Foundations of Software
Fall 2021

Week 5

Plan

PREVIOUSLY: untyped lambda calculus

TODAY: types!!

1. Two example languages:
   1.1 typing arithmetic expressions
   1.2 simply typed lambda calculus (STLC)
2. For each:
   2.1 Define types
   2.2 Specify typing rules
   2.3 Prove soundness: *progress* and *preservation*

NEXT: lambda calculus extensions
NEXT: polymorphic typing

Types

Outline

1. begin with a set of terms, a set of values, and an evaluation relation
2. define a set of *types* classifying values according to their "shapes"
3. define a *typing relation* $\mathtt{t} : \mathtt{T}$ that classifies terms according to the shape of the values that result from evaluating them
4. check that the typing relation is *sound* in the sense that,
   4.1 if $\mathtt{t} : \mathtt{T}$ and $\mathtt{t} \longrightarrow^* \mathtt{v}$, then $\mathtt{v} : \mathtt{T}$
   4.2 if $\mathtt{t} : \mathtt{T}$, then evaluation of $\mathtt{t}$ will not get stuck

Recall: Arithmetic Expressions – Syntax

`t ::=`		*terms*
	`true`	*constant true*
	`false`	*constant false*
	`if t then t else t`	*conditional*
	`0`	*constant zero*
	`succ t`	*successor*
	`pred t`	*predecessor*
	`iszero t`	*zero test*
`v ::=`		*values*
	`true`	*true value*
	`false`	*false value*
	`nv`	*numeric value*
`nv ::=`		*numeric values*
	`0`	*zero value*
	`succ nv`	*successor value*

Recall: Arithmetic Expressions – Evaluation Rules

$$\texttt{if true then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 \longrightarrow \texttt{t}_2 \qquad \text{(E-IfTrue)}$$

$$\texttt{if false then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 \longrightarrow \texttt{t}_3 \qquad \text{(E-IfFalse)}$$

$$\texttt{pred 0} \longrightarrow \texttt{0} \qquad \text{(E-PredZero)}$$

$$\texttt{pred (succ nv}_1\texttt{)} \longrightarrow \texttt{nv}_1 \qquad \text{(E-PredSucc)}$$

$$\texttt{iszero 0} \longrightarrow \texttt{true} \qquad \text{(E-IszeroZero)}$$

$$\texttt{iszero (succ nv}_1\texttt{)} \longrightarrow \texttt{false} \qquad \text{(E-IszeroSucc)}$$

Recall: Arithmetic Expressions – Evaluation Rules

$$\frac{\texttt{t}_1 \longrightarrow \texttt{t}_1'}{\texttt{if } \texttt{t}_1 \texttt{ then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 \longrightarrow \texttt{if } \texttt{t}_1' \texttt{ then } \texttt{t}_2 \texttt{ else } \texttt{t}_3} \qquad \text{(E-If)}$$

$$\frac{\texttt{t}_1 \longrightarrow \texttt{t}_1'}{\texttt{succ } \texttt{t}_1 \longrightarrow \texttt{succ } \texttt{t}_1'} \qquad \text{(E-Succ)}$$

$$\frac{\texttt{t}_1 \longrightarrow \texttt{t}_1'}{\texttt{pred } \texttt{t}_1 \longrightarrow \texttt{pred } \texttt{t}_1'} \qquad \text{(E-Pred)}$$

$$\frac{\texttt{t}_1 \longrightarrow \texttt{t}_1'}{\texttt{iszero } \texttt{t}_1 \longrightarrow \texttt{iszero } \texttt{t}_1'} \qquad \text{(E-IsZero)}$$

Types

In this language, values have two possible “shapes”: they are either booleans or numbers.

`T ::=`		*types*
	`Bool`	*type of booleans*
	`Nat`	*type of numbers*

Typing Rules

$$\texttt{true : Bool} \qquad \text{(T-True)}$$

$$\texttt{false : Bool} \qquad \text{(T-False)}$$

$$\frac{\texttt{t}_1 : \texttt{Bool} \quad \texttt{t}_2 : \texttt{T} \quad \texttt{t}_3 : \texttt{T}}{\texttt{if } \texttt{t}_1 \texttt{ then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 : \texttt{T}} \qquad \text{(T-If)}$$

$$\texttt{0 : Nat} \qquad \text{(T-Zero)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{succ } \texttt{t}_1 : \texttt{Nat}} \qquad \text{(T-Succ)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{pred } \texttt{t}_1 : \texttt{Nat}} \qquad \text{(T-Pred)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{iszero } \texttt{t}_1 : \texttt{Bool}} \qquad \text{(T-IsZero)}$$

Typing Derivations

Every pair $(\texttt{t}, \texttt{T})$ in the typing relation can be justified by a *derivation tree* built from instances of the inference rules.

$$\dfrac{\dfrac{\dfrac{}{\texttt{0 : Nat}}\,\text{T-Zero}}{\texttt{iszero 0 : Bool}}\,\text{T-IsZero} \qquad \dfrac{}{\texttt{0 : Nat}}\,\text{T-Zero} \qquad \dfrac{\dfrac{}{\texttt{0 : Nat}}\,\text{T-Zero}}{\texttt{pred 0 : Nat}}\,\text{T-Pred}}{\texttt{if iszero 0 then 0 else pred 0 : Nat}}\,\text{T-If}$$

Proofs of properties about the typing relation often proceed by induction on typing derivations.

Imprecision of Typing

Like other static program analyses, type systems are generally *imprecise*: they do not predict exactly what kind of value will be returned by every program, but just a conservative (safe) approximation.

$$\frac{\texttt{t}_1 : \texttt{Bool} \quad \texttt{t}_2 : \texttt{T} \quad \texttt{t}_3 : \texttt{T}}{\texttt{if } \texttt{t}_1 \texttt{ then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 : \texttt{T}} \qquad \text{(T-If)}$$

Using this rule, we cannot assign a type to

```
if true then 0 else false
```

even though this term will certainly evaluate to a number.

Type Safety

The safety (or soundness) of this type system can be expressed by two properties:

1. *Progress:* A well-typed term is not stuck
   If $t : T$, then either t is a value or else $t \longrightarrow t'$ for some t'.
2. *Preservation:* Types are preserved by one-step evaluation
   If $t : T$ and $t \longrightarrow t'$, then $t' : T$.

Inversion

Lemma:

1. If $\texttt{true} : \texttt{R}$, then $\texttt{R} = \texttt{Bool}$.
2. If $\texttt{false} : \texttt{R}$, then $\texttt{R} = \texttt{Bool}$.
3. If $\texttt{if}\ \texttt{t}_1\ \texttt{then}\ \texttt{t}_2\ \texttt{else}\ \texttt{t}_3 : \texttt{R}$, then $\texttt{t}_1 : \texttt{Bool}$, $\texttt{t}_2 : \texttt{R}$, and $\texttt{t}_3 : \texttt{R}$.
4. If $\texttt{0} : \texttt{R}$, then $\texttt{R} = \texttt{Nat}$.
5. If $\texttt{succ}\ \texttt{t}_1 : \texttt{R}$, then $\texttt{R} = \texttt{Nat}$ and $\texttt{t}_1 : \texttt{Nat}$.
6. If $\texttt{pred}\ \texttt{t}_1 : \texttt{R}$, then $\texttt{R} = \texttt{Nat}$ and $\texttt{t}_1 : \texttt{Nat}$.
7. If $\texttt{iszero}\ \texttt{t}_1 : \texttt{R}$, then $\texttt{R} = \texttt{Bool}$ and $\texttt{t}_1 : \texttt{Nat}$.

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Proof: ...

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Proof: ...

This leads directly to a recursive algorithm for calculating the type of a term...

Typechecking Algorithm

```
typeof(t) = if t = true then Bool
            else if t = false then Bool
            else if t = if t1 then t2 else t3 then
              let T1 = typeof(t1) in
              let T2 = typeof(t2) in
              let T3 = typeof(t3) in
              if T1 = Bool and T2=T3 then T2
              else "not typable"
            else if t = 0 then Nat
            else if t = succ t1 then
              let T1 = typeof(t1) in
              if T1 = Nat then Nat else "not typable"
            else if t = pred t1 then
              let T1 = typeof(t1) in
              if T1 = Nat then Nat else "not typable"
            else if t = iszero t1 then
              let T1 = typeof(t1) in
              if T1 = Nat then Bool else "not typable"
```

Properties of the Typing Relation

Recall: Typing Rules

$$\texttt{true} : \texttt{Bool} \qquad \text{(T-True)}$$

$$\texttt{false} : \texttt{Bool} \qquad \text{(T-False)}$$

$$\frac{\texttt{t}_1 : \texttt{Bool} \quad \texttt{t}_2 : \texttt{T} \quad \texttt{t}_3 : \texttt{T}}{\texttt{if } \texttt{t}_1 \texttt{ then } \texttt{t}_2 \texttt{ else } \texttt{t}_3 : \texttt{T}} \qquad \text{(T-If)}$$

$$\texttt{0} : \texttt{Nat} \qquad \text{(T-Zero)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{succ } \texttt{t}_1 : \texttt{Nat}} \qquad \text{(T-Succ)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{pred } \texttt{t}_1 : \texttt{Nat}} \qquad \text{(T-Pred)}$$

$$\frac{\texttt{t}_1 : \texttt{Nat}}{\texttt{iszero } \texttt{t}_1 : \texttt{Bool}} \qquad \text{(T-IsZero)}$$

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Canonical Forms

Lemma:

1. If $\texttt{v}$ is a value of type $\texttt{Bool}$, then $\texttt{v}$ is either $\texttt{true}$ or $\texttt{false}$.
2. If $\texttt{v}$ is a value of type $\texttt{Nat}$, then $\texttt{v}$ is a numeric value.

Proof:

Canonical Forms

Lemma:

1. If v is a value of type Bool, then v is either true or false.
2. If v is a value of type Nat, then v is a numeric value.

Proof: Recall the syntax of values:

v	::=	*values*
	true	*true value*
	false	*false value*
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nv	::=	*numeric values*
	0	*zero value*
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For part 1,

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For part 1, if v is true or false, the result is immediate.

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For part 1, if v is true or false, the result is immediate. But v cannot be 0 or succ nv, since the inversion lemma tells us that v would then have type Nat, not Bool.

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For part 1, if v is true or false, the result is immediate. But v cannot be 0 or succ nv, since the inversion lemma tells us that v would then have type Nat, not Bool. Part 2 is similar.

Progress

Theorem: Suppose $\mathtt{t}$ is a well-typed term (that is, $\mathtt{t} : \mathtt{T}$ for some type $\mathtt{T}$). Then either $\mathtt{t}$ is a value or else there is some $\mathtt{t}'$ with $\mathtt{t} \longrightarrow \mathtt{t}'$.

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Case T-If: $\mathtt{t} = \mathtt{if}\ \mathtt{t}_1\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3$
$\mathtt{t}_1 : \mathtt{Bool} \quad \mathtt{t}_2 : \mathtt{T} \quad \mathtt{t}_3 : \mathtt{T}$

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By the induction hypothesis, either $\mathtt{t}_1$ is a value or else there is some $\mathtt{t}_1'$ such that $\mathtt{t}_1 \longrightarrow \mathtt{t}_1'$. If $\mathtt{t}_1$ is a value, then the canonical forms lemma tells us that it must be either $\mathtt{true}$ or $\mathtt{false}$, in which case either E-IfTrue or E-IfFalse applies to $\mathtt{t}$. On the other hand, if $\mathtt{t}_1 \longrightarrow \mathtt{t}_1'$, then, by E-If, $\mathtt{t} \longrightarrow \mathtt{if}\ \mathtt{t}_1'\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3$.

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Proof: By induction on a derivation of $\mathtt{t} : \mathtt{T}$.

The cases for rules T-Zero, T-Succ, T-Pred, and T-IsZero are similar.

(Recommended: Try to reconstruct them.)

Preservation

Theorem: If $\mathtt{t} : \mathtt{T}$ and $\mathtt{t} \longrightarrow \mathtt{t}'$, then $\mathtt{t}' : \mathtt{T}$.

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Case T-TRUE: $\mathtt{t} = \mathtt{true}$ $\mathtt{T} = \mathtt{Bool}$

Then $\mathtt{t}$ is a value.

Preservation

Theorem: If $\mathtt{t} : \mathtt{T}$ and $\mathtt{t} \longrightarrow \mathtt{t}'$, then $\mathtt{t}' : \mathtt{T}$.

Proof: By induction on the given typing derivation.

Case T-IF:

$\mathtt{t} = \mathtt{if}\ \mathtt{t}_1\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3$ $\mathtt{t}_1 : \mathtt{Bool}$ $\mathtt{t}_2 : \mathtt{T}$ $\mathtt{t}_3 : \mathtt{T}$

There are three evaluation rules by which $\mathtt{t} \longrightarrow \mathtt{t}'$ can be derived: E-IFTRUE, E-IFFALSE, and E-IF. Consider each case separately.

Preservation

Theorem: If $\mathtt{t} : \mathtt{T}$ and $\mathtt{t} \longrightarrow \mathtt{t}'$, then $\mathtt{t}' : \mathtt{T}$.

Proof: By induction on the given typing derivation.

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Subcase E-IFTRUE: $\mathtt{t}_1 = \mathtt{true}$ $\mathtt{t}' = \mathtt{t}_2$

Immediate, by the assumption $\mathtt{t}_2 : \mathtt{T}$.

(E-IFFALSE subcase: Similar.)

Preservation

Theorem: If $\mathtt{t} : \mathtt{T}$ and $\mathtt{t} \longrightarrow \mathtt{t}'$, then $\mathtt{t}' : \mathtt{T}$.

Proof: By induction on the given typing derivation.

Case T-IF:
$\mathtt{t} = \mathtt{if}\ \mathtt{t}_1\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3 \quad \mathtt{t}_1 : \mathtt{Bool} \quad \mathtt{t}_2 : \mathtt{T} \quad \mathtt{t}_3 : \mathtt{T}$

There are three evaluation rules by which $\mathtt{t} \longrightarrow \mathtt{t}'$ can be derived: E-IFTRUE, E-IFFALSE, and E-IF. Consider each case separately.

Subcase E-IF: $\quad \mathtt{t}_1 \longrightarrow \mathtt{t}_1' \qquad \mathtt{t}' = \mathtt{if}\ \mathtt{t}_1'\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3$

Applying the IH to the subderivation of $\mathtt{t}_1 : \mathtt{Bool}$ yields $\mathtt{t}_1' : \mathtt{Bool}$. Combining this with the assumptions that $\mathtt{t}_2 : \mathtt{T}$ and $\mathtt{t}_3 : \mathtt{T}$, we can apply rule T-IF to conclude that $\mathtt{if}\ \mathtt{t}_1'\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3 : \mathtt{T}$, that is, $\mathtt{t}' : \mathtt{T}$.

Messing With It

Messing with it: Remove a rule

What if we remove E-PREDZERO ?

Messing with it: Remove a rule

What if we remove E-PREDZERO ?

Then `pred 0` type checks, but it is stuck and is not a value. Thus the progress theorem fails.

Messing with it: If

What if we change the rule for typing `if`'s to the following ?:

$$\frac{\mathtt{t_1 : Bool} \quad \mathtt{t_2 : Nat} \quad \mathtt{t_3 : Nat}}{\mathtt{if\ t_1\ then\ t_2\ else\ t_3 : Nat}} \quad \text{(T-If)}$$

Messing with it: If

What if we change the rule for typing `if`'s to the following ?:

$$\frac{\mathtt{t_1 : Bool} \quad \mathtt{t_2 : Nat} \quad \mathtt{t_3 : Nat}}{\mathtt{if\ t_1\ then\ t_2\ else\ t_3 : Nat}} \quad \text{(T-If)}$$

The system is still sound. Some `if`'s do not type, but those that do are fine.

Meassing with it: adding bit

`t`	::=	*terms*
	...	
	bit(t)	*boolean to natural*

1. evaluation rule
2. typing rule
3. progress and preservation updates

The Simply Typed Lambda-Calculus

The simply typed lambda-calculus

The system we are about to define is commonly called the *simply typed lambda-calculus*, or $\lambda_{\rightarrow}$ for short.

Unlike the untyped lambda-calculus, the "pure" form of $\lambda_{\rightarrow}$ (with no primitive values or operations) is not very interesting; to talk about $\lambda_{\rightarrow}$, we always begin with some set of "base types."

- So, strictly speaking, there are *many* variants of $\lambda_{\rightarrow}$, depending on the choice of base types.
- For now, we'll work with a variant constructed over the booleans.

Untyped lambda-calculus with booleans

`t ::=`		*terms*
	`x`	*variable*
	`λx.t`	*abstraction*
	`t t`	*application*
	`true`	*constant true*
	`false`	*constant false*
	`if t then t else t`	*conditional*
`v ::=`		*values*
	`λx.t`	*abstraction value*
	`true`	*true value*
	`false`	*false value*

"Simple Types"

`T ::=`		*types*
	`Bool`	*type of booleans*
	`T→T`	*types of functions*

What are some examples?

Type Annotations

We now have a choice to make. Do we...

- annotate lambda-abstractions with the expected type of the argument

  $$\lambda x{:}T_1.\ t_2$$

  (as in most mainstream programming languages), or
- continue to write lambda-abstractions as before

  $$\lambda x.\ t_2$$

  and ask the typing rules to "guess" an appropriate annotation (as in OCaml)?

Both are reasonable choices, but the first makes the job of defining the typing rules simpler. Let's take this choice for now.

Typing rules

$$\mathtt{true} : \mathtt{Bool} \qquad \text{(T-TRUE)}$$

$$\mathtt{false} : \mathtt{Bool} \qquad \text{(T-FALSE)}$$

$$\frac{\mathtt{t_1} : \mathtt{Bool} \qquad \mathtt{t_2} : \mathtt{T} \qquad \mathtt{t_3} : \mathtt{T}}{\mathtt{if}\ \mathtt{t_1}\ \mathtt{then}\ \mathtt{t_2}\ \mathtt{else}\ \mathtt{t_3} : \mathtt{T}} \qquad \text{(T-IF)}$$

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$$\frac{???}{\lambda \mathtt{x}{:}\mathtt{T_1}.\mathtt{t_2} : \mathtt{T_1} \to \mathtt{T_2}} \qquad \text{(T-ABS)}$$

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$$\frac{\mathtt{t_1} : \mathtt{Bool} \qquad \mathtt{t_2} : \mathtt{T} \qquad \mathtt{t_3} : \mathtt{T}}{\mathtt{if}\ \mathtt{t_1}\ \mathtt{then}\ \mathtt{t_2}\ \mathtt{else}\ \mathtt{t_3} : \mathtt{T}} \qquad \text{(T-IF)}$$

$$\frac{\Gamma, \mathtt{x}{:}\mathtt{T_1} \vdash \mathtt{t_2} : \mathtt{T_2}}{\Gamma \vdash \lambda \mathtt{x}{:}\mathtt{T_1}.\mathtt{t_2} : \mathtt{T_1} \to \mathtt{T_2}} \qquad \text{(T-ABS)}$$

$$\frac{\mathtt{x}{:}\mathtt{T} \in \Gamma}{\Gamma \vdash \mathtt{x} : \mathtt{T}} \qquad \text{(T-VAR)}$$

Typing rules

$$\Gamma \vdash \mathtt{true} : \mathtt{Bool} \qquad \text{(T-TRUE)}$$

$$\Gamma \vdash \mathtt{false} : \mathtt{Bool} \qquad \text{(T-FALSE)}$$

$$\frac{\Gamma \vdash \mathtt{t_1} : \mathtt{Bool} \qquad \Gamma \vdash \mathtt{t_2} : \mathtt{T} \qquad \Gamma \vdash \mathtt{t_3} : \mathtt{T}}{\Gamma \vdash \mathtt{if}\ \mathtt{t_1}\ \mathtt{then}\ \mathtt{t_2}\ \mathtt{else}\ \mathtt{t_3} : \mathtt{T}} \qquad \text{(T-IF)}$$

$$\frac{\Gamma, \mathtt{x}{:}\mathtt{T_1} \vdash \mathtt{t_2} : \mathtt{T_2}}{\Gamma \vdash \lambda \mathtt{x}{:}\mathtt{T_1}.\mathtt{t_2} : \mathtt{T_1} \to \mathtt{T_2}} \qquad \text{(T-ABS)}$$

$$\frac{\mathtt{x}{:}\mathtt{T} \in \Gamma}{\Gamma \vdash \mathtt{x} : \mathtt{T}} \qquad \text{(T-VAR)}$$

$$\frac{\Gamma \vdash \mathtt{t_1} : \mathtt{T_{11}} \to \mathtt{T_{12}} \qquad \Gamma \vdash \mathtt{t_2} : \mathtt{T_{11}}}{\Gamma \vdash \mathtt{t_1}\ \mathtt{t_2} : \mathtt{T_{12}}} \qquad \text{(T-APP)}$$

Typing Derivations

What derivations justify the following typing statements?

- $\vdash$ `(λx:Bool.x) true` : `Bool`
- `f:Bool→Bool` $\vdash$
  `f (if false then true else false)` : `Bool`
- `f:Bool→Bool` $\vdash$
  `λx:Bool. f (if x then false else x)` : `Bool→Bool`

Properties of $\lambda_{\rightarrow}$

The fundamental property of the type system we have just defined is *soundness* with respect to the operational semantics.

1. *Progress:* A closed, well-typed term is not stuck
   If $\vdash t : T$*, then either* t *is a value or else* $t \longrightarrow t'$ *for some* t'*.*
2. *Preservation:* Types are preserved by one-step evaluation
   If $\Gamma \vdash t : T$ *and* $t \longrightarrow t'$*, then* $\Gamma \vdash t' : T$*.*

Proving progress

Same steps as before...

