λ-calculus, effects and call-by-push-value

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April 2, 2023

Outline

Types

We're going to look at simply typed λ-calculus with arithmetic, including not just function types, but also sum and product types.

Here is the syntax of types:

$$A \quad ::= \quad \texttt{bool} \mid \texttt{nat} \mid A \to A \mid 1 \mid A \times A \mid 0 \mid A + A$$
$$\mid \textstyle\sum_{i \in \mathbb{N}} A_i \mid \prod_{i \in \mathbb{N}} A_i \quad \text{(optional extra)}$$

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Why no brackets?

- You might expect $A ::= \quad \cdots \mid (A)$.
- But our definition is abstract syntax.
- This means a type—or a term—is a tree of symbols, not a string of symbols.

Typing Judgement

Example

$$\mathtt{x} : \mathtt{nat},\ \mathtt{y} : \mathtt{nat} \vdash \lambda \mathtt{z}_{\mathtt{nat} \to \mathtt{nat}}.\ \mathtt{z}\,(\mathtt{x} + \mathtt{x}) : (\mathtt{nat} \to \mathtt{nat}) \to \mathtt{nat}$$

In English:

Given declarations of $\mathtt{x} : \mathtt{nat}$ and $\mathtt{y} : \mathtt{nat}$,

$\lambda \mathtt{z}_{\mathtt{nat} \to \mathtt{nat}}.\ \mathtt{z}\,(\mathtt{x} + \mathtt{x})$ is a term of type $(\mathtt{nat} \to \mathtt{nat}) \to \mathtt{nat}$.

The typing judgement takes the form $\Gamma \vdash M : A$.

- Γ is a typing context, a list of typed distinct identifiers.
- M is a term.
- A is a type.

Identifiers

The most basic typing rules, not associated with any particular type.

Free identifier

$$\frac{}{\Gamma \vdash \mathtt{x} : A}\,(\mathtt{x} : A) \in \Gamma$$

Multiple local declaration, e.g. of two identifiers

$$\frac{\Gamma \vdash M : A \quad \Gamma \vdash M' : B \quad \Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash N : C}{\Gamma \vdash \mathtt{let}\ (\mathtt{x}\ \mathtt{be}\ M,\ \mathtt{y}\ \mathtt{be}\ M').\ N : C}$$

Typing rules for $A \to B$

Introduction rule

$$\frac{\Gamma, \mathtt{x} : A \vdash M : B}{\Gamma \vdash \lambda \mathtt{x}_A . M : A \to B}$$

Elimination rule

$$\frac{\Gamma \vdash M : A \to B \quad \Gamma \vdash N : A}{\Gamma \vdash M\, N : B}$$

Type annotations in terms

- For Γ and M, there's at most one A such that $\Gamma \vdash M : A$
- and at most one derivation of $\Gamma \vdash M : A$.
- This is because of our type annotations.
- Some formulations omit some or all of these.

Typing rules for `bool`

Two introduction rules:

$$\frac{}{\Gamma \vdash \texttt{true} : \texttt{bool}} \qquad \frac{}{\Gamma \vdash \texttt{false} : \texttt{bool}}$$

Elimination rule

$$\frac{\Gamma \vdash M : \texttt{bool} \quad \Gamma \vdash N : B \quad \Gamma \vdash N' : B}{\Gamma \vdash \texttt{match}\ M\ \texttt{as}\ \{\texttt{true}.\ N,\ \texttt{false}.\ N'\} : B}$$

It's a pretentious notation for `if` M `then` N `else` N'.

Typing rules for arithmetic

These are *ad hoc* rules.

$$\frac{}{\Gamma \vdash 17 : \mathtt{nat}} \qquad \frac{\Gamma \vdash M : \mathtt{nat} \quad \Gamma \vdash M' : \mathtt{nat}}{\Gamma \vdash M + M' : \mathtt{nat}}$$

Typing rules for $A + B$

Two introduction rules

$$\frac{\Gamma \vdash M : A}{\Gamma \vdash \mathtt{inl}^{A,B}\ M : A + B} \qquad \frac{\Gamma \vdash M : B}{\Gamma \vdash \mathtt{inr}^{A,B}\ M : A + B}$$

Elimination rule

$$\frac{\Gamma \vdash M : A + B \quad \Gamma, \mathtt{x} : A \vdash N : C \quad \Gamma, \mathtt{y} : B \vdash N' : C}{\Gamma \vdash \mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\ N,\ \mathtt{inr}\ \mathtt{y}.\ N'\} : C}$$

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Likewise for $\sum_{i \in \mathbb{N}} A_i$.

Typing rules for 0

Zero introduction rules

Elimination rule

$$\frac{\Gamma \vdash M : 0}{\Gamma \vdash \mathtt{match}\ M\ \mathtt{as}\ \{\}^{A} : A}$$

Typing rules for $A \times B$

Introduction rule

$$\frac{\Gamma \vdash M : A \quad \Gamma \vdash N : B}{\Gamma \vdash \langle M, N \rangle : A \times B}$$

Two options for elimination

- Pattern-matching product. Elimination rule

$$\frac{\Gamma \vdash M : A \times B \quad \Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash N : C}{\Gamma \vdash \mathtt{match}\ M\ \mathtt{as}\ \langle \mathtt{x}, \mathtt{y} \rangle .\ N : C}$$

- Projection product. Two elimination rules

$$\frac{\Gamma \vdash M : A \times B}{\Gamma \vdash M^{\mathtt{l}} : A} \qquad \frac{\Gamma \vdash M : A \times B}{\Gamma \vdash M^{\mathtt{r}} : B}$$

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$$\frac{\Gamma \vdash M : A \times B}{\Gamma \vdash M^{\mathtt{l}} : A} \qquad \frac{\Gamma \vdash M : A \times B}{\Gamma \vdash M^{\mathtt{r}} : B}$$

$\prod_{i \in \mathbb{N}} A_i$ is a projection product.

Typing rules for 1

Introduction rule

$$\frac{}{\Gamma \vdash \langle\,\rangle : 1}$$

Two options for elimination

- Pattern-match unit. Elimination rule

$$\frac{\Gamma \vdash M : 1 \quad \Gamma \vdash N : C}{\Gamma \vdash \mathtt{match}\ M\ \mathtt{as}\ \langle\,\rangle.\ N : C}$$

- Projection unit. Zero elimination rules

Weakening is admissible

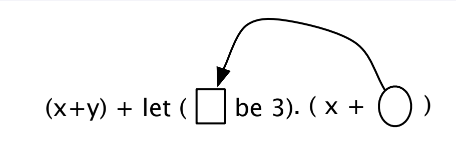
Theorem

If $\Gamma \vdash M : A$ and $\Gamma \subseteq \Gamma'$ then $\Gamma' \vdash M : A$.

Binding diagrams (Quine, Bourbaki)

Example

The term $(\mathtt{x} + \mathtt{y}) + \mathtt{let}\ (\mathtt{y}\ \mathsf{be}\ 3).\ (\mathtt{x} + \mathtt{y})$ has binding diagram



- Terms are α-equivalent when they have the same binding diagram.

$$M \equiv_\alpha N \quad \overset{\text{def}}{\Leftrightarrow} \quad \mathsf{BD}(M) = \mathsf{BD}(N)$$

- The collection of binding diagrams forms an initial algebra [FPT; AR].
- We'll skate over this issue. It's not specific to λ-calculus.

Substitution

Subsitution is an operation on binding diagrams, not on terms.

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Multiple substitution, e.g. for two identifiers

If $\Gamma \vdash M : A$ and $\Gamma \vdash M' : B$ and $\Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash N : C$,

we define $\Gamma \vdash N[M/\mathtt{x}, M'/\mathtt{y}] : C$.

Example

$$
\begin{array}{rcl}
M & = & \lambda \mathtt{y}_{\mathtt{nat}}.\ \mathtt{y} + 3 \\
M' & = & 7 \\
N & = & \mathtt{x}\,(5 + \mathtt{y}) \\
N[M/\mathtt{x}, M'/\mathtt{y}] & = & (\lambda \mathtt{z}_{\mathtt{nat}}.\ \mathtt{z} + 3)\,(5 + 7)
\end{array}
$$

Types denote sets

- Every type A denotes a set $[\![A]\!]$.
- For example, $[\![\mathtt{nat} \to \mathtt{nat}]\!]$ is the set of functions $\mathbb{N} \to \mathbb{N}$.

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- This means: a closed term of type $\vdash M : A$
  denotes an element of $[\![A]\!]$.

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- This means: a closed term of type $\vdash M : A$ denotes an element of $[\![A]\!]$.
- For example, $\lambda \mathtt{x}_{\mathtt{nat}}.\, \mathtt{x} + 3$ denotes $\lambda a \in \mathbb{N}.\, a + 3$.

Semantics of types

Notation

For sets X and Y,

- $X \to Y$ is the set of functions from X to Y.
- $X \times Y$ is $\{\langle x, y\rangle \mid x \in X, y \in Y\}$.
- $X + Y$ is $\{\mathsf{inl}\ x \mid x \in X\} \cup \{\mathsf{inr}\ y \mid y \in Y\}$.

$$
\begin{array}{rcl}
[\![\texttt{bool}]\!] & = & \mathbb{B} = \{\mathsf{true}, \mathsf{false}\} \\
[\![\texttt{nat}]\!] & = & \mathbb{N} \\
[\![A \to B]\!] & = & [\![A]\!] \to [\![B]\!] \\
[\![1]\!] & = & 1 = \{\langle\,\rangle\} \\
[\![A + B]\!] & = & [\![A]\!] + [\![B]\!] \\
[\![A \times B]\!] & = & [\![A]\!] \times [\![B]\!] \\
[\![0]\!] & = & \emptyset
\end{array}
$$

Semantic environments

Let Γ be a typing context.

- A semantic environment ρ for Γ provides an element $\rho_{\mathtt{x}} \in [\![A]\!]$ for each $(\mathtt{x} : A) \in \Gamma$.
- $[\![\Gamma]\!]$ is the set of semantic environments for Γ.

$$[\![\Gamma]\!] \stackrel{\text{def}}{=} \prod_{(\mathtt{x}:A)\in\Gamma} [\![A]\!]$$

Semantics of typing judgement

Given a typing judgement $\Gamma \vdash M : A$,

we shall define $[\![M]\!]$, or more precisely $[\![\Gamma \vdash M : A]\!]$.

It's a function from $[\![\Gamma]\!]$ to $[\![A]\!]$.

Example

$$\mathtt{x} : \mathtt{nat}, \mathtt{y} : \mathtt{nat} \vdash \lambda \mathtt{z}_{\mathtt{nat} \to \mathtt{nat}}. \mathtt{z}(\mathtt{x} + \mathtt{y}) : (\mathtt{nat} \to \mathtt{nat}) \to \mathtt{nat}$$

denotes the function

$$\begin{array}{rcl} [\![\mathtt{x} : \mathtt{nat}, \mathtt{y} : \mathtt{nat}]\!] & \longrightarrow & (\mathbb{N} \to \mathbb{N}) \to \mathbb{N} \\ \rho & \longmapsto & \lambda z \in \mathbb{N} \to \mathbb{N}.\, z(\rho_{\mathtt{x}} + \rho_{\mathtt{y}}) \end{array}$$

Semantics of terms

$$\frac{}{\Gamma \vdash 17 : \texttt{nat}}$$

$$[\![17]\!] \ : \ \rho \longmapsto 17$$

$$\frac{\Gamma \vdash M : \texttt{nat} \quad \Gamma \vdash M' : \texttt{nat}}{\Gamma \vdash M + M' : \texttt{nat}}$$

$$[\![M + M']\!] \ : \ \rho \longmapsto [\![M]\!]\rho + [\![M']\!]\rho$$

More semantic equations

$$\frac{}{\Gamma \vdash \mathtt{x} : A}\,(\mathtt{x} : A) \in \Gamma$$

$$[\![\mathtt{x}]\!] \;:\; \rho \longmapsto \rho_{\mathtt{x}}$$

$$\frac{\Gamma, \mathtt{x} : A \vdash M : B}{\Gamma \vdash \lambda \mathtt{x}_A.\, M : A \to B}$$

$$[\![\lambda \mathtt{x}_A.\, M]\!] \;:\; \rho \longmapsto \lambda a \in [\![A]\!].\, [\![M]\!](\rho, \mathtt{x} \mapsto a)$$

More semantic equations

$$\frac{\Gamma \vdash M : A}{\Gamma \vdash \mathtt{inl}^{A,B}\ M : A + B}$$

$$[\![\mathtt{inl}^{A,B}\ M]\!]\ :\ \rho \longmapsto \mathsf{inl}\ [\![M]\!]\rho$$

$$\frac{\Gamma \vdash M : A + B \quad \Gamma, \mathtt{x} : A \vdash N : C \quad \Gamma, \mathtt{y} : B \vdash N' : C}{\Gamma \vdash \mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\ N, \mathtt{inr}\ \mathtt{y}.\ N'\} : C}$$

$$[\![\mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\ N, \mathtt{inr}\ \mathtt{y}.\ N'\}]\!]\ :\ \rho \longmapsto$$
$$\mathsf{match}\ [\![M]\!]\rho\ \mathsf{as}\ \{\mathsf{inl}\ a.\ [\![N]\!](\rho, \mathtt{x} \mapsto a), \mathsf{inr}\ b.\ [\![N']\!](\rho, \mathtt{y} \mapsto b)\}$$

Basic properties

Semantic Coherence

If type annotations are omitted,

then $\Gamma \vdash M : A$ can have more than one derivation.

We must prove that $[\![\Gamma \vdash M : A]\!]$ doesn't depend on the derivation.

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Weakening Lemma

If $\Gamma \vdash M : A$ and $\Gamma \subseteq \Gamma'$ then

$$[\![\Gamma' \vdash M : A]\!]\rho = [\![\Gamma \vdash M]\!](\rho \upharpoonright_{\Gamma})$$

Substitution

Binding Diagrams

- We can give denotational semantics of binding diagrams.
- $[\![\Gamma \vdash M : A]\!] = [\![\Gamma \vdash \mathsf{BD}(M) : A]\!]$
- So α-equivalent terms have the same denotation.

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Binding Diagrams

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- So α-equivalent terms have the same denotation.

Substitution Lemma

For binding diagrams $\Gamma \vdash M : A$ and $\Gamma \vdash M' : B$ and $\Gamma, \mathtt{x} : A \vdash N : C$, we can recover $[\![N[M/\mathtt{x}, M'/\mathtt{y}]]\!]$ from $[\![N]\!]$ and $[\![M]\!]$ and $[\![M']\!]$.

$$[\![N[M/\mathtt{x}, M'/\mathtt{y}]]\!] \;:\; \rho \longmapsto [\![N]\!](\rho, \mathtt{x} \mapsto [\![M]\!]\rho, \mathtt{y} \mapsto [\![M']\!]\rho)$$

β-laws

The β-law for $A \to B$

$$\frac{\Gamma \vdash M : A \quad \Gamma, \mathtt{x} : A \vdash N : B}{\Gamma \vdash (\lambda \mathtt{x}_A .\, N)\, M = N[M/\mathtt{x}] : B}$$

Introduction inside an elimination may be removed.

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Introduction inside an elimination may be removed.

Two β-laws for projection product $A \times B$

$$\frac{\Gamma \vdash M : A \quad \Gamma \vdash N : A'}{\Gamma \vdash \langle M, N \rangle^{\mathtt{1}} = M : A}$$

Zero β-laws for projection unit 1

More β-laws

Two β-laws for `bool`

$$\frac{\Gamma \vdash N : C \quad \Gamma \vdash N' : C}{\Gamma \vdash \texttt{match true as } \{\texttt{true}.\, N,\ \texttt{false}.\, N'\} = N : C}$$

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$$\frac{\Gamma \vdash M : A \quad \Gamma, \mathtt{x} : A \vdash N : C \quad \Gamma, \mathtt{y} : B \vdash N' : C}{\Gamma \vdash \mathtt{match\ inl}^{A,B}\ M\ \mathtt{as}\ \{\mathtt{inl\ x}.\, N,\ \mathtt{inr\ y}.\, N'\} = N[M/\mathtt{x}] : C}$$

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Zero β-laws for 0

β-law for local declaration

$$\frac{\Gamma \vdash M : A \quad \Gamma \vdash M' : B \quad \Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash N : C}{\Gamma \vdash \mathtt{let}\ (\mathtt{x}\ \mathtt{be}\ M,\ \mathtt{y}\ \mathtt{be}\ M').\ N = N[M/\mathtt{x}, M'/\mathtt{y}] : C}$$

η-laws

η-law for $A \to B$, everything is λ

$$\frac{\Gamma \vdash M : A \to B}{\Gamma \vdash M = \lambda \mathtt{x}_A .\, M\, \mathtt{x} : A \to B}\ \mathtt{x} \notin \Gamma$$

Introduction outside an elimination may be inserted.

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Introduction outside an elimination may be inserted.

η-law for projection product $A \times B$, everything is a tuple

$$\frac{\Gamma \vdash M : A \times B}{\Gamma \vdash M = \langle M^{\mathtt{l}}, M^{\mathtt{r}} \rangle : A \times B}$$

η-law for projection unit 1, everything is a tuple

$$\frac{\Gamma \vdash M : 1}{\Gamