Foundations of Programming Languages and Software Engineering

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Overview

- Basics
  - Relations
  - Induction

- Terms and All That
  - Syntax
  - Semantics
Binary Relations

**Definition**

- A binary relation on sets $M_1$ and $M_2$ is a set $R \subseteq M_1 \times M_2$ of pairs of elements from $M_1$ and $M_2$, respectively. If $M_1 = M_2 = M$, we simply call $R$ a binary relation on $M$.

- We say that $m_1 \in M_1$ and $m_2 \in M_2$ are related by $R$ iff $(m_1, m_2) \in R$.

- We often write $m_1 \mathrel{R} m_2$ instead of $(m_1, m_2) \in R$. 

Properties of Binary Relations (1)

Definition

Let $R$ be a binary relation on $M$.

- $R$ is **reflexive** iff $m \, R \, m$ for all $m \in M$.
- $R$ is **symmetric** iff $m \, R \, m'$ implies $m' \, R \, m$.
- $R$ is **transitive** iff $m_1 \, R \, m_2$ and $m_2 \, R \, m_3$ imply $m_1 \, R \, m_3$.
- $R$ is an **equivalence relation** iff it is reflexive, symmetric, and transitive.
Properties of Binary Relations (2)

Definition

Let $R$ be a binary relation on $M$.

- The **reflexive closure** of $R$ is the smallest reflexive relation $R'$ such that $R \subseteq R'$.

- The **transitive closure** of $R$ is the smallest transitive relation $R'$ such that $R \subseteq R'$. It is often written $R^+$.  

- The **reflexive and transitive closure** of $R$ is the smallest reflexive and transitive relation $R'$ such that $R \subseteq R'$. It is often written $R^*$.  

Suppose $P$ is some property on natural numbers.

### Principle of ordinary induction on natural numbers

If $P(0)$

and, for all $i \in \mathbb{N}$, $P(i)$ implies $P(i + 1)$,

then $P(n)$ holds for all $n \in \mathbb{N}$.

The assumption "$P(i)$" in the induction step is called the induction hypothesis (IH for short).
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**Principle of complete induction on natural numbers**

If, for each $n \in \mathbb{N}$,

given $P(i)$ for all $i < n$

we can show $P(n)$,

then $P(n)$ holds for all $n \in \mathbb{N}$.
Lemma
For all $n \in \mathbb{N}$, $\sum_{i=1}^{n}(2i - 1) = n^2$.

**Proof.** The proof is by ordinary induction on $n$.

- If $n = 0$, then both sides of the equation are 0.
- Suppose the lemma holds for some $k \in \mathbb{N}$. We then have:

  $$\sum_{i=1}^{k+1}(2i - 1) = \sum_{i=1}^{k}(2i - 1) + (2(k + 1) - 1)$$

  $$(\text{IH})$$

  $$\equiv k^2 + 2k + 1$$

  $$= (k + 1)^2$$
Definition

A signature $\Sigma$ is a set of function symbols, where each $f \in \Sigma$ is associated with a natural number $n$ called the arity of $f$.

$\Sigma^{(n)}$ denotes the set of all $n$-ary elements of $\Sigma$.

The elements of $\Sigma^{(0)}$ are also called constant symbols.
Example

Signature $\Sigma_{prop}$ for propositional logic

$$\Sigma_{prop} = \{ T^{(0)}, F^{(0)}, \neg^{(1)}, \land^{(2)}, \lor^{(2)} \}$$

$$\Sigma_{prop}^{(0)} = \{ T, F \}$$

$$\Sigma_{prop}^{(1)} = \{ \neg \}$$

$$\Sigma_{prop}^{(2)} = \{ \land, \lor \}$$
Terms

**Definition**

Let $\Sigma$ be a signature and $X$ a set of variables such that $\Sigma \cap X = \emptyset$. The set $T(\Sigma, X)$ of all $\Sigma$-terms over $X$ is inductively defined as

- $X \subseteq T(\Sigma, X)$,
- for all $n \in \mathbb{N}$, all $f \in \Sigma^{(n)}$, and all $t_1, \ldots, t_n \in T(\Sigma, X)$, we have $f(t_1, \ldots, t_n) \in T(\Sigma, X)$

**Note:**

- For a constant symbol $f \in \Sigma^{(0)}$, we often write the term $f(\text)\text$ as $f$.
- From now on, we leave the variable set $X = \{x, x_1, x_2, \ldots, y, y_1, y_2, \ldots, z, z_1, z_2 \ldots\}$ implicit.
Example

Suppose $\Sigma = \Sigma_{prop}$. Then

$$\lor(\neg(x_{42}), \land(T, x_3)) \in T(\Sigma, X)$$
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**Alternative notation**

Infix notation (with implicit operator precedence order):

$$\neg x_{42} \lor T \land x_{3}$$
In our current view, equality of terms means syntactic equality.

Therefore, if \( t, s \in T(\Sigma, X) \) and \( t = f(t_1, \ldots, t_n) \) and \( s = g(s_1, \ldots, s_m) \), and \( t = s \), then \( f = g \), \( n = m \), and \( t_i = s_i \) for all \( i \in \{1, \ldots, n\} \).
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Later, we consider a kind of semantic equality: \( + (1, 3) \) might be equal to \( + (2, 2) \).
Definition
Suppose $t \in T(\Sigma, X)$.

- The set of positions of term $t$ is a set $\text{Pos}(t)$ of strings over the alphabet of natural numbers. It is inductively defined as follows:
  - If $t = x \in X$, then $\text{Pos}(t) := \{\epsilon\}$
  - If $t = f(t_1, ..., t_n)$, then
    \[
    \text{Pos}(t) := \{\epsilon\} \cup \bigcup_{i=1}^{n}\{ip \mid p \in \text{Pos}(t_i)\}
    \]
- The position $\epsilon$ is called the root position of $t$, the function or variable at this position is called the root symbol of $t$.
- The size $|t|$ of $t$ is the cardinality of $\text{Pos}(t)$. 

Positions and Size of Terms
**Definition (Subterm)**

For \( p \in Pos(t) \), the **subterm** of \( t \) at position \( p \), denoted by \( t|_p \), is defined by induction on the length of \( p \):

\[
\begin{align*}
    t|_\epsilon & := t \\
    f(t_1, \ldots, t_n)|_{ip} & := t_i|_p
\end{align*}
\]

\( (ip \in Pos(t) \) implies that \( t = f(t_1, \ldots, t_n) \) with \( 0 \leq i \leq n \).)
Subterms and Replacing

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**Definition (Replacing)**

For \( p \in Pos(t) \), we denote by \( t[s]_p \) the term that is obtained from \( t \) by replacing the subterm at position \( p \) by \( s \), i.e.

\[
\begin{align*}
  t[s]_\epsilon & := s \\
  f(t_1, \ldots, t_n)[s]_{ip} & := f(t_1, \ldots, t_i[s]_p, \ldots, t_n)
\end{align*}
\]
Examples

Suppose $t = \lor(\neg(x_{42}), \land(T, x_3))$

- $\text{Pos}(t) = \{\epsilon, 1, 11, 2, 21, 22\}$
- $|t| = 6$ (number of nodes in the tree)
- $t|_2 = \land(T, x_3)$
- $t[\neg(F)]|_2 = \lor(\neg(x_{42}), \neg(F))$
An Induction Principle for Terms

To prove that a property $P$ holds for all $t \in T(\Sigma, X)$, we have to show the following properties:

- **Base case**
  
  $P(x)$ holds for all $x \in X$ and $P(f)$ holds for all $f \in \Sigma^{(0)}$.

- **Induction step**
  
  Suppose $n > 0$, $f \in \Sigma^{(n)}$, and $t_1, \ldots, t_n \in T(\Sigma, X)$. Then $P(f(t_1, \ldots, t_n))$ holds assuming $P(t_1), \ldots, P(t_n)$. 
Example for Term Induction

Lemma
For all terms \( t \), the set \( Pos(t) \) is prefix closed, i.e. if \( wv \in Pos(t) \) then \( w \in Pos(t) \).
Substitutions

Definition

Let $\Sigma$ be a signature.

- A $T(\Sigma, X)$-substitution is a function $\sigma : X \rightarrow T(\Sigma, X)$ such that $\sigma(x) \neq x$ for only finitely many $x$s.
- The domain of $\sigma$ is $\text{Dom}(\sigma) := \{x \in X \mid \sigma(x) \neq x\}$.
- We write $\{x_1 \mapsto t_1, \ldots, x_n \mapsto t_n\}$ for a substitution that maps $x_i$ to $t_i$ and has domain $\text{Dom}(\sigma) = \{x_1, \ldots, x_n\}$.
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- A $T(\Sigma, X)$-substitution $\sigma$ is extended to a mapping $\sigma : T(\Sigma, X) \rightarrow T(\Sigma, X)$ on arbitrary terms as follows: $\sigma(f(t_1, \ldots, t_n)) := f(\sigma(t_1), \ldots, \sigma(t_n))$.
Substitutions. Explanation

Note

Applying the extension of a substitution $\sigma$ to a term simultaneously replaces all occurrences of a variable by their respective $\sigma$-image.
Example

A substitution on terms from $T(\Sigma_{\text{prop}}, X)$

\[
\Sigma = \Sigma_{\text{prop}} \\
\sigma = \{x \mapsto \neg z, y \mapsto x \lor \text{F}\} \\
t = x \lor y \land z \\
\sigma(t) = \neg z \lor (x \lor \text{F}) \land z
\]
Composing Substitutions

**Definition**

The composition $\sigma \tau$ of two substitutions $\sigma$ and $\tau$ is defined as $\sigma \tau(x) := \sigma(\tau(x))$.

**Lemma**

Composition of substitutions is an associative operation where the identity substitution is the unit.
Definition

Let $\Sigma$ be a signature. A $\Sigma$-algebra $\mathcal{A} = (A, \mathcal{J})$ consists of

- a carrier set $A$, and
- an interpretation function $\mathcal{J}$ that associates with each function symbol $f \in \Sigma^{(n)}$ a function $\mathcal{J}(f) : A^n \to A$. 
The $\Sigma_{prop}$-Algebra $A_{prop}$

$$A_{prop} = (A_{prop}, I_{prop})$$

$$A_{prop} = \{0, 1\}$$

$$I_{prop}(F) = 0$$

$$I_{prop}(T) = 1$$

$$I_{prop}(\neg)(x) = 1 - x$$

$$I_{prop}(\lor)(x, y) = \max(x, y)$$

$$I_{prop}(\land)(x, y) = \min(x, y)$$
Let $\mathcal{A} = (A, \mathcal{J})$ be a $\Sigma$-algebra.

- A **variable assignment** is a function $\alpha : X \rightarrow A$ that assigns every variable a value in the carrier set.

- Given a variable assignment $\alpha$, the **interpretation function** $\mathcal{J}$ is extended to a function on terms, $\mathcal{J}_\alpha : T(\Sigma, X) \rightarrow A$, as follows:
  
  $\mathcal{J}_\alpha(x) = \alpha(x)$  \hspace{1cm} (x \in X)

  $\mathcal{J}_\alpha(f(t_1, \ldots, t_n)) = \mathcal{J}(f)(\mathcal{J}_\alpha(t_1), \ldots, \mathcal{J}_\alpha(t_n))$

- The restriction of $\mathcal{J}_\alpha$ to variable free-terms, $\mathcal{J}_\alpha : T(\Sigma, \emptyset) \rightarrow A$, is usually denoted by $\mathcal{J}$ since the $\alpha$ does not matter.
Example

Interpretation of $\bigvee (\neg (x_{42}), \land (T, x_3)) \in T(\Sigma_{prop}, X)$

Suppose $\alpha : X \rightarrow A_{prop}$ is a function such that

\[
\alpha(x_{42}) = 0 \\
\alpha(x_3) = 1
\]

Then we have

\[
J_\alpha(\bigvee (\neg (x_{42}), \land (T, x_3))) = J(\bigvee)(J_\alpha(\neg (x_{42})), J_\alpha(\land (T, x_3))) \\
= \max(J(\neg)(J_\alpha(x_{42})), J(\land)(J_\alpha(T), J_\alpha(x_3)))) \\
= \max(1 - \alpha(x_{42}), \min(J(T), \alpha(x_3)))) \\
= \max(1 - 0, \min(1, 1)) = 1
\]