

Foundations of Software Fall 2022

Week 5

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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

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Types

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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* $t : T$ 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 $t : T$ and $t \longrightarrow^* v$, then $v : T$
 - 4.2 if $t : T$, then evaluation of t will not get stuck

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Recall: Arithmetic Expressions – Syntax

$t ::=$	<i>terms</i>
true	<i>constant true</i>
false	<i>constant false</i>
if t then t else t	<i>conditional</i>
0	<i>constant zero</i>
succ t	<i>successor</i>
pred t	<i>predecessor</i>
iszero t	<i>zero test</i>
$v ::=$	<i>values</i>
true	<i>true value</i>
false	<i>false value</i>
nv	<i>numeric value</i>
$nv ::=$	<i>numeric values</i>
0	<i>zero value</i>
succ nv	<i>successor value</i>

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Recall: Arithmetic Expressions – Evaluation Rules

if true then t_2 else $t_3 \longrightarrow t_2$	(E-IFTRUE)
if false then t_2 else $t_3 \longrightarrow t_3$	(E-IFFALSE)
pred 0 \longrightarrow 0	(E-PREDZERO)
pred (succ nv_1) $\longrightarrow nv_1$	(E-PREDSUCC)
iszero 0 \longrightarrow true	(E-ISZEROZERO)
iszero (succ nv_1) \longrightarrow false	(E-ISZEROSUCC)

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Recall: Arithmetic Expressions – Evaluation Rules

$$\frac{t_1 \longrightarrow t'_1}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 \longrightarrow \text{if } t'_1 \text{ then } t_2 \text{ else } t_3} \quad (\text{E-IF})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{succ } t_1 \longrightarrow \text{succ } t'_1} \quad (\text{E-SUCC})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{pred } t_1 \longrightarrow \text{pred } t'_1} \quad (\text{E-PRED})$$

$$\frac{t_1 \longrightarrow t'_1}{\text{iszero } t_1 \longrightarrow \text{iszero } t'_1} \quad (\text{E-ISZERO})$$

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Types

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

$T ::=$	<i>types</i>
<code>Bool</code>	<i>type of booleans</i>
<code>Nat</code>	<i>type of numbers</i>

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Typing Rules

$\text{true} : \text{Bool}$	(T-TRUE)
$\text{false} : \text{Bool}$	(T-FALSE)
$\frac{t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T}$	(T-IF)
$0 : \text{Nat}$	(T-ZERO)
$\frac{t_1 : \text{Nat}}{\text{succ } t_1 : \text{Nat}}$	(T-SUCC)
$\frac{t_1 : \text{Nat}}{\text{pred } t_1 : \text{Nat}}$	(T-PRED)
$\frac{t_1 : \text{Nat}}{\text{iszero } t_1 : \text{Bool}}$	(T-ISZERO)

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Typing Derivations

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

$\frac{\text{————— T-ZERO}}{0 : \text{Nat}}$	$\frac{\text{————— T-ZERO}}{0 : \text{Nat}}$	$\frac{\text{————— T-ZERO}}{0 : \text{Nat}}$
$\frac{\text{————— T-ISZERO}}{\text{iszero } 0 : \text{Bool}}$	$\frac{\text{————— T-ZERO}}{0 : \text{Nat}}$	$\frac{\text{————— T-PRED}}{\text{pred } 0 : \text{Nat}}$
$\frac{\text{————— T-IF}}{\text{if iszero } 0 \text{ then } 0 \text{ else pred } 0 : \text{Nat}}$		

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

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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.

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

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.

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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 $t' : T$.

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Inversion

Lemma:

1. If `true` : R, then $R = \text{Bool}$.
2. If `false` : R, then $R = \text{Bool}$.
3. If `if t1 then t2 else t3` : R, then $t_1 : \text{Bool}$, $t_2 : R$, and $t_3 : R$.
4. If `0` : R, then $R = \text{Nat}$.
5. If `succ t1` : R, then $R = \text{Nat}$ and $t_1 : \text{Nat}$.
6. If `pred t1` : R, then $R = \text{Nat}$ and $t_1 : \text{Nat}$.
7. If `iszero t1` : R, then $R = \text{Bool}$ and $t_1 : \text{Nat}$.

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Proof: ...

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4. If `0` : R, then $R = \text{Nat}$.
5. If `succ t1` : R, then $R = \text{Nat}$ and $t_1 : \text{Nat}$.
6. If `pred t1` : R, then $R = \text{Nat}$ and $t_1 : \text{Nat}$.
7. If `iszero t1` : R, then $R = \text{Bool}$ and $t_1 : \text{Nat}$.

Proof: ...

