Lecture 3: Induction and Operational Semantics

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Recursive Data Types (trees)

data Ast = ANum Integer
    | APlus Ast Ast
    | ATimes Ast Ast

eval (ANum x) = x
eval (ATimes x y) = (eval x) * (eval y)
eval (APlus x y) = (eval x) + (eval y)

Prelude> eval (ATimes (APlus (ANum 5) (ANum 6)) (ANum 7))
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-- this tree corresponds to the expression ((5+6)*7)
mylex' :: [Char] -> [Token]
mylex' [] = []
mylex' (x:xs)
  | x `elem` ['0'..'9']  = (Number (digitToInt x)):(mylex' xs)
  | x == '('             = LParen:(mylex' xs)
  | x == ')'             = RParen:(mylex' xs)
  | x == '+'             = Plus:(mylex' xs)
  | x == '-'             = Minus:(mylex' xs)
  | x == '*'             = Times:(mylex' xs)
  | x == ' '             = mylex' xs
  | otherwise            = error "Bad"

mylex2 :: [Token] -> Int -> Bool -> [Token]
mylex2 [] _ False = []
mylex2 [] x True = [Number x]
mylex2 ((Number y):xs) d state = mylex2 xs (d*10+y) True
mylex2 (x:xs) d True = (Number d):x:(mylex2 xs 0 False)
mylex2 (x:xs) d False = x:(mylex2 xs 0 False)

mylex :: [Char] -> [Token]
mylex xs = mylex2 (mylex' xs) 0 False
mylex' :: [Char] -> [Token]
mylex' [] = []
mylex' (x:xs)
    | x `elem` ['0'..'9'] = (Number (digitToInt x)):(mylex' xs)
    | isOperator x       = (operatorToToken x):(mylex' xs)
    | x == ' '           = mylex' xs
    | otherwise          = error "Bad"

isOperator x = x `elem` ['+', '-', '*', '(', ')']

operatorToToken '*' = Times
operatorToToken '-' = Minus
operatorToToken '+' = Plus
operatorToToken '(' = LParen
operatorToToken ')' = RParen

...
parse :: [Token] -> (Ast, [Token])
parse ((Number y):xs) = (ANum y, xs)
parse (LParen:xs) = ((opToNode op) left right, remainder)
  where (left, op:rest) = parse xs
  (right, RParen:remainder) = parse rest

opToNode :: Token -> Ast -> Ast -> Ast
opToNode Times = ATimes
opToNode Plus = APlus
opToNode Minus = AMinus

calc :: [Char] -> Int
calc = eval . fst . parse . mylex
The functional programming style used in OCaml is based on treating programs as data — i.e., on writing functions that manipulate other functions as their inputs and outputs.

Everything in this course is based on treating programs as mathematical objects — i.e., we will be building mathematical theories whose basic objects of study are programs (and whole programming languages).

Jargon: We will be studying the metatheory of programming languages.
Warning!

The material in the next couple of lectures is more slippery than it may first appear.

“I believe it when I hear it” is not a sufficient test of understanding.

A much better test is “I can explain it so that someone else believes it.”
Basics of Induction
(Review)
Induction

Principle of ordinary induction on natural numbers

Suppose that $P$ is a predicate on the natural numbers. Then:

- If $P(0)$
- and, for all $i$, $P(i)$ implies $P(i+1)$,
- then $P(n)$ holds for all $n$. 

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Example

Theorem: \(2^0 + 2^1 + ... + 2^n = 2^{n+1} - 1\), for every \(n\).

Proof:

\(\diamond\) Let \(P(i)\) be “\(2^0 + 2^1 + ... + 2^i = 2^{i+1} - 1\).”

\(\diamond\) Show \(P(0)\):

\[
2^0 = 1 = 2^1 - 1
\]

\(\diamond\) Show that \(P(i)\) implies \(P(i + 1)\):

\[
\begin{align*}
2^0 + 2^1 + ... + 2^{i+1} & = (2^0 + 2^1 + ... + 2^i) + 2^{i+1} \\
& = (2^{i+1} - 1) + 2^{i+1} & \text{by IH} \\
& = 2 \cdot (2^{i+1}) - 1 \\
& = 2^{i+2} - 1
\end{align*}
\]

\(\diamond\) The result (\(P(n)\) for all \(n\)) follows by the principle of induction.
Theorem: \(2^0 + 2^1 + \ldots + 2^n = 2^{n+1} - 1\), for every \(n\).

Proof: By induction on \(n\).

\(\blacklozenge\) Base case \((n = 0)\):

\[
2^0 = 1 = 2^1 - 1
\]

\(\blacklozenge\) Inductive case \((n = i + 1)\):

\[
2^0 + 2^1 + \ldots + 2^{i+1} = (2^0 + 2^1 + \ldots + 2^i) + 2^{i+1} \\
= (2^{i+1} - 1) + 2^{i+1} \quad \text{IH} \\
= 2 \cdot (2^{i+1}) - 1 \\
= 2^{i+2} - 1
\]
What’s wrong w/ this induction?

**Theorem(?!):** All horses are the same color.

**Proof:** Let $P(n)$ be the predicate “in all non-empty collections of $n$ horses, all the horses are the same color.” We show that $P(n)$ holds for all $n$ by induction on $n$ (using 1 as the base case).

**Base case:** Clearly, $P(1)$ holds.

**Induction case:** Given $P(n)$, we must show $P(n + 1)$.

Consider an arbitrary collection of $n + 1$ horses. Remove one horse temporarily. Now we have $n$ horses and hence, by the induction hypothesis, these $n$ horses are all the same color. Now call the exiled horse back and send a different horse away. Again, we have a collection of $n$ horses, which, by the induction hypothesis, are all the same color. Moreover, these $n$ horses are the same color as the first collection. Thus, the horse we brought back was the same color as the second horse we sent away, and all the $n + 1$ horses are the same color.
Complete Induction

Principle of complete induction on natural numbers

Suppose that $P$ is a predicate on the natural numbers. Then:
If, for each natural number $n$,
given $P(i)$ for all $i < n$
we can show $P(n)$,
then $P(n)$ holds for all $n$.

Principle of ordinary induction on natural numbers

Suppose that $P$ is a predicate on the natural numbers. Then:
If $P(0)$
and, for all $i$, $P(i)$ implies $P(i + 1)$,
then $P(n)$ holds for all $n$. 
Ordinary and complete induction are interderivable — assuming one, we can prove the other. why?

Thus, the choice of which to use for a particular proof is purely a question of style.

We’ll see some other (equivalent) styles as we go along.
Syntax
Here is a BNF grammar for a very simple language of arithmetic expressions:

\[ t ::= \]

- `true`
- `false`
- `if t then t else t`
- `0`
- `succ t`
- `pred t`
- `iszero t`

**Terms**:
- `constant true`
- `constant false`
- `conditional`
- `constant zero`
- `successor`
- `predecessor`
- `zero test`

**Terminology:**
- `t` here is a *metavariable*
Abstract vs. concrete syntax

Q1: Does this grammar define a set of character strings, a set of token lists, or a set of abstract syntax trees?
Abstract vs. concrete syntax

Q1: Does this grammar define a set of character strings, a set of token lists, or a set of abstract syntax trees?

A: In a sense, all three. But we are primarily interested, here, in abstract syntax trees.

For this reason, grammars like the one on the previous slide are sometimes called abstract grammars. An abstract grammar defines a set of abstract syntax trees and suggests a mapping from character strings to trees.

We then write terms as linear character strings rather than trees simply for convenience. If there is any potential confusion about what tree is intended, we use parentheses to disambiguate.
Q: So, are

\[
\begin{align*}
\text{succ} & \ 0 \\
\text{succ} & \ (0) \\
(((\text{succ} \ (((0)))))),
\end{align*}
\]

“the same term”?

What about

\[
\begin{align*}
\text{succ} & \ 0 \\
\text{pred} \ (\text{succ} \ (\text{succ} \ 0))
\end{align*}
\]
A more explicit form of the definition

The set \( \mathcal{T} \) of terms is the smallest set such that

1. \( \{ \text{true}, \text{false}, 0 \} \subseteq \mathcal{T} \);

2. if \( t_1 \in \mathcal{T} \), then \( \{ \text{succ } t_1, \text{pred } t_1, \text{iszero } t_1 \} \subseteq \mathcal{T} \);

3. if \( t_1 \in \mathcal{T} \), \( t_2 \in \mathcal{T} \), and \( t_3 \in \mathcal{T} \), then if \( t_1 \) then \( t_2 \) else \( t_3 \in \mathcal{T} \).
Inference rules

An alternate notation for the same definition:

\[
\begin{align*}
\text{true } & \in T \\
\text{false } & \in T \\
0 & \in T \\
\text{succ } t_1 & \in T \\
\text{pred } t_1 & \in T \\
\text{iszero } t_1 & \in T \\
\frac{t_1 \in T \quad t_2 \in T \quad t_3 \in T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \in T}
\end{align*}
\]

Note that “the smallest set closed under...” is implied (but often not stated explicitly).

Terminology:

- axiom vs. rule
- concrete rule vs. rule scheme
Define an infinite sequence of sets, $S_0$, $S_1$, $S_2$, ..., as follows:

$$S_i = \emptyset$$

$$S_{i+1} = \{\text{true, false, 0}\} \cup \{\text{succ } t_1, \text{pred } t_1, \text{iszero } t_1 \mid t_1 \in S_i\} \cup \{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \mid t_1, t_2, t_3 \in S_i\}$$

Now let

$$S = \bigcup_i S_i$$

Terms, concretely
Comparing the definitions

We have seen two different presentations of terms:

1. as the *smallest* set that is *closed* under certain rules (*T*)
   - explicit inductive definition
   - BNF shorthand
   - inference rule shorthand

2. as the *limit* (*S*) of a series of sets (of larger and larger terms)
Comparing the definitions

We have seen two different presentations of terms:

1. as the smallest set that is closed under certain rules ($\mathcal{T}$)
   - explicit inductive definition
   - BNF shorthand
   - inference rule shorthand

2. as the limit ($\mathcal{S}$) of a series of sets (of larger and larger terms)

What does it mean to assert that “these presentations are equivalent”?

prove it! (HW3)
Induction on Syntax
Why two definitions?

The two ways of defining the set of terms are both useful:

1. the definition of terms as the smallest set with a certain closure property is compact and easy to read

2. the definition of the set of terms as the limit of a sequence gives us an induction principle for proving things about terms...
**Induction on Terms**

**Definition:** The depth of a term $t$ is the smallest $i$ such that $t \in S_i$.

From the definition of $S$, it is clear that, if a term $t$ is in $S_i$, then all of its immediate subterms must be in $S_{i-1}$, i.e., they must have strictly smaller depths.

This observation justifies the **principle of induction on terms**.

Let $P$ be a predicate on terms.

If, for each term $s$,

- given $P(r)$ for all immediate subterms $r$ of $s$,
- we can show $P(s)$,

then $P(t)$ holds for all $t$. 
Inductive Function Definitions

The set of constants appearing in a term \( t \), written \( \text{Consts}(t) \), is defined as follows:

\[
\begin{align*}
\text{Consts}(\text{true}) &= \{\text{true}\} \\
\text{Consts}(\text{false}) &= \{\text{false}\} \\
\text{Consts}(0) &= \{0\} \\
\text{Consts}(\text{succ } t_1) &= \text{Consts}(t_1) \\
\text{Consts}(\text{pred } t_1) &= \text{Consts}(t_1) \\
\text{Consts}(\text{iszero } t_1) &= \text{Consts}(t_1) \\
\text{Consts}(\text{if } t_1 \text{ then } t_2 \text{ else } t_3) &= \text{Consts}(t_1) \cup \text{Consts}(t_2) \cup \text{Consts}(t_3)
\end{align*}
\]

Simple, right?
First question:

Normally, a “definition” just assigns a convenient name to a previously-known thing. But here, the “thing” on the right-hand side involves the very name that we are “defining”!

So in what sense is this a definition??
Second question: Suppose we had written this instead...

The set of constants appearing in a term $t$, written $\text{BadConsts}(t)$, is defined as follows:

$$
\begin{align*}
\text{BadConsts}(\text{true}) &= \{\text{true}\} \\
\text{BadConsts}(\text{false}) &= \{\text{false}\} \\
\text{BadConsts}(0) &= \{0\} \\
\text{BadConsts}(0) &= \{} \\
\text{BadConsts}(\text{succ } t_1) &= \text{BadConsts}(t_1) \\
\text{BadConsts}(\text{pred } t_1) &= \text{BadConsts}(t_1) \\
\text{BadConsts}(\text{iszero } t_1) &= \text{BadConsts}(\text{iszero } (\text{iszero } t_1))
\end{align*}
$$

What is the essential difference between these two definitions? How do we tell the difference between well-formed inductive definitions and ill-formed ones?

What, exactly, does a well-formed inductive definition mean?
First, recall that a function can be viewed as a two-place relation (called the “graph” of the function) with certain properties:

- It is total: every element of its domain occurs at least once in its graph.
- It is deterministic: every element of its domain occurs at most once in its graph.
We have seen how to define relations inductively. E.g....

Let \textbf{Consts} be the smallest two-place relation closed under the following rules:

\[
\begin{align*}
(t_{\text{true}}, \{\text{true}\}) & \in \text{Consts} \\
(t_{\text{false}}, \{\text{false}\}) & \in \text{Consts} \\
(0, \{0\}) & \in \text{Consts} \\
(t_{1}, C) & \in \text{Consts} \\
(\text{succ } t_{1}, C) & \in \text{Consts} \\
(\text{pred } t_{1}, C) & \in \text{Consts} \\
(t_{1}, C) & \in \text{Consts} \\
(\text{iszero } t_{1}, C) & \in \text{Consts} \\
(t_{1}, C_{1}) & \in \text{Consts} \\
(t_{2}, C_{2}) & \in \text{Consts} \\
(t_{3}, C_{3}) & \in \text{Consts} \\
(\text{if } t_{1} \text{ then } t_{2} \text{ else } t_{3}, (\text{Consts}(t_{1}) \cup \text{Consts}(t_{2}) \cup \text{Consts}(t_{3}))) & \in \text{Consts}
\end{align*}
\]
This definition certainly defines a relation (i.e., the smallest one with a certain closure property).

Q: How can we be sure that this relation is a function?
This definition certainly defines a relation (i.e., the smallest one with a certain closure property).

Q: How can we be sure that this relation is a function?

A: Prove it!
Theorem: The relation $\text{Consts}$ defined by the inference rules a couple of slides ago is total and deterministic.

I.e., for each term $t$ there is exactly one set of terms $C$ such that $(t, C) \in \text{Consts}$.

Proof:
**Theorem**: The relation $\text{Consts}$ defined by the inference rules a couple of slides ago is total and deterministic.

I.e., for each term $t$ there is exactly one set of terms $C$ such that $(t, C) \in \text{Consts}$.

**Proof**: By induction on $t$. 
**Theorem:** The relation $\text{Consts}$ defined by the inference rules a couple of slides ago is total and deterministic.

i.e., for each term $t$ there is exactly one set of terms $C$ such that $(t, C) \in \text{Consts}$.

**Proof:** By induction on $t$.

To apply the induction principle for terms, we must show, for an arbitrary term $t$, that if

for each immediate subterm $s$ of $t$, there is exactly one set of terms $C_s$ such that $(s, C_s) \in \text{Consts}$

then

there is exactly one set of terms $C$ such that $(t, C) \in \text{Consts}$.
Proceed by cases on the form of $t$.

- If $t$ is 0, true, or false, then we can immediately see from the definition of $\textit{Consts}$ that there is exactly one set of terms $C$ (namely $\{t\}$) such that $(t, C) \in \textit{Consts}$. 

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- If $t$ is $\text{succ } t_1$, then the induction hypothesis tells us that there is exactly one set of terms $C_1$ such that $(t_1, C_1) \in \text{Consts}$. But then it is clear from the definition of $\text{Consts}$ that there is exactly one set $C$ (namely $C_1$) such that $(t, C) \in \text{Consts}$.
Proceed by cases on the form of $t$.

♦ If $t$ is 0, true, or false, then we can immediately see from the definition of $\text{Consts}$ that there is exactly one set of terms $C$ (namely $\{t\}$) such that $(t, C) \in \text{Consts}$.

♦ If $t$ is $\text{succ } t_1$, then the induction hypothesis tells us that there is exactly one set of terms $C_1$ such that $(t_1, C_1) \in \text{Consts}$. But then it is clear from the definition of $\text{Consts}$ that there is exactly one set $C$ (namely $C_1$) such that $(t, C) \in \text{Consts}$.

Similarly when $t$ is $\text{pred } t_1$ or $\text{iszero } t_1$.

\[
\begin{align*}
(t_1, C) & \in \text{Consts} \\
(\text{succ } t_1, C) & \in \text{Consts} \\
(t_1, C) & \in \text{Consts} \\
(\text{pred } t_1, C) & \in \text{Consts} \\
(t_1, C) & \in \text{Consts} \\
(\text{iszero } t_1, C) & \in \text{Consts}
\end{align*}
\]

$(t_1, C_1) \in \text{Consts}$  $(t_2, C_2) \in \text{Consts}$  $(t_3, C_3) \in \text{Consts}$

$(\text{if } t_1 \text{ then } t_2 \text{ else } t_3, (\text{Consts}(t_1) \cup \text{Consts}(t_2) \cup \text{Consts}(t_3)))) \in \text{Consts}$
If \( t \) is \( \text{if}\ s_1 \ \text{then}\ s_2 \ \text{else}\ s_3 \), then the induction hypothesis tells us:

- there is exactly one set of terms \( C_1 \) such that \((t_1, C_1) \in \text{Consts}\)
- there is exactly one set of terms \( C_2 \) such that \((t_2, C_3) \in \text{Consts}\)
- there is exactly one set of terms \( C_3 \) such that \((t_3, C_3) \in \text{Consts}\)

But then it is clear from the definition of \( \text{Consts} \) that there is exactly one set \( C \) (namely \( C_1 \cup C_2 \cup C_3 \)) such that \((t, C) \in \text{Consts}\).

\[
\begin{align*}
(t_1, C) & \in \text{Consts} \\
(succ\ t_1, C) & \in \text{Consts} \\
(t_1, C) & \in \text{Consts} \\
(pred\ t_1, C) & \in \text{Consts} \\
(t_1, C) & \in \text{Consts} \\
(iszero\ t_1, C) & \in \text{Consts} \\
(t_1, C_1) & \in \text{Consts} \\
(t_2, C_2) & \in \text{Consts} \\
(t_3, C_3) & \in \text{Consts} \\
(if\ t_1\ then\ t_2\ else\ t_3,\ (\text{Consts}(t_1)\ \cup\ \text{Consts}(t_2)\ \cup\ \text{Consts}(t_3))) & \in \text{Consts}
\end{align*}
\]
How about the bad definition?

\[
(\text{true}, \{\text{true}\}) \in \text{BadConsts}
\]

\[
(\text{false}, \{\text{false}\}) \in \text{BadConsts}
\]

\[
(0, \{0\}) \in \text{BadConsts}
\]

\[
(0, \{\} \} \in \text{BadConsts}
\]

\[
(t_1, C) \in \text{BadConsts} \\
\text{(succ } t_1, C) \in \text{BadConsts}
\]

\[
(t_1, C) \in \text{BadConsts} \\
\text{(pred } t_1, C) \in \text{BadConsts}
\]

\[
(\text{iszero} (\text{iszero } t_1), C) \in \text{BadConsts} \\
(\text{iszero } t_1, C) \in \text{BadConsts}
\]
This set of rules defines a perfectly good relation — it’s just that this relation does not happen to be a function!

Just for fun, let’s calculate some cases of this relation...

♦ For what values of \( C \) do we have \((\text{false}, C) \in \text{Consts}\)?

♦ For what values of \( C \) do we have \((\text{succ 0}, C) \in \text{Consts}\)?

♦ For what values of \( C \) do we have \((\text{if false then 0 else 0}, C) \in \text{Consts}\)?

♦ For what values of \( C \) do we have \((\text{iszero 0}, C) \in \text{Consts}\)?
Another Inductive Definition

\[
\begin{align*}
\text{size}(\text{true}) & = 1 \\
\text{size}(\text{false}) & = 1 \\
\text{size}(0) & = 1 \\
\text{size}(\text{succ } t_1) & = \text{size}(t_1) + 1 \\
\text{size}(\text{pred } t_1) & = \text{size}(t_1) + 1 \\
\text{size}(\text{iszero } t_1) & = \text{size}(t_1) + 1 \\
\text{size}(\text{if } t_1 \text{ then } t_2 \text{ else } t_3) & = \text{size}(t_1) + \text{size}(t_2) + \text{size}(t_3) + 1
\end{align*}
\]
Another proof by induction

**Theorem:** The number of distinct constants in a term is at most the size of the term. i.e., \(|\text{Consts}(t)| \leq \text{size}(t)|.

**Proof:**
Another proof by induction

**Theorem:** The number of distinct constants in a term is at most the size of the term. I.e., $|\text{Consts}(t)| \leq \text{size}(t)$.

**Proof:** By induction on $t$. 
Another proof by induction

**Theorem:** The number of distinct constants in a term is at most the size of the term. I.e., $|\text{Consts}(t)| \leq \text{size}(t)$.

**Proof:** By induction on $t$.

Assuming the desired property for immediate subterms of $t$, we must prove it for $t$ itself.
Another proof by induction

**Theorem:** The number of distinct constants in a term is at most the size of the term. I.e., $|\text{Consts}(t)| \leq \text{size}(t)$.

**Proof:** By induction on $t$.

Assuming the desired property for immediate subterms of $t$, we must prove it for $t$ itself.

There are three cases to consider:

- **Case:** $t$ is a constant
- **Immediate:** $|\text{Consts}(t)| = |[t]| = 1 = \text{size}(t)$.
Another proof by induction

**Theorem:** The number of distinct constants in a term is at most the size of the term. I.e., $|\text{Consts}(t)| \leq \text{size}(t)$.

