking of pasta against rice or of pasta against bread.
- Example 2: $\subset$ relation for sets
- It doesn't work to simply require that the strict order is total. Why?

Strict Total Orders – Definition

Definition (Trichotomy)

A binary relation R over set S is trichotomous if for all $x, y \in S$ exactly one of xRy, yRx or $x = y$ is true.

Definition (Strict total order)

A binary relation $\prec$ over S is a strict total order if $\prec$ is trichotomous and a strict order.

A strict total order completely ranks the elements of set S.

Example: $<$ relation over $\mathbb{N}_0$ gives the standard ordering $0, 1, 2, 3, \ldots$ of natural numbers.

Special Elements

Special elements are defined almost as for partial orders:

Definition (Least/greatest/minimal/maximal element of a set)

Let $\prec$ be a strict order over set S.

An element $x \in S$ is the least element of S if for all $y \in S$ where $y \neq x$ it holds that $x \prec y$.

It is the greatest element of S if for all $y \in S$ where $y \neq x$, $y \prec x$.

Element $x \in S$ is a minimal element of S if there is no $y \in S$ with $y \prec x$.

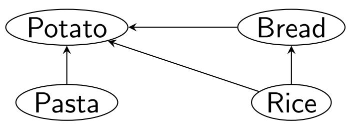
It is a maximal element of S if there is no $y \in S$ with $x \prec y$.

Special Elements – Example

Consider again the previous example:

$S = \{\text{Pasta}, \text{Potato}, \text{Bread}, \text{Rice}\}$

$\prec \; = \{(\text{Pasta}, \text{Potato}), (\text{Bread}, \text{Potato}), (\text{Rice}, \text{Potato}), (\text{Rice}, \text{Bread})\}$



Is there a least and a greatest element?
Which elements are maximal or minimal?

Summary

- An equivalence relation is reflexive, symmetric and transitive.
- A partial order $x \preceq y$ is reflexive, antisymmetric and transitive.
  - If x is the greatest element of a set S, it is greater than every element: for all $y \in S$ it holds that $y \preceq x$.
  - If x is a maximal element of set S then it is not smaller than any other element y: there is no $y \in S$ with $x \preceq y$ and $x \neq y$.
  - A total order is a partial order without incomparable objects.
- A strict order is irreflexive, asymmetric and transitive.
  - Strict total orders and special elements are analogously defined as for partial orders but with a special treatment of equal elements.