Proving progress

Same steps as before...

- inversion lemma for typing relation
- canonical forms lemma
- progress theorem

Inversion

Lemma:

1. If $\Gamma \vdash \mathtt{true} : \mathtt{R}$, then $\mathtt{R} = \mathtt{Bool}$.
2. If $\Gamma \vdash \mathtt{false} : \mathtt{R}$, then $\mathtt{R} = \mathtt{Bool}$.
3. If $\Gamma \vdash \mathtt{if}\ \mathtt{t}_1\ \mathtt{then}\ \mathtt{t}_2\ \mathtt{else}\ \mathtt{t}_3 : \mathtt{R}$, then $\Gamma \vdash \mathtt{t}_1 : \mathtt{Bool}$ and $\Gamma \vdash \mathtt{t}_2, \mathtt{t}_3 : \mathtt{R}$.

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4. If $\Gamma \vdash \mathtt{x} : \mathtt{R}$, then $\mathtt{x}{:}\mathtt{R} \in \Gamma$.

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5. If $\Gamma \vdash \lambda\texttt{x}{:}\texttt{T}_1\texttt{.t}_2 : \texttt{R}$, then $\texttt{R} = \texttt{T}_1{\rightarrow}\texttt{R}_2$ for some $\texttt{R}_2$ with $\Gamma, \texttt{x}{:}\texttt{T}_1 \vdash \texttt{t}_2 : \texttt{R}_2$.

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5. If $\Gamma \vdash \lambda\texttt{x}{:}\texttt{T}_1\texttt{.t}_2 : \texttt{R}$, then $\texttt{R} = \texttt{T}_1{\rightarrow}\texttt{R}_2$ for some $\texttt{R}_2$ with $\Gamma, \texttt{x}{:}\texttt{T}_1 \vdash \texttt{t}_2 : \texttt{R}_2$.

6. If $\Gamma \vdash \texttt{t}_1\ \texttt{t}_2 : \texttt{R}$, then there is some type $\texttt{T}_{11}$ such that $\Gamma \vdash \texttt{t}_1 : \texttt{T}_{11}{\rightarrow}\texttt{R}$ and $\Gamma \vdash \texttt{t}_2 : \texttt{T}_{11}$.

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Canonical Forms

Lemma:

1. If v is a value of type `Bool`, then v is either `true` or `false`.
2. If v is a value of type $T_1 \rightarrow T_2$, then v has the form $\lambda x{:}T_1.t_2$.

Progress

Theorem: Suppose $\mathtt{t}$ is a closed, well-typed term (that is, $\vdash \mathtt{t} : \mathtt{T}$ for some $\mathtt{T}$). Then either $\mathtt{t}$ is a value or else there is some $\mathtt{t}'$ with $\mathtt{t} \longrightarrow \mathtt{t}'$.

Proof: By induction

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Consider the case for application, where $\mathtt{t} = \mathtt{t}_1\ \mathtt{t}_2$ with $\vdash \mathtt{t}_1 : \mathtt{T}_{11} \to \mathtt{T}_{12}$ and $\vdash \mathtt{t}_2 : \mathtt{T}_{11}$.

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Proof: By induction on typing derivations. The cases for boolean constants and conditions are the same as before. The variable case is trivial (because $\mathtt{t}$ is closed). The abstraction case is immediate, since abstractions are values.
Consider the case for application, where $\mathtt{t} = \mathtt{t}_1\ \mathtt{t}_2$ with $\vdash \mathtt{t}_1 : \mathtt{T}_{11} \rightarrow \mathtt{T}_{12}$ and $\vdash \mathtt{t}_2 : \mathtt{T}_{11}$. By the induction hypothesis, either $\mathtt{t}_1$ is a value or else it can make a step of evaluation, and likewise $\mathtt{t}_2$. If $\mathtt{t}_1$ can take a step, then rule E-App1 applies to $\mathtt{t}$. If $\mathtt{t}_1$ is a value and $\mathtt{t}_2$ can take a step, then rule E-App2 applies. Finally, if both $\mathtt{t}_1$ and $\mathtt{t}_2$ are values, then the canonical forms lemma tells us that $\mathtt{t}_1$ has the form $\lambda\mathtt{x}{:}\mathtt{T}_{11}.\mathtt{t}_{12}$, and so rule E-AppAbs applies to $\mathtt{t}$.