**Proof:** By induction on $t$.

Assuming the desired property for immediate subterms of $t$, we must prove it for $t$ itself.

There are three cases to consider:

**Case:** $t$ is a constant

Immediate: $|\text{Consts}(t)| = |\{t\}| = 1 = \text{size}(t)$.

**Case:** $t = \text{succ } t_1$, $\text{pred } t_1$, or $\text{iszero } t_1$

By the induction hypothesis, $|\text{Consts}(t_1)| \leq \text{size}(t_1)$. We now calculate as follows: $|\text{Consts}(t)| = |\text{ Consts}(t_1)| \leq \text{size}(t_1) < \text{size}(t)$. 
Case: \( t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 \)

By the induction hypothesis, \(|\text{Consts}(t_1)| \leq \text{size}(t_1)|
\| \text{Consts}(t_2)| \leq \text{size}(t_2)|, \text{and } |\text{Consts}(t_3)| \leq \text{size}(t_3)|. \text{ We now calculate as follows:}

\[
|\text{Consts}(t)| = |\text{Consts}(t_1) \cup \text{Consts}(t_2) \cup \text{Consts}(t_3)| \\
\leq |\text{Consts}(t_1)| + |\text{Consts}(t_2)| + |\text{Consts}(t_3)| \\
\leq \text{size}(t_1) + \text{size}(t_2) + \text{size}(t_3) \\
< \text{size}(t).
\]

Q: what if we remove the +1’s?

- \(\text{size(true)} = 1\)
- \(\text{size(false)} = 1\)
- \(\text{size(0)} = 1\)
- \(\text{size(succ } t_1) = \text{size}(t_1) + 1\)
- \(\text{size(pred } t_1) = \text{size}(t_1) + 1\)
- \(\text{size(iszero } t_1) = \text{size}(t_1) + 1\)
- \(\text{size(if } t_1 \text{ then } t_2 \text{ else } t_3) = \text{size}(t_1) + \text{size}(t_2) + \text{size}(t_3) + 1\)
Operational Semantics
Abstract Machines

An abstract machine consists of:

- a set of states
- a transition relation on states, written \( \rightarrow \)

A state records all the information in the machine at a given moment. For example, an abstract-machine-style description of a conventional microprocessor would include the program counter, the contents of the registers, the contents of main memory, and the machine code program being executed.

For the very simple languages we are considering at the moment, however, the term being evaluated is the whole state of the abstract machine.

Nb. Often, the transition relation is actually a partial function: i.e., from a given state, there is at most one possible next state. But in general there may be many.
Operational semantics for Booleans

Syntax of terms and values

$$t ::= \begin{align*}
\text{true} & \quad \text{constant true} \\
\text{false} & \quad \text{constant false} \\
\text{if } t \text{ then } t \text{ else } t & \quad \text{conditional}
\end{align*}$$

$$v ::= \begin{align*}
\text{true} & \quad \text{true value} \\
\text{false} & \quad \text{false value}
\end{align*}$$
The evaluation relation $t \rightarrow t'$ is the smallest relation closed under the following rules:

- If true then $t_2$ else $t_3 \rightarrow t_2$  \hspace{1cm} (E-IFTRUE)

- If false then $t_2$ else $t_3 \rightarrow t_3$ \hspace{1cm} (E-IFFALSE)

\[
\frac{t_1 \rightarrow t'_1}{if \ t_1 \ then \ t_2 \ else \ t_3 \rightarrow if \ t'_1 \ then \ t_2 \ else \ t_3} \hspace{1cm} (E-IF)
\]
**Terminology**

**Computation rules:**

\[
\text{if true then } t_2 \text{ else } t_3 \rightarrow t_2 \quad (E-\text{IFTRUE})
\]

\[
\text{if false then } t_2 \text{ else } t_3 \rightarrow t_3 \quad (E-\text{IFFALSE})
\]

**Congruence rule:**

\[
\begin{align*}
  t_1 &\rightarrow t_1' \\
\hline
  \text{if } t_1 \text{ then } t_2 \text{ else } t_3 &\rightarrow \text{if } t_1' \text{ then } t_2 \text{ else } t_3 \\
\end{align*}
\]  
\[ \quad (E-\text{IF})\]

Computation rules perform “real” computation steps.

Congruence rules determine where computation rules can be applied next.
Syntax/Semantics of Untyped Booleans

<table>
<thead>
<tr>
<th>Syntax</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t ::= \true$</td>
<td>if true then $t_2$ else $t_3$ → $t_2$ (E-IFTRUE)</td>
</tr>
<tr>
<td>$t ::= \false$</td>
<td>if false then $t_2$ else $t_3$ → $t_3$ (E-IFFALSE)</td>
</tr>
<tr>
<td>$t ::= \text{if } t \text{ then } t_2 \text{ else } t_3$</td>
<td>$t_1 → t_1'$ if $t_1$ then $t_2$ else $t_3$ → if $t_1'$ then $t_2$ else $t_3$ (E-IF)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v ::= \true$</td>
</tr>
<tr>
<td>$v ::= \false$</td>
</tr>
</tbody>
</table>

Figure 3-1: Booleans (B)

Syntax is about structure and grammaticality, but no meaning.

Semantics is about the meaning and relationship to the real world.
Evaluation, more explicitly

$\rightarrow$ is the smallest two-place relation closed under the following rules:

$((\text{if} \, \text{true} \, \text{then} \, t_2 \, \text{else} \, t_3), t_2) \in \rightarrow$

$((\text{if} \, \text{false} \, \text{then} \, t_2 \, \text{else} \, t_3), t_3) \in \rightarrow$

$(t_1, t'_1) \in \rightarrow$

$((\text{if} \, t_1 \, \text{then} \, t_2 \, \text{else} \, t_3), (\text{if} \, t'_1 \, \text{then} \, t_2 \, \text{else} \, t_3)) \in \rightarrow$
Digression

Suppose we wanted to change our evaluation strategy so that the `then` and `else` branches of an `if` get evaluated (in that order) before the guard. How would we need to change the rules?
Suppose we wanted to change our evaluation strategy so that the *then* and *else* branches of an *if* get evaluated (in that order) before the guard. How would we need to change the rules?

Suppose, moreover, that if the evaluation of the *then* and *else* branches leads to the same value, we want to immediately produce that value (“short-circuiting” the evaluation of the guard). How would we need to change the rules?
Digression

Suppose we wanted to change our evaluation strategy so that the `then` and `else` branches of an `if` get evaluated (in that order) before the guard. How would we need to change the rules?

Suppose, moreover, that if the evaluation of the `then` and `else` branches leads to the same value, we want to immediately produce that value (“short-circuiting” the evaluation of the guard). How would we need to change the rules?

Of the rules we just invented, which are computation rules and which are congruence rules?
Evaluation, more explicitly

\[ \rightarrow \text{ is the smallest two-place relation closed under the following rules:} \]

\[ ((\text{if true then } t_2 \text{ else } t_3), t_2) \in \rightarrow \]

\[ ((\text{if false then } t_2 \text{ else } t_3), t_3) \in \rightarrow \]

\[ (t_1, t'_1) \in \rightarrow \]

\[ ((\text{if } t_1 \text{ then } t_2 \text{ else } t_3), (\text{if } t'_1 \text{ then } t_2 \text{ else } t_3)) \in \rightarrow \]
Even more explicitly...

What is the generating function corresponding to these rules?

(exercise)
Reasoning about Evaluation
Derivations

We can record the “justification” for a particular pair of terms that are in the evaluation relation in the form of a tree.

(on the board)

Terminology:

- These trees are called derivation trees (or just derivations)
- The final statement in a derivation is its conclusion
- We say that the derivation is a witness for its conclusion (or a proof of its conclusion) — it records all the reasoning steps that justify the conclusion.
• currently, the derivation tree is always a sequence, never branching, since no rules require more than one premises

• but later in this course we’ll see real trees

\[
\begin{align*}
s & \overset{\text{def}}{=} \text{if true then false else false} \\
t & \overset{\text{def}}{=} \text{if } s \text{ then true else true} \\
u & \overset{\text{def}}{=} \text{if false then true else true}
\end{align*}
\]

\[
\begin{array}{c}
\hline
s \rightarrow \text{false} \\
\hline
\frac{E-\text{IF}}{t \rightarrow u}
\end{array}
\]

\[
\begin{array}{c}
\hline
\text{if } t \text{ then false else false} \rightarrow \text{if } u \text{ then false else false}
\end{array}
\]
Observation

**Lemma:** Suppose we are given a derivation tree $D$ witnessing the pair $(t, t')$ in the evaluation relation. Then either

1. the final rule used in $D$ is E-IFTRUE and we have
   $$ t = \text{if true then } t_2 \text{ else } t_3 $$
   and $t' = t_2$, for some $t_2$ and $t_3$, or

2. the final rule used in $D$ is E-IFFALSE and we have
   $$ t = \text{if false then } t_2 \text{ else } t_3 $$
   and $t' = t_3$, for some $t_2$ and $t_3$, or

3. the final rule used in $D$ is E-IF and we have
   $$ t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 $$
   and $t' = \text{if } t'_1 \text{ then } t_2 \text{ else } t_3$, for some $t_1$, $t'_1$, $t_2$, and $t_3$; moreover, the immediate subderivation of $D$ witnesses $(t_1, t'_1) \in \rightarrow$.  

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We can now write proofs about evaluation “by induction on derivation trees.”

Given an arbitrary derivation $\mathcal{D}$ with conclusion $t \rightarrow t'$, we assume the desired result for its immediate sub-derivation (if any) and proceed by a case analysis (using the previous lemma) of the final evaluation rule used in constructing the derivation tree.

E.g....
Induction on Derivations — Example

Theorem: If \( t \rightarrow t' \) — i.e., if \( (t, t') \in \rightarrow \) — then \( \text{size}(t) > \text{size}(t') \).

Proof: By induction on a derivation \( D \) of \( t \rightarrow t' \).

1. Suppose the final rule used in \( D \) is E-\text{IF}\text{TRUE}, with 
   \( t = \text{if true then } t_2 \text{ else } t_3 \) and \( t' = t_2 \). Then the result is immediate from the definition of \text{size}.

2. Suppose the final rule used in \( D \) is E-\text{IF}\text{FALSE}, with 
   \( t = \text{if false then } t_2 \text{ else } t_3 \) and \( t' = t_3 \). Then the result is again immediate from the definition of \text{size}.

3. Suppose the final rule used in \( D \) is E-\text{IF}, with 
   \( t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 \) and \( t' = \text{if } t'_1 \text{ then } t_2 \text{ else } t_3 \), where \( (t_1, t'_1) \in \rightarrow \) is witnessed by a derivation \( D_\infty \). By the induction hypothesis, \( \text{size}(t_1) > \text{size}(t'_1) \). But then, by the definition of \text{size}, we have \( \text{size}(t) > \text{size}(t') \).
Normal forms

A normal form is a term that cannot be evaluated any further — i.e., a term $t$ is a normal form (or “is in normal form”) if there is no $t'$ such that $t \rightarrow t'$.

A normal form is a state where the abstract machine is halted — i.e., it can be regarded as a “result” of evaluation.
Normal forms

A normal form is a term that cannot be evaluated any further — i.e., a term $t$ is a normal form (or “is in normal form”) if there is no $t'$ such that $t \rightarrow t'$.

A normal form is a state where the abstract machine is halted — i.e., it can be regarded as a “result” of evaluation.

Recall that we intended the set of values (the boolean constants true and false) to be exactly the possible “results of evaluation.”

Did we get this definition right?
Values = normal forms

Theorem: A term $t$ is a value iff it is in normal form.

Proof:
Theorem: A term $t$ is a value iff it is in normal form.

Proof: The $\iff$ direction is immediate from the definition of the evaluation relation.
Values = normal forms

**Theorem:** A term \( t \) is a value iff it is in normal form.

**Proof:** The \( \rightarrow \) direction is immediate from the definition of the evaluation relation.

For the \( \leftarrow \) direction,
**Values = normal forms**

**Theorem:** A term $t$ is a value iff it is in normal form.

**Proof:** The $\iff$ direction is immediate from the definition of the evaluation relation.

For the $\Leftarrow$ direction, it is convenient to prove the contrapositive: If $t$ is not a value, then it is not a normal form.
**Theorem:** A term $t$ is a value iff it is in normal form.

**Proof:** The $\implies$ direction is immediate from the definition of the evaluation relation.

For the $\impliedby$ direction, it is convenient to prove the contrapositive: If $t$ is not a value, then it is not a normal form. The argument goes by induction on $t$.

Note, first, that $t$ must have the form $\text{if } t_1 \text{ then } t_2 \text{ else } t_3$ (otherwise it would be a value). If $t_1$ is $\text{true}$ or $\text{false}$, then rule $E-$IFTRUE or $E-$IFFALSE applies to $t$, and we are done. Otherwise, $t_1$ is not a value and so, by the induction hypothesis, there is some $t'_1$ such that $t_1 \longrightarrow t'_1$. But then rule $E-$IF yields

$$\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \longrightarrow \text{if } t'_1 \text{ then } t_2 \text{ else } t_3$$

i.e., $t$ is not in normal form.
New syntactic forms

\[ t ::= \ldots \]

- \( 0 \)  \hspace{1cm} constant zero
- \( \text{succ } t \)  \hspace{1cm} successor
- \( \text{pred } t \)  \hspace{1cm} predecessor
- \( \text{iszero } t \)  \hspace{1cm} zero test

\[ v ::= \ldots \]

- \( \text{nv} \)  \hspace{1cm} numeric value

\[ \text{nv} ::= \]

- \( 0 \)  \hspace{1cm} zero value
- \( \text{succ } \text{nv} \)  \hspace{1cm} successor value
New evaluation rules

\[
\begin{align*}
t_1 &\rightarrow t'_1 \\
\text{succ } t_1 &\rightarrow \text{succ } t'_1 \\
\text{pred } 0 &\rightarrow 0 \\
\text{pred } (\text{succ } n v_1) &\rightarrow n v_1 \\
t_1 &\rightarrow t'_1 \\
\text{pred } t_1 &\rightarrow \text{pred } t'_1 \\
\text{iszero } 0 &\rightarrow \text{true} \\
\text{iszero } (\text{succ } n v_1) &\rightarrow \text{false} \\
t_1 &\rightarrow t'_1 \\
\text{iszero } t_1 &\rightarrow \text{iszero } t'_1
\end{align*}
\]

(E-Succ)
(E-PredZero)
(E-PredSucc)
(E-Pred)
(E-IszeroZero)
(E-IszeroSucc)
(E-Iszero)
Syntax/Semantics of Arithmetics

Syntax

$t :=\$

true
false
if $t$ then $t$ else $t$

terms: constant true
constant false
conditional

$v :=\$

true
false

values: true value
false value

Evaluation

$t \rightarrow t'$

if true then $t_2$ else $t_3 \rightarrow t_2$
(E-IFTRUE)

if false then $t_2$ else $t_3 \rightarrow t_3$
(E-IFFALSE)

$t_1 \rightarrow t_1'$

if $t_1$ then $t_2$ else $t_3 \rightarrow t_1$
(E-IF)

$\rightarrow if t'_1 then t_2 else t_3$

Extends $B$ (3-1)

New syntactic forms

$t :=\$

... 0
succt
pred $t$
iszert $t$

terms: constant zero
successor
predecessor
zero test

$v :=\$

... $nv$

values: numeric value

New evaluation rules

$t \rightarrow t'$

t$_1 \rightarrow t'_1$
(E-SUC)

succt $t_1 \rightarrow succt'_1$

pred $0 \rightarrow 0$
(E-PREDZERO)

pred (succt $n_1$) $\rightarrow n_1$
(E-PREDSUCC)

t$_1 \rightarrow t'_1$
(E-PRED)

pred $t_1 \rightarrow pred'_1$

iszert $0 \rightarrow true$
(E-ISZEROZERO)

iszert (succt $n_1$) $\rightarrow false$
(E-ISZEROSUCC)

iszert $t_1 \rightarrow iszert t'_1$
(E-ISZERO)

Figure 3-2: Arithmetic expressions (NB)
A Derivation Tree

New syntactic forms

\[ t ::= \ldots \]

- \( 0 \)
- \( \text{succ } t \)
- \( \text{pred } t \)
- \( \text{iszero } t \)

\[ n ::= \ldots \]

- \( n_v \)

\[ n_v ::= \]

- \( 0 \)
- \( \text{succ } n_v \)

New evaluation rules

\[ t \rightarrow t' \]  (E-Succ)
\[ \text{succ } t_1 \rightarrow \text{succ } t'_1 \]  (E-Succ)
\[ \text{pred } 0 \rightarrow 0 \]  (E-PredZero)
\[ \text{pred } (\text{succ } n_v) \rightarrow n_v \]  (E-PredSucc)
\[ t_1 \rightarrow t'_1 \]  (E-Pred)
\[ \text{iszero } 0 \rightarrow \text{true} \]  (E-IszeroZero)
\[ \text{iszero } (\text{succ } n_v) \rightarrow \text{false} \]  (E-IszeroSucc)
\[ t_1 \rightarrow t'_1 \]  (E-Iszero)
\[ \text{iszero } t_1 \rightarrow \text{iszero } t'_1 \]

Figure 3-2: Arithmetic expressions (NB)
Values are normal forms

Our observation a few slides ago that all values are in normal form still holds for the extended language.
Is the converse true? i.e., is every normal form a value?
Is the converse true? I.e., is every normal form a value?

No: some terms are stuck.

Formally, a stuck term is one that is a normal form but not a value.

Stuck terms model run-time errors.

if 0 then true else false

syntax says it’s grammatical, but there is no semantic rule to apply

what’s the problem? => type mismatch the “t” in “if t ...” should be a boolean!
(don’t think in the C/C++ way!)
Syntactic Error and Types

- syntactic error: I want to going.  I eat with slowly.
- semantic error: colorless green ideas sleep furiously (Chomsky)
- PL's job is to catch more errors as (static) syntactic errors.
The multi-step evaluation relation, \( \rightarrow^* \), is the reflexive, transitive closure of single-step evaluation.

I.e., it is the smallest relation closed under the following rules:

\[
\begin{align*}
\text{t} & \rightarrow \text{t}' \\
\hline
\text{t} & \rightarrow^* \text{t}' \\
\text{t} & \rightarrow^* \text{t} \\
\hline
\text{t} & \rightarrow^* \text{t}' & \text{t}' & \rightarrow^* \text{t}'' \\
\hline
\text{t} & \rightarrow^* \text{t}''
\end{align*}
\]
Termination of evaluation

Theorem: For every $t$ there is some normal form $t'$ such that $t \rightarrow^* t'$.

Proof:
Termination of evaluation

Theorem: For every $t$ there is some normal form $t'$ such that $t \rightarrow^{*} t'$.

Proof:

♦ First, recall that single-step evaluation strictly reduces the size of the term:

if $t \rightarrow t'$, then $\text{size}(t) > \text{size}(t')$

♦ Now, assume (for a contradiction) that

$t_0, t_1, t_2, t_3, t_4, \ldots$

is an infinite-length sequence such that

$t_0, \rightarrow t_1, \rightarrow t_2, \rightarrow t_3, \rightarrow t_4, \rightarrow \cdots$,

♦ Then

$\text{size}(t_0), \text{size}(t_1), \text{size}(t_2), \text{size}(t_3), \text{size}(t_4), \ldots$

is an infinite, strictly decreasing, sequence of natural numbers.

♦ But such a sequence cannot exist — contradiction!
Termination Proofs

Most termination proofs have the same basic form:

**Theorem:** The relation $R \subseteq X \times X$ is terminating — i.e., there are no infinite sequences $x_0, x_1, x_2, \text{etc.}$ such that $(x_i, x_{i+1}) \in R$ for each $i$.

**Proof:**

1. Choose
   - a well-founded set $(W, \prec)$ — i.e., a set $W$ with a partial order $\prec$ such that there are no infinite descending chains $w_0 > w_1 > w_2 > \ldots$ in $W$
   - a function $f$ from $X$ to $W$

2. Show $f(x) > f(y)$ for all $(x, y) \in R$

3. Conclude that there are no infinite sequences $x_0, x_1, x_2, \text{etc.}$ such that $(x_i, x_{i+1}) \in R$ for each $i$), since, if there were, we could construct an infinite descending chain in $W$.  

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Big-Step Semantics

\[ \begin{align*}
\text{V} \Downarrow \text{V} & \quad \text{(B-VALUE)} \\
\frac{t_1 \Downarrow \text{true} \quad t_2 \Downarrow v_2}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \Downarrow v_2} & \quad \text{(B-IFTRUE)} \\
\frac{t_1 \Downarrow \text{false} \quad t_3 \Downarrow v_3}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \Downarrow v_3} & \quad \text{(B-IFFALSE)} \\
\frac{t_1 \Downarrow \text{nv}_1}{\text{succ } t_1 \Downarrow \text{succ } \text{nv}_1} & \quad \text{(B-SUCC)} \\
\frac{t_1 \Downarrow 0}{\text{pred } t_1 \Downarrow 0} & \quad \text{(B-PREDZERO)} \\
\frac{t_1 \Downarrow \text{succ } \text{nv}_1}{\text{pred } t_1 \Downarrow \text{nv}_1} & \quad \text{(B-PREDSUCC)} \\
\frac{t_1 \Downarrow 0}{\text{iszero } t_1 \Downarrow \text{true}} & \quad \text{(B-ISZEROLE)} \\
\frac{t_1 \Downarrow \text{succ } \text{nv}_1}{\text{iszero } t_1 \Downarrow \text{false}} & \quad \text{(B-ISZERSUCCEEDS)}
\end{align*} \]

Show that the small-step and big-step semantics for this language coincide, i.e. \( t \rightarrow^* v \iff t \Downarrow v \). \[\Box\]
When will a derivation tree branch?