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

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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"
```

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Properties of the Typing Relation

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Recall: Typing Rules

$\text{true} : \text{Bool}$	(T-TRUE)
$\text{false} : \text{Bool}$	(T-FALSE)
$\frac{t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T}$	(T-IF)
$0 : \text{Nat}$	(T-ZERO)
$\frac{t_1 : \text{Nat}}{\text{succ } t_1 : \text{Nat}}$	(T-SUCC)
$\frac{t_1 : \text{Nat}}{\text{pred } t_1 : \text{Nat}}$	(T-PRED)
$\frac{t_1 : \text{Nat}}{\text{iszero } t_1 : \text{Bool}}$	(T-ISZERO)

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Recall: Inversion

Lemma:

1. If `true` : R , then $R = \text{Bool}$.
2. If `false` : R , then $R = \text{Bool}$.
3. If `if` t_1 `then` t_2 `else` t_3 : R , then t_1 : Bool , t_2 : R , and t_3 : R .
4. If `0` : R , then $R = \text{Nat}$.
5. If `succ` t_1 : R , then $R = \text{Nat}$ and t_1 : Nat .
6. If `pred` t_1 : R , then $R = \text{Nat}$ and t_1 : Nat .
7. If `iszero` t_1 : R , then $R = \text{Bool}$ and t_1 : Nat .

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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 `Nat`, then v is a numeric value.

Proof:

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Canonical Forms

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1. If v is a value of type `Bool`, then v is either `true` or `false`.
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Proof: Recall the syntax of values:

$v ::=$	<i>values</i>
<code>true</code>	<i>true value</i>
<code>false</code>	<i>false value</i>
<code>nv</code>	<i>numeric value</i>
$nv ::=$	<i>numeric values</i>
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For part 1,

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<code>succ nv</code>	<i>successor value</i>

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

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2. If v is a value of type `Nat`, then v is a numeric value.

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$nv ::=$	<i>numeric values</i>
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<code>succ nv</code>	<i>successor value</i>

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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<code>true</code>	<i>true value</i>
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<code>nv</code>	<i>numeric value</i>
$nv ::=$	<i>numeric values</i>
<code>0</code>	<i>zero value</i>
<code>succ nv</code>	<i>successor value</i>

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.

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Progress

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

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Proof: By induction on a derivation of $t : T$.

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The T-TRUE, T-FALSE, and T-ZERO cases are immediate, since t in these cases is a value.

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Proof: By induction on a derivation of $t : T$.

The T-TRUE, T-FALSE, and T-ZERO cases are immediate, since t in these cases is a value.

Case T-IF: $t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3$
 $t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T$

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Progress

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

Proof: By induction on a derivation of $t : T$.

The T-TRUE, T-FALSE, and T-ZERO cases are immediate, since t in these cases is a value.

Case T-IF: $t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3$
 $t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T$

By the induction hypothesis, either t_1 is a value or else there is some t'_1 such that $t_1 \longrightarrow t'_1$. If t_1 is a value, then the canonical forms lemma tells us that it must be either `true` or `false`, in which case either E-IFTRUE or E-IFFALSE applies to t . On the other hand, if $t_1 \longrightarrow t'_1$, then, by E-IF, $t \longrightarrow \text{if } t'_1 \text{ then } t_2 \text{ else } t_3$.

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Progress

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

Proof: By induction on a derivation of $t : T$.

The cases for rules T-ZERO, T-SUCC, T-PRED, and T-ISZERO are similar.

(Recommended: Try to reconstruct them.)

Preservation

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

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Proof: By induction on the given typing derivation.

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Preservation

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

Proof: By induction on the given typing derivation.

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

Then t is a value.

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Preservation

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

Proof: By induction on the given typing derivation.

Case T-IF:

$t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 \quad t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T$

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

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Preservation

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

Proof: By induction on the given typing derivation.

Case T-IF:

$t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 \quad t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T$

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

Subcase E-IFTRUE: $t_1 = \text{true} \quad t' = t_2$

Immediate, by the assumption $t_2 : T$.

(E-IFFALSE subcase: Similar.)

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Preservation

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

Proof: By induction on the given typing derivation.

Case T-IF:

$t = \text{if } t_1 \text{ then } t_2 \text{ else } t_3 \quad t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T$

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

Subcase E-IF: $t_1 \longrightarrow t'_1 \quad t' = \text{if } t'_1 \text{ then } t_2 \text{ else } t_3$

Applying the IH to the subderivation of $t_1 : \text{Bool}$ yields

$t'_1 : \text{Bool}$. Combining this with the assumptions that $t_2 : T$ and

$t_3 : T$, we can apply rule T-IF to conclude that

