Type Systems

Lecture 3: Consistency and Termination

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From Type Safety to Stronger Properties

- In the last lecture, we saw how evaluation corresponded to proof normalization
- This was an act of knowledge transfer from computation to logic
- Are there any transfers we can make in the other direction?

Logical Consistency

- An important property of any logic is consistency: there are no proofs of $\bot$!
- Otherwise, the $\bot$E rule will let us prove anything.
- What does this look like in a programming language?

Types and Values

$$
\begin{array}{llll}
\text{Types} & X & ::= & 1 \mid X \times Y \mid 0 \mid X + Y \mid X \to Y \\
\text{Values} & v & ::= & \langle\rangle \mid \langle v, v' \rangle \mid \lambda x : A.\, e \mid \mathsf{L}\, v \mid \mathsf{R}\, v
\end{array}
$$

- There are no values of type 0
- I.e., no normal forms of type 0
- But what about non-normal forms?

What Type Safety Does, and Doesn't Show

- We have proved type safety:
  - Progress: If $\cdot \vdash e : X$ then e is a value or $e \leadsto e'$.
  - Type preservation If $\cdot \vdash e : X$ and $e \leadsto e'$ then $\cdot \vdash e' : X$.

- If there were a closed term of type 0, then progress means it must always step (since there are no values of type 0)
- But the term it would step to also has type 0 (by preservation)
- So any closed term of type 0 must loop – it must step forever.

A Naive Proof that Does Not Work

Theorem: If $\cdot \vdash e : X$ then there is a value v such that $e \leadsto^* v$.

“Proof”: By structural induction on $\cdot \vdash e : X$

(1)	$\dfrac{\overbrace{\Gamma \vdash e : X \to Y}^{(2)} \qquad \overbrace{\Gamma \vdash e' : X}^{(3)}}{\Gamma \vdash e\, e' : Y}$	Assumption
(4)	$e \leadsto^* v$	Induction on (2)
(5)	$e' \leadsto^* v'$	Induction on (3)
(6)	$\cdot \vdash v : X \to Y$	Preservation on (2), (4)
(7)	$\cdot \vdash v' : X$	Preservation on (3), (5)
(8)	$\cdot \vdash v \equiv \lambda x : X.\, e'' : X \to Y$	Canonical forms on (6)
(9)	$x : X \vdash e'' : Y$	Subderivation
(10)	$\underbrace{\cdot \vdash [v'/x]e'' : Y}_{\text{Can't do induction on this!}}$	Substitution

A Minimal Typed Lambda Calculus

$$
\begin{array}{llcl}
\text{Types} & X & ::= & 1 \mid X \to Y \mid 0 \\
\text{Terms} & e & ::= & x \mid \langle\rangle \mid \lambda x : X.\, e \mid e\, e' \mid \mathsf{abort}\, e \\
\text{Values} & v & ::= & \langle\rangle \mid \lambda x : X.\, e
\end{array}
$$

$$\frac{X : X \in \Gamma}{\Gamma \vdash x : X}\ \textsc{Hyp} \qquad\qquad \frac{}{\Gamma \vdash \langle\rangle : 1}\ 1\mathrm{I}$$

$$\frac{\Gamma, X \vdash e : Y}{\Gamma \vdash \lambda x : X.\, e : X \to Y}\ {\to}\mathrm{I} \qquad\qquad \frac{\Gamma \vdash e : X \to Y \qquad \Gamma \vdash e' : X}{\Gamma \vdash e\, e' : Y}\ {\to}\mathrm{E}$$

$$\frac{\Gamma \vdash e : 0}{\Gamma \vdash \mathsf{abort}\, e : Z}\ 0\mathrm{E}$$

Reductions

$$\frac{e \rightsquigarrow e'}{\mathsf{abort}\, e \rightsquigarrow \mathsf{abort}\, e'}$$

$$\frac{e_1 \rightsquigarrow e_1'}{e_1\, e_2 \rightsquigarrow e_1'\, e_2} \qquad \frac{e_2 \rightsquigarrow e_2'}{v_1\, e_2 \rightsquigarrow v_1\, e_2'}$$

$$\frac{}{(\lambda x : X.\, e)\, v \rightsquigarrow [v/x]e}$$

Theorem (Determinacy): If $e \rightsquigarrow e'$ and $e \rightsquigarrow e''$ then $e' = e''$

Proof: By structural induction on $e \rightsquigarrow e'$

Why Can’t We Prove Termination

- We can’t prove termination by structural induction
- Problem is that knowing a term evaluates to a function doesn’t tell us that applying the function terminates
- We need to assume something stronger

A Logical Relation

1. We say that <u>e halts</u> if and only if there is a v such that $e \leadsto^* v$.
2. Now, we will define a type-indexed family of set of terms:
   - $\mathrm{Halt}_0 = \emptyset$ (i.e, for all e, $e \notin \mathrm{Halt}_0$)
   - $e \in \mathrm{Halt}_1$ holds just when e halts.
   - $e \in \mathrm{Halt}_{X \to Y}$ holds just when
     1. e halts
     2. For all e', if $e' \in \mathrm{Halt}_X$ then $(e\ e') \in \mathrm{Halt}_Y$.
3. Hereditary definition:
   - Halt_1 halts
   - $\mathrm{Halt}_{1 \to 1}$ preserves the property of halting
   - $\mathrm{Halt}_{(1 \to 1) \to (1 \to 1)}$ preserves the property of preserving the property of halting...

The Goal

Imagine we can prove:

Conjecture: If $\cdot \vdash e : X$, then $e \in \mathrm{Halt}_X$.

Then we know that every closed program terminates! But to prove this, we need to first establish a lemma or two.

Closure Lemma, 1/5

Lemma: If $e \rightsquigarrow e'$ then $e' \in \mathrm{Halt}_X$ iff $e \in \mathrm{Halt}_X$.

Proof: By induction on X:

- Case $X = 1, \Rightarrow$:

(1)	$e \rightsquigarrow e'$	Assumption
(2)	$e' \in \mathrm{Halt}_1$	Assumption
(3)	$e' \rightsquigarrow^* v$	Definition of Halt_1
(4)	$e \rightsquigarrow^* v$	Def. of transitive closure, (1) and (3)
(5)	$e \in \mathrm{Halt}_1$	Definition of Halt_1

Closure Lemma, 2/5

- Case $X = 1$, $\Leftarrow$:

(1)	$e \leadsto e'$	Assumption
(2)	$e \in \mathrm{Halt}_1$	Assumption
(3)	$e \leadsto^* v$	Definition of Halt_1
(4)	e is not a value:	Since $e \leadsto e'$
(5)	$e \leadsto e''$ and $e'' \leadsto^* v$	Definition of $e \leadsto^* v$
(6)	$e'' = e'$	By determinacy on (1), (5)
(7)	$e' \leadsto^* v$	By equality (6) on (5)
(8)	$e' \in \mathrm{Halt}_1$	Definition of Halt_1

Closure Lemma, 3/5

- Case $X = Y \to Z$, $\Rightarrow$:

(1)	$e \rightsquigarrow e'$	Assumption
(2)	$e' \in \text{Halt}_{Y \to Z}$	Assumption
(3)	$e' \rightsquigarrow^* v$	Def. of $\text{Halt}_{Y \to Z}$
(4)	$\forall t \in \text{Halt}_Y, e'\ t \in \text{Halt}_Z$	”
(5)	$e \rightsquigarrow^* v$	Transitive closure, (1) and (3)
	Assume $t \in \text{Halt}_Y$:	
(6)	$e\ t \rightsquigarrow e'\ t$	By congruence rule on (1)
(7)	$e'\ t \in \text{Halt}_Z$	By (4)
	$e\ t \in \text{Halt}_Z$	By induction on (6), (7)
(8)	$\forall t \in \text{Halt}_Y, e\ t \in \text{Halt}_Z$	
(9)	$e \in \text{Halt}_{Y \to Z}$	Def of $\text{Halt}_{Y \to Z}$ on (5), (8)

Closure Lemma, 4/5

- Case $X = Y \to Z$, $\Leftarrow$:

(1)	$e \rightsquigarrow e'$	Assumption
(2)	$e \in \text{Halt}_{Y \to Z}$	Assumption
(3)	$e \rightsquigarrow^* v$	Def. of $\text{Halt}_{Y \to Z}$
(4)	$\forall t \in \text{Halt}_Y, e\ t \in \text{Halt}_Z$	"
	e is not a value	Since (1)
(5)	$e \rightsquigarrow e''$ and $e'' \rightsquigarrow^* v$	Definition of $e \rightsquigarrow^* v$
(6)	$e'' = e'$	By determinacy on (1), (5)
	Assume $t \in \text{Halt}_Y$:	
(7)	$e\ t \rightsquigarrow e'\ t$	By congruence rule on (1)
(8)	$e\ t \in \text{Halt}_Z$	By (4)
	$e'\ t \in \text{Halt}_Z$	By induction on (6), (7)
(9)	$\forall t \in \text{Halt}_Y, e'\ t \in \text{Halt}_Z$	
(10)	$e' \in \text{Halt}_{Y \to Z}$	Def of $\text{Halt}_{Y \to Z}$ on (5), (8)

Closure Lemma, 5/5

- Case $X = 0$, $\Rightarrow$:
  (1) $e \rightsquigarrow e'$ Assumption
  (2) $e' \in \text{Halt}_0$ Assumption
  (3) $e' \in \emptyset$ Definition of Halt_0
  (4) Contradiction!

- Case $X = 0$, $\Leftarrow$:
  (1) $e \rightsquigarrow e'$ Assumption
  (2) $e \in \text{Halt}_0$ Assumption
  (3) $e \in \emptyset$ Definition of Halt_0
  (4) Contradiction!

The Fundamental Lemma

Lemma:

If we have that:

- $x_1 : X_1, \ldots, x_n : X_n \vdash e : Z$, and
- for $i \in \{1 \ldots n\}$, $v_i \in \mathrm{Halt}_{X_i}$

then $[v_1/x_1, \ldots, v_n/x_n]e \in \mathrm{Halt}_Z$

Proof:

By structural induction on $x_1 : X_1, \ldots, x_n : X_n \vdash e : Z$!

The Fundamental Lemma, 1/5

- Case Hyp:

$$
\begin{array}{lll}
(1) & \dfrac{x_j : X_j \in \overrightarrow{x_i : X_i}}{\overrightarrow{x_i : X_i} \vdash x_j : X_j}\ \textsc{Hyp} & \text{Assumption} \\
(2) & [\overrightarrow{v_i / x_i}]x_j = v_j & \text{Def. of substitution} \\
(3) & v_j \in \mathrm{Halt}_{X_j} & \text{Assumption} \\
(4) & [\overrightarrow{v_i / x_i}]x_j \in \mathrm{Halt}_{X_j} & \text{Equality (2) on (3)}
\end{array}
$$

The Fundamental Lemma, 2/5

- Case 1I:

(1)	$\dfrac{}{\overrightarrow{x_i : X_i} \vdash \langle\rangle : 1}\,1\mathrm{I}$	Assumption
(2)	$[\overrightarrow{v_i/x_i}]\,\langle\rangle = \langle\rangle$	Def. of substitution
(3)	$\langle\rangle \leadsto^* \langle\rangle$	Def. of transitive closure
(4)	$\langle\rangle \in \mathrm{Halt}_1$	Def. of Halt_1
(5)	$[\overrightarrow{v_i/x_i}]\,\langle\rangle \in \mathrm{Halt}_1$	Equality (2) on (4)

The Fundamental Lemma, 3a/5

- Case →I:

(1) $\dfrac{\overrightarrow{x_i : X_i}, y : Y \vdash e : Z}{\overrightarrow{x_i : X_i} \vdash \lambda y : Y.\, e : Y \to Z} \to\mathrm{I}$ Assumption

(2) $\overrightarrow{x_i : X_i, y : Y} \vdash e : Z$ Subderivation of (1)

(3) $[\overrightarrow{v_i/x_i}](\lambda y : Y.\, e) = \lambda y : Y.\, [\overrightarrow{v_i/x_i}]e$ Def of substitution

(4) $\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e \leadsto^* \lambda y : Y.\, [\overrightarrow{v_i/x_i}]e$ Def of closure (first goal)

The Fundamental Lemma, 3b/5

Case →I:

	WTS $\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e \in \mathrm{Halt}_{Y \to Z}$	
(5)	Assume $t \in \mathrm{Halt}_Y$:	
(6)	$t \rightsquigarrow^* v_y$	Def of Halt_Y
(7)	$v_y \in \mathrm{Halt}_Y$	Closure on (6)
(8)	$(\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\; t \rightsquigarrow^* (\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\; v_y$	Congruence on (6)
(9)	$(\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\; v_y \rightsquigarrow [\overrightarrow{v_i/x_i}, v_y/y]e$	Reduction rule
(10)	$[\overrightarrow{v_i/x_i}, v_y/y]e \in \mathrm{Halt}_Z$	Induction
(11)	$(\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\; t \in \mathrm{Halt}_Z$	Closure
(12)	$\forall t \in \mathrm{Halt}_Y, (\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\; t \in \mathrm{Halt}_Z$	(Second goal)

The Fundamental Lemma, 3c/5

Case →I:

(4)	$\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e \leadsto^* \lambda y : Y.\, [\overrightarrow{v_i/x_i}]e$	First goal
(12)	$\forall t \in \mathrm{Halt}_Y, (\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e)\ t \in \mathrm{Halt}_Z$	Second goal
(13)	$(\lambda y : Y.\, [\overrightarrow{v_i/x_i}]e) \in \mathrm{Halt}_{Y \to Z}$	Def. of $\mathrm{Halt}_{Y \to Z}$

The Fundamental Lemma, 4/5

- Case →E:

(1)	$\dfrac{\overrightarrow{x_i : X_i} \vdash e : Y \to Z \qquad \overrightarrow{x_i : X_i} \vdash e' : Y}{\overrightarrow{x_i : X_i} \vdash e\,e' : Z}\,{\to}\mathrm{E}$	Assumption
(2)	$\overrightarrow{x_i : X_i} \vdash e : Y \to Z$	Subderivation
(3)	$\overrightarrow{x_i : X_i} \vdash e' : Y$	Subderivation
(4)	$[\overrightarrow{v_i/x_i}]e \in \mathrm{Halt}_{Y \to Z}$	Induction
(5)	$\forall t \in \mathrm{Halt}_Y, [\overrightarrow{v_i/x_i}]e\ t \in \mathrm{Halt}_Z$	Def of $\mathrm{Halt}_{Y \to Z}$
(6)	$[\overrightarrow{v_i/x_i}]e' \in \mathrm{Halt}_Y$	Induction
(7)	$([\overrightarrow{v_i/x_i}]e)\ ([\overrightarrow{v_i/x_i}]e') \in \mathrm{Halt}_Z$	Instantiate (5) w/ (6)
(8)	$[\overrightarrow{v_i/x_i}](e\ e') \in \mathrm{Halt}_Z$	Def. of substitution

The Fundamental Lemma, 5/5

- Case 0E:

(1)	$\dfrac{\overrightarrow{x_i : X_i} \vdash e : 0}{\overrightarrow{x_i : X_i} \vdash \text{abort}\, e : Z}\ 0\text{E}$	Assumption
(2)	$\overrightarrow{x_i : X_i} \vdash e : 0$	Subderivation
(3)	$[\overrightarrow{v_i/x_i}]e \in \text{Halt}_0$	Induction
(4)	$[\overrightarrow{v_i/x_i}]e \in \emptyset$	Def of Halt_0
(5)	Contradiction!	

Consistency

Theorem: There are no terms $\cdot \vdash e : 0$.

Proof:

(1) $\cdot \vdash e : 0$ Assumption
(2) $e \in \mathrm{Halt}_0$ Fundamental lemma
(3) $e \in \emptyset$ Definition of Halt_0
(4) Contradiction!

Conclusions

- Consistency and termination are very closely linked
- We have proved that the simply-typed lambda calculus is a total programming language
- Since every closed program reduces to a value, and there are no values of empty type, there are no programs of empty type
- We seem to have circumvented the Halting Theorem?
- No: we do not accept all terminating programs!

Exercises

1. Extend the logical relation to support products
2. (Harder) Extend the logical relation to support sum types