CS 4110

Programming Languages & Logics

Lecture 18
Evaluation Contexts and Definitional Translation

Review: Call-by-Value

Here are the syntax and CBV semantics of λ-calculus:

$$
\begin{aligned}
e &::= x \mid \lambda x.\, e \mid e_1\, e_2 \\
v &::= \lambda x.\, e
\end{aligned}
$$

$$
\frac{e_1 \to e_1'}{e_1\, e_2 \to e_1'\, e_2} \qquad \frac{e \to e'}{v\, e \to v\, e'}
$$

$$
\frac{}{(\lambda x.\, e)\, v \to e\{v/x\}}\ \beta
$$

There are two kinds of rules: *congruence rules* that specify evaluation order and *computation rules* that specify the "interesting" reductions.

Evaluation Contexts

Evaluation contexts let us separate out these two kinds of rules.

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An evaluation context E is an expression with a "hole" in it: a single occurrence of the special symbol $[\cdot]$ in place of a subexpression.

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An evaluation context E is an expression with a “hole” in it: a single occurrence of the special symbol $[\cdot]$ in place of a subexpression.

$$E ::= [\cdot] \mid E\ e \mid v\ E$$

We write $E[e]$ to mean the evaluation context E where the hole has been replaced with the expression e.

Examples

$$E_1 = [\cdot]\,(\lambda x.\,x)$$
$$E_1[\lambda y.\,y\,y] = (\lambda y.\,y\,y)\,\lambda x.\,x$$

Examples

$$
\begin{aligned}
E_1 &= [\cdot]\,(\lambda x.\, x) \\
E_1[\lambda y.\, y\, y] &= (\lambda y.\, y\, y)\;\lambda x.\, x
\end{aligned}
$$

$$
\begin{aligned}
E_2 &= (\lambda z.\, z\, z)\,[\cdot] \\
E_2[\lambda x.\, \lambda y.\, x] &= (\lambda z.\, z\, z)\,(\lambda x.\, \lambda y.\, x)
\end{aligned}
$$

Examples

$$
\begin{aligned}
E_1 &= [\cdot]\,(\lambda x.\, x) \\
E_1[\lambda y.\, y\, y] &= (\lambda y.\, y\, y)\ \lambda x.\, x
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$$

$$
\begin{aligned}
E_2 &= (\lambda z.\, z\, z)\ [\cdot] \\
E_2[\lambda x.\, \lambda y.\, x] &= (\lambda z.\, z\, z)\ (\lambda x.\, \lambda y.\, x)
\end{aligned}
$$

$$
\begin{aligned}
E_3 &= ([\cdot]\ \lambda x.\, x\, x)\ ((\lambda y.\, y)\ (\lambda y.\, y)) \\
E_3[\lambda f.\, \lambda g.\, f\, g] &= ((\lambda f.\, \lambda g.\, f\, g)\ \lambda x.\, x\, x)\ ((\lambda y.\, y)\ (\lambda y.\, y))
\end{aligned}
$$

CBV With Evaluation Contexts

With evaluation contexts, we can define the evaluation semantics for the CBV λ-calculus with just two rules: one for evaluation contexts, and one for β-reduction.

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With this syntax:

$$E ::= [\cdot] \mid E\, e \mid v\, E$$

The small-step rules are:

$$\frac{e \to e'}{E[e] \to E[e']}$$

$$\frac{}{(\lambda x.\, e)\, v \to e\{v/x\}}\ \beta$$

CBN With Evaluation Contexts

We can also define the semantics of CBN λ-calculus with evaluation contexts.

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For call-by-name, the syntax for evaluation contexts is different:

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But the small-step rules are the same:

$$\frac{e \to e'}{E[e] \to E[e']}$$

$$\frac{}{(\lambda x.\, e)\, e' \to e\{e'/x\}}\ \beta$$

Definitional Translation

We know how to encode Booleans, conditionals, natural numbers, and recursion in λ-calculus.

Can we define a *real* programming language by translating everything in it into the λ-calculus?

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Can we define a *real* programming language by translating everything in it into the λ-calculus?

In definitional translation, we define a denotational semantics where the target is a simpler programming language instead of mathematical objects.

Multi-Argument λ-calculus

Let's define a version of the λ-calculus that allows functions to take multiple arguments.

$$e ::= x \mid \lambda x_1, \ldots, x_n.\, e \mid e_0\, e_1\ \ldots\ e_n$$

Multi-Argument λ-calculus

We can define a CBV operational semantics:

$$E ::= [\cdot] \mid v_0 \; \ldots \; v_{i-1} \, E \, e_{i+1} \; \ldots \; e_n$$

$$\frac{e \rightarrow e'}{E[e] \rightarrow E[e']}$$

$$\frac{}{(\lambda x_1, \ldots, x_n.\, e_0)\, v_1 \; \ldots \; v_n \rightarrow e_0\{v_1/x_1\}\{v_2/x_2\} \ldots \{v_n/x_n\}}\ \beta$$

The evaluation contexts ensure that we evaluate multi-argument applications $e_0 \; e_1 \; \ldots \; e_n$ from left to right.

Definitional Translation

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Definitional Translation

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We can define a translation $\mathcal{T}[\![\cdot]\!]$ that takes an expression in the multi-argument λ-calculus and returns an equivalent expression in the pure λ-calculus.

$$
\begin{aligned}
\mathcal{T}[\![x]\!] &= x \\
\mathcal{T}[\![\lambda x_1, \dots, x_n.\, e]\!] &= \lambda x_1. \; \dots \; \lambda x_n.\, \mathcal{T}[\![e]\!] \\
\mathcal{T}[\![e_0\, e_1\, e_2 \; \dots \; e_n]\!] &= (\dots((\mathcal{T}[\![e_0]\!]\; \mathcal{T}[\![e_1]\!])\; \mathcal{T}[\![e_2]\!]) \dots \; \mathcal{T}[\![e_n]\!])
\end{aligned}
$$

This translation *curries* the multi-argument λ-calculus.

Products (Pairs) and Let

Syntax

$$
\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.\, e \\
\mid {} & e_1\ e_2 \\
\mid {} & (e_1, e_2) \\
\mid {} & \#1\ e \\
\mid {} & \#2\ e \\
\mid {} & \mathsf{let}\ x = e_1\ \mathsf{in}\ e_2
\end{aligned}
$$

$$
\begin{aligned}
v ::= {} & \lambda x.\, e \\
\mid {} & (v_1, v_2)
\end{aligned}
$$

Products (Pairs) and Let

Evaluation Contexts

$$
\begin{aligned}
E ::= {} & [\cdot] \\
& \mid E\; e \\
& \mid v\; E \\
& \mid (E, e) \\
& \mid (v, E) \\
& \mid \#1\; E \\
& \mid \#2\; E \\
& \mid \mathsf{let}\; x = E\; \mathsf{in}\; e_2
\end{aligned}
$$

Products (Pairs) and Let

Semantics

$$\frac{e \to e'}{E[e] \to E[e']}$$

$$\frac{}{(\lambda x.\, e)\; v \to e\{v/x\}}\;\beta$$

$$\frac{}{\#1\,(v_1, v_2) \to v_1} \qquad \frac{}{\#2\,(v_1, v_2) \to v_2}$$

$$\frac{}{\text{let}\; x = v \;\text{in}\; e \to e\{v/x\}}$$

Products (Pairs) and Let

Translation

$$
\begin{aligned}
\mathcal{T}[\![x]\!] &= x \\
\mathcal{T}[\![\lambda x.\, e]\!] &= \lambda x.\, \mathcal{T}[\![e]\!] \\
\mathcal{T}[\![e_1\ e_2]\!] &= \mathcal{T}[\![e_1]\!]\ \mathcal{T}[\![e_2]\!] \\
\mathcal{T}[\![(e_1, e_2)]\!] &= (\lambda x.\, \lambda y.\, \lambda f.\, f\, x\, y)\ \mathcal{T}[\![e_1]\!]\ \mathcal{T}[\![e_2]\!] \\
\mathcal{T}[\![\#1\ e]\!] &= \mathcal{T}[\![e]\!]\ (\lambda x.\, \lambda y.\, x) \\
\mathcal{T}[\![\#2\ e]\!] &= \mathcal{T}[\![e]\!]\ (\lambda x.\, \lambda y.\, y) \\
\mathcal{T}[\![\mathrm{let}\, x = e_1 \text{ in } e_2]\!] &= (\lambda x.\, \mathcal{T}[\![e_2]\!])\ \mathcal{T}[\![e_1]\!]
\end{aligned}
$$

Laziness

Consider the call-by-name λ-calculus...

Syntax

$$\begin{aligned} e ::= &\ x \\ \mid &\ e_1\ e_2 \\ \mid &\ \lambda x.\, e \end{aligned}$$

$$v ::= \lambda x.\, e$$

Semantics

$$\frac{e_1 \to e_1'}{e_1\ e_2 \to e_1'\ e_2} \qquad \frac{}{(\lambda x.\, e_1)\ e_2 \to e_1\{e_2/x\}}\ \beta$$

Laziness

Translation

$$
\begin{aligned}
\mathcal{T}[\![x]\!] &= x\,(\lambda y.\, y)\\
\mathcal{T}[\![\lambda x.\, e]\!] &= \lambda x.\, \mathcal{T}[\![e]\!]\\
\mathcal{T}[\![e_1\; e_2]\!] &= \mathcal{T}[\![e_1]\!]\,(\lambda z.\, \mathcal{T}[\![e_2]\!]) \qquad z \text{ is not a free variable of } e_2
\end{aligned}
$$

References

Syntax

$$
\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.\, e \\
\mid {} & e_0\; e_1
\end{aligned}
$$

$$v ::= \lambda x.\, e$$

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Syntax

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\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.\, e \\
\mid {} & e_0\ e_1 \\
\mid {} & \mathsf{ref}\ e
\end{aligned}
$$

$$v ::= \lambda x.\, e$$

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\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.\, e \\
\mid {} & e_0\ e_1 \\
\mid {} & \mathsf{ref}\ e \\
\mid {} & !e
\end{aligned}
$$

$$v ::= \lambda x.\, e$$

References

Syntax

$$
\begin{aligned}
e ::= {} & x \\
\mid {} & \lambda x.\, e \\
\mid {} & e_0\ e_1 \\
\mid {} & \mathsf{ref}\ e \\
\mid {} & !e \\
\mid {} & e_1 := e_2
\end{aligned}
$$

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v ::= \lambda x.\, e
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\mid {} & E := e
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$$

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E ::= {} & [\cdot] \\
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\mid {} & v\ E \\
\mid {} & \text{ref}\ E \\
\mid {} & !E \\
\mid {} & E := e \\
\mid {} & v := E
\end{aligned}
$$

References

Semantics

$$\frac{\langle \sigma, e\rangle \to \langle \sigma', e'\rangle}{\langle \sigma, E[e]\rangle \to \langle \sigma', E[e']\rangle} \qquad \frac{}{\langle \sigma, (\lambda x.\, e)\, v\rangle \to \langle \sigma, e\{v/x\}\rangle}\ \beta$$

$$\frac{\ell \notin dom(\sigma)}{\langle \sigma, \mathsf{ref}\, v\rangle \to \langle \sigma[\ell \mapsto v], \ell\rangle} \qquad \frac{\sigma(\ell) = v}{\langle \sigma,\ !\ell\rangle \to \langle \sigma, v\rangle}$$

$$\frac{}{\langle \sigma, \ell := v\rangle \to \langle \sigma[\ell \mapsto v], v\rangle}$$

References

Translation

...left as an exercise to the reader. ;-)

Adequacy

How do we know if a translation is correct?

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Every target evaluation should represent a source evaluation...

Definition (Soundness)

$\forall e \in \mathbf{Exp}_{\text{src}}.$ if $\mathcal{T}[\![e]\!] \rightarrow^{*}_{\text{trg}} v'$ then $\exists v.\ e \rightarrow^{*}_{\text{src}} v$
and v' equivalent to v

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and v' equivalent to v

...and every source evaluation should have a target evaluation:

Definition (Completeness)

$\forall e \in \mathbf{Exp}_{\text{src}}.$ if $e \rightarrow^{*}_{\text{src}} v$ then $\exists v'.\ \mathcal{T}[\![e]\!] \rightarrow^{*}_{\text{trg}} v'$
and v' equivalent to v