$\text{if } t'_1 \text{ then } t_2 \text{ else } t_3 : T$, that is, $t' : T$.

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Messing With It

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Messing with it: Remove a rule

What if we remove E-PREDZERO ?

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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.

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Messing with it: If

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

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

Messing with it: If

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

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

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

Messing with it: adding bit

$t ::=$

\dots
 $\text{bit}(t)$

terms

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 λ_{\rightarrow} for short.

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

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

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Untyped lambda-calculus with booleans

$t ::=$	<i>terms</i>
x	<i>variable</i>
$\lambda x. t$	<i>abstraction</i>
$t \ t$	<i>application</i>
true	<i>constant true</i>
false	<i>constant false</i>
$\text{if } t \text{ then } t \text{ else } t$	<i>conditional</i>
 $v ::=$	 <i>values</i>
$\lambda x. t$	<i>abstraction value</i>
true	<i>true value</i>
false	<i>false value</i>

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“Simple Types”

$T ::=$

Bool

$T \rightarrow T$

types

type of booleans

types of functions

What are some examples?

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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.

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Typing rules

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

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

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

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Typing rules

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

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

$$\frac{t_1 : \text{Bool} \quad t_2 : T \quad t_3 : T}{\text{if } t_1 \text{ then } t_2 \text{ else } t_3 : T} \quad (\text{T-IF})$$
$$\frac{???}{\lambda x:T_1. t_2 : T_1 \rightarrow T_2} \quad (\text{T-ABS})$$

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Typing rules

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

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

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

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

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

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Typing rules

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

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

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

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

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

$$\frac{\Gamma \vdash t_1 : T_{11} \rightarrow T_{12} \quad \Gamma \vdash t_2 : T_{11}}{\Gamma \vdash t_1 \ t_2 : T_{12}} \quad (\text{T-APP})$$

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Typing Derivations

What derivations justify the following typing statements?

- ▶ $\vdash (\lambda x:\text{Bool}.x) \text{ true} : \text{Bool}$
- ▶ $f:\text{Bool} \rightarrow \text{Bool} \vdash$
 $f (\text{if false then true else false}) : \text{Bool}$
- ▶ $f:\text{Bool} \rightarrow \text{Bool} \vdash$
 $\lambda x:\text{Bool}. f (\text{if } x \text{ then false else } x) : \text{Bool} \rightarrow \text{Bool}$

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Properties of λ_{\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 $\Gamma \vdash t' : T$.

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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 $\Gamma \vdash \text{true} : R$, then $R = \text{Bool}$.
2. If $\Gamma \vdash \text{false} : R$, then $R = \text{Bool}$.
3. If $\Gamma \vdash \text{if } t_1 \text{ then } t_2 \text{ else } t_3 : R$, then $\Gamma \vdash t_1 : \text{Bool}$ and $\Gamma \vdash t_2, t_3 : R$.

Inversion

Lemma:

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3. If $\Gamma \vdash \text{if } t_1 \text{ then } t_2 \text{ else } t_3 : R$, then $\Gamma \vdash t_1 : \text{Bool}$ and $\Gamma \vdash t_2, t_3 : R$.
4. If $\Gamma \vdash x : R$, then

Inversion

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

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Inversion

Lemma:

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2. If $\Gamma \vdash \text{false} : R$, then $R = \text{Bool}$.
3. If $\Gamma \vdash \text{if } t_1 \text{ then } t_2 \text{ else } t_3 : R$, then $\Gamma \vdash t_1 : \text{Bool}$ and $\Gamma \vdash t_2, t_3 : R$.
4. If $\Gamma \vdash x : R$, then $x : R \in \Gamma$.
5. If $\Gamma \vdash \lambda x : T_1. t_2 : R$, then

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Inversion

Lemma:

1. If $\Gamma \vdash \text{true} : R$, then $R = \text{Bool}$.
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3. If $\Gamma \vdash \text{if } t_1 \text{ then } t_2 \text{ else } t_3 : R$, then $\Gamma \vdash t_1 : \text{Bool}$ and $\Gamma \vdash t_2, t_3 : R$.
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6. If $\Gamma \vdash t_1 \ t_2 : R$, then there is some type T_{11} such that $\Gamma \vdash t_1 : T_{11} \rightarrow R$ and $\Gamma \vdash t_2 : T_{11}$.

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Canonical Forms

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

Proof: By induction

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Proof: By induction on typing derivations.

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Consider the case for application, where $t = t_1 \ t_2$ with $\vdash t_1 : T_{11} \rightarrow T_{12}$ and $\vdash t_2 : T_{11}$. By the induction hypothesis, either t_1 is a value or else it can make a step of evaluation, and likewise t_2 . If t_1 can take a step, then rule E-APP1 applies to t . If t_1 is a value and t_2 can take a step, then rule E-APP2 applies. Finally, if both t_1 and t_2 are values, then the canonical forms lemma tells us that t_1 has the form $\lambda x:T_{11}.t_{12}$, and so rule E-APPABS applies to t .

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