AAA551: Programming Language Theory

Inductive Definitions

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Inductive Definitions

- A technique for formally defining a set.
- The set is defined in terms of itself.
- The only way of defining an infinite set by a finite means.

Example

Definition

A natural number n is in S if and only if

1. $n = 0$, or
2. $n - 3 \in S$.

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What is the set S?

- $\{0, 3, 6, 9, \ldots\} \subseteq S$
- $\{0, 3, 6, 9, \ldots\} \supseteq S$

A Bottom-up Version

Definition

S is the *smallest* set such that $S \subseteq \mathbb{N}$ and S satisfies the following two conditions:

1. $0 \in S$, and
2. if $n \in S$, then $n + 3 \in S$.

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What is the set S?

- If the two conditions are satisfied, $\{0, 3, 6, 9, \ldots\} \subseteq S$.
- S is the **smallest** such a set.
- The smallest set is unique.

Rules of Inference

$$\frac{A}{B}$$

- A: hypothesis (antecedent)
- B: conclusion (consequent)
- "if A is true then B is also true".
- $\overline{B}$: axiom.

Defining a Set by Rules of Inferences

Definition

$$\frac{}{0 \in S}$$

$$\frac{n \in S}{(n+3) \in S}$$

Interpret the rules as follows:

"A natural number n is in S iff $n \in S$ can be derived from the axiom by applying the inference rules finitely many times"

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Note that this interpretation enforces that S is the smallest set closed under the inference rules.

Summary

In inductive definitions, a set is defined in terms of itself. Three styles:

- Top-down
- Bottom-up
- Rules of inference

In PL, we mainly use the rules-of-inference method.

Exercises

1. What set is defined by the following inductive rules?

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$$\frac{}{3} \qquad \frac{x \quad y}{x+y}$$

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3. Define the following set as rules of inference:

$$S = \{a, b, aa, ab, ba, bb, aaa, aab, aba, abb, baa, bab, bba, bbb, \ldots\}$$

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4. Define the following set as rules of inference:

$$S = \{x^n y^{n+1} \mid n \in \mathbb{N}\}$$

Contents

- More examples of inductive definitions
  - natural numbers, strings, booleans
  - lists, binary trees
  - arithmetic expressions, propositional logic
- Structural induction
  - three example proofs

Natural Numbers

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is inductively defined:

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The inference rules can be expressed by a grammar:

$$n \to 0 \mid n+1$$

Interpretation:

- 0 is a natural number.
- If n is a natural number then so is $n+1$.

Strings

The set of strings over alphabet $\{\mathtt{a}, \ldots, \mathtt{z}\}$, e.g., ϵ, a, b, . . . , z, aa, ab, . . . , az, ba, . . . az, aaa, . . . , zzz, and so on.

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$$\frac{}{\epsilon} \qquad \frac{\alpha}{\mathtt{a}\alpha} \qquad \frac{\alpha}{\mathtt{b}\alpha} \quad \cdots \qquad \frac{\alpha}{\mathtt{z}\alpha}$$

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or simply,

$$\frac{}{\boldsymbol{\epsilon}} \qquad \frac{\boldsymbol{\alpha}}{\boldsymbol{x}\boldsymbol{\alpha}}\ \boldsymbol{x} \in \{\mathtt{a}, \ldots, \mathtt{z}\}$$

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or simply,

$$\frac{}{\epsilon} \qquad \frac{\alpha}{x\alpha}\ x \in \{\mathtt{a}, \ldots, \mathtt{z}\}$$

In grammar:

$$\begin{array}{rcl} \alpha & \rightarrow & \epsilon \\ & \mid & x\alpha \quad (x \in \{\mathtt{a}, \ldots, \mathtt{z}\}) \end{array}$$

Boolean Values

The set of boolean values:

$$\mathbb{B} = \{\boldsymbol{true}, \boldsymbol{false}\}.$$

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$$\mathbb{B} = \{true, false\}.$$

If a set is finite, just enumerate all of its elements by axioms:

$$\frac{}{true} \qquad \frac{}{false}$$

In grammar:

$$b \to true \mid false$$

Lists

Examples of lists of integers:

1. **nil**
2. $\mathbf{14} \cdot$ **nil**
3. $\mathbf{3} \cdot \mathbf{14} \cdot$ **nil**
4. $\mathbf{-7} \cdot \mathbf{3} \cdot \mathbf{14} \cdot$ **nil**

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2. $\mathbf{14 \cdot}$ **nil**
3. $\mathbf{3 \cdot 14 \cdot}$ **nil**
4. $\mathbf{-7 \cdot 3 \cdot 14 \cdot}$ **nil**

Inference rules:

$$\frac{}{\textbf{nil}} \qquad \frac{l}{n \cdot l}\ n \in \mathbb{Z}$$

In grammar:

$$\begin{array}{rcl} l & \to & \textbf{nil} \\ & \mid & n \cdot l \quad (n \in \mathbb{Z}) \end{array}$$

Lists

A proof that $-\mathbf{7} \cdot \mathbf{3} \cdot \mathbf{14} \cdot \textbf{nil}$ is a list of integers:

$$\cfrac{\cfrac{\cfrac{\overline{\textbf{nil}}}{\mathbf{14} \cdot \textbf{nil}}\ 14 \in \mathbb{Z}}{\mathbf{3} \cdot \mathbf{14} \cdot \textbf{nil}}\ \mathbf{3} \in \mathbb{Z}}{-\mathbf{7} \cdot \mathbf{3} \cdot \mathbf{14} \cdot \textbf{nil}}\ -\mathbf{7} \in \mathbb{Z}$$

The proof tree is also called *derivation tree* or *deduction tree*.

Binary Trees

Examples of binary trees:

1. $\mathbf{leaf}$
2. $(2, \mathbf{leaf}, \mathbf{leaf})$
3. $(1, (2, \mathbf{leaf}, \mathbf{leaf}), \mathbf{leaf})$
4. $(1, (2, \mathbf{leaf}, \mathbf{leaf}), (3, (4, \mathbf{leaf}, \mathbf{leaf}), \mathbf{leaf}))$

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Inference rules:

$$\frac{}{\textbf{leaf}} \qquad \frac{t_1 \quad t_2}{(n, t_1, t_2)}\ n \in \mathbb{Z}$$

In grammar:

$$\begin{array}{rcl} t & \rightarrow & \textbf{leaf} \\ & \mid & (n, t, t) \quad (n \in \mathbb{Z}) \end{array}$$

Binary Trees

A proof that

$$(\mathbf{1}, (\mathbf{2}, \textsf{leaf}, \textsf{leaf}), (\mathbf{3}, (\mathbf{4}, \textsf{leaf}, \textsf{leaf}), \textsf{leaf}))$$

is a binary tree:

$$\frac{\dfrac{\overline{\textsf{leaf}}}{(\mathbf{2}, \textsf{leaf}, \textsf{leaf})}\ \mathbf{2} \in \mathbb{Z} \quad \dfrac{\dfrac{\overline{\textsf{leaf}}}{(\mathbf{4}, \textsf{leaf}, \textsf{leaf})}\ \mathbf{4} \in \mathbb{Z}}{(\mathbf{3}, (\mathbf{4}, \textsf{leaf}, \textsf{leaf}), \textsf{leaf})}\ \mathbf{3} \in \mathbb{Z}}{(\mathbf{1}, (\mathbf{2}, \textsf{leaf}, \textsf{leaf}), (\mathbf{3}, (\mathbf{4}, \textsf{leaf}, \textsf{leaf}), \textsf{leaf}))}\ \mathbf{1} \in \mathbb{Z}$$

Binary Trees: a different version

Binary tree examples: $\mathbf{1}$, $(\mathbf{1}, \textbf{nil})$, $(\mathbf{1}, \mathbf{2})$, $((\mathbf{1}, \mathbf{2}), \textbf{nil})$, $((\mathbf{1}, \mathbf{2}), (\mathbf{3}, \mathbf{4}))$.

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Binary tree examples: $\mathbf{1}$, $(\mathbf{1}, \textbf{nil})$, $(\mathbf{1}, \mathbf{2})$, $((\mathbf{1}, \mathbf{2}), \textbf{nil})$, $((\mathbf{1}, \mathbf{2}), (\mathbf{3}, \mathbf{4}))$.
Inference rules:

$$\frac{}{\boldsymbol{n}}\ \boldsymbol{n} \in \mathbb{Z} \qquad \frac{\boldsymbol{t}}{(\boldsymbol{t}, \textbf{nil})} \qquad \frac{\boldsymbol{t}}{(\textbf{nil}, \boldsymbol{t})} \qquad \frac{\boldsymbol{t_1} \quad \boldsymbol{t_2}}{(\boldsymbol{t_1}, \boldsymbol{t_2})}$$

In grammar:

$$\begin{array}{rcll} \boldsymbol{t} & \rightarrow & \boldsymbol{n} & (\boldsymbol{n} \in \mathbb{Z}) \\ & \mid & (\boldsymbol{t}, \textbf{nil}) & \\ & \mid & (\textbf{nil}, \boldsymbol{t}) & \\ & \mid & (\boldsymbol{t}, \boldsymbol{t}) & \end{array}$$

A proof that $((\mathbf{1}, \mathbf{2}), (\mathbf{3}, \textbf{nil}))$ is a binary tree:

$$\frac{\dfrac{\overline{\mathbf{1}} \quad \overline{\mathbf{2}}}{(\mathbf{1}, \mathbf{2})} \qquad \dfrac{\overline{\mathbf{3}}}{(\mathbf{3}, \textbf{nil})}}{((\mathbf{1}, \mathbf{2}), (\mathbf{3}, \textbf{nil}))}$$

Expressions

Expression examples: $\mathbf{2}$, $\mathbf{-2}$, $\mathbf{1+2}$, $\mathbf{1+(2*(-3))}$, etc.

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Inference rules:

$$\frac{}{n}\; n \in \mathbb{Z} \qquad \frac{e}{-e} \qquad \frac{e_1 \quad e_2}{e_1 + e_2} \qquad \frac{e_1 \quad e_2}{e_1 * e_2}$$

In grammar:

$$\begin{array}{rcll} e & \rightarrow & n & (n \in \mathbb{Z}) \\ & \mid & -e & \\ & \mid & e + e & \\ & \mid & e * e & \end{array}$$

Example:

$$\dfrac{\dfrac{}{\mathbf{1}} \quad \dfrac{\dfrac{}{\mathbf{2}} \quad \dfrac{\dfrac{}{\mathbf{3}}}{(-\mathbf{3})}}{(\mathbf{2} * (-\mathbf{3}))}}{(\mathbf{1} + (\mathbf{2} * (-\mathbf{3})))}$$

Propositional Logic

Examples:

- T, F
- $T \wedge F$
- $T \vee F$
- $(T \wedge F) \wedge (T \vee F)$
- $T \Rightarrow (F \Rightarrow T)$

Propositional Logic

Syntax:

$$\begin{array}{rcl} f & \rightarrow & T \mid F \\ & \mid & \neg f \\ & \mid & f \wedge f \\ & \mid & f \vee f \\ & \mid & f \Rightarrow f \end{array}$$

Semantics ($[\![f]\!]$):

$$\begin{array}{rcl} [\![T]\!] & = & \mathit{true} \\ [\![F]\!] & = & \mathit{false} \\ [\![\neg f]\!] & = & \text{not } [\![f]\!] \\ [\![f_1 \wedge f_2]\!] & = & [\![f_1]\!] \text{ andalso } [\![f_2]\!] \\ [\![f_1 \vee f_2]\!] & = & [\![f_1]\!] \text{ orelse } [\![f_2]\!] \\ [\![f_1 \Rightarrow f_2]\!] & = & [\![f_1]\!] \text{ implies } [\![f_2]\!] \end{array}$$

Propositional Logic

$$
\begin{aligned}
[\![(T \wedge (T \vee F)) \Rightarrow F]\!] &= [\![T \wedge (T \vee F)]\!] \text{ implies } [\![F]\!] \\
&= ([\![T]\!] \text{ andalso } [\![T \vee F]\!]) \text{ implies } \mathit{false} \\
&= (\mathit{true} \text{ andalso } ([\![T]\!] \text{ orelse } [\![F]\!])) \text{ implies } \mathit{false} \\
&= (\mathit{true} \text{ andalso } (\mathit{true} \text{ orelse } \mathit{false})) \text{ implies } \mathit{false} \\
&= \mathit{false}
\end{aligned}
$$

Structural Induction

A technique for proving properties about inductively defined sets.

To prove that a proposition $P(s)$ is true for all structures s, prove the following:

1. (Base case) P is true on simple structures (those without substructures)
2. (Inductive case) If P is true on the substructures of s, then it is true on s itself. The assumption is called *induction hypothesis (I.H.)*.

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Prove that for all $x \in S$, x is divisible by 3.

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  Let $x = 3k_1$ and $y = 3k_2$. Using I.H., we derive

  $$x + y \text{ is divisible by } 3$$

  as follows:

  $$\begin{array}{rcll} x+y & = & 3k_1 + 3k_2 & \cdots \text{by I.H.} \\ & = & 3(k_1 + 3k_2) & \end{array}$$

□

Example 2

Let S be the set defined by the following inference rules:

$$\frac{}{()} \qquad \frac{x}{(x)} \qquad \frac{x \quad y}{xy}$$

Prove that every element of the set has the same number of ('s and)'s.

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Proof Restate the claim formally:

$$\text{If } x \in S \text{ then } l(x) = r(x)$$

where $l(x)$ and $r(x)$ denote the number of ('s and)'s, respectively.

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where $l(x)$ and $r(x)$ denote the number of ('s and)'s, respectively.
We prove it by structural induction:

- (Base case): The base case is when $x = ()$. Then $l(x) = 1 = r(x)$.

Example 2

- (Inductive case): There are two inductive cases:

$$\frac{x}{(x)} \qquad \frac{x \quad y}{xy}$$

Induction hypotheses (I.H.):

$$l(x) = r(x), \qquad l(y) = r(y).$$

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  - The first case. We prove $l((x)) = r((x))$:

$$\begin{array}{rcll} l((x)) & = & l(x) + 1 & \cdots \text{by definition of } l((x)) \\ & = & r(x) + 1 & \cdots \text{by I.H.} \\ & = & r((x)) & \cdots \text{by definition of } r((x)) \end{array}$$

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- The second case. We prove $l(xy) = r(xy)$:

$$\begin{array}{rcll} l(xy) & = & l(x) + l(y) & \cdots \text{by definition of } l(xy) \\ & = & r(x) + r(y) & \cdots \text{by I.H.} \\ & = & r(xy) & \cdots \text{by definition of } r(xy) \end{array}$$

□

Example 3

Let T be the set of binary trees:

$$\frac{}{\textbf{leaf}} \qquad \frac{t_1 \quad t_2}{(n, t_1, t_2)}\ n \in \mathbb{Z}$$

Prove that for all such trees, the number of leaves is always one more than the number of internal nodes.

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Proof. Restate the claim more formally:

$$\text{If } t \in T \text{ then } l(t) = i(t) + 1$$

where $l(t)$ and $i(t)$ denote the number of leaves and internal nodes, respectively.

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- (Inductive case): The induction hypothesis:

$$l(t_1) = i(t_1) + 1, \qquad l(t_2) = i(t_2) + 1$$

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- (Inductive case): The induction hypothesis:

  $$l(t_1) = i(t_1) + 1, \qquad l(t_2) = i(t_2) + 1$$

  Using I.H., we prove $l((n, t_1, t_2)) = i((n, t_1, t_2)) + 1$:

  $$\begin{array}{lcll} l((n, t_1, t_2)) & = & l(t_1) + l(t_2) & \\ & = & i(t_1) + 1 + i(t_2) + 1 & \text{by induction hypothesis} \\ & = & i(n, t_1, t_2) + 1 & \end{array}$$

Summary

- Computer science is full of inductive definitions.
  - primitive values: booleans, characters, integers, strings, etc
  - compound values: lists, trees, graphs, etc
  - language syntax and semantics
- Structural induction
  - a general technique for reasoning about inductively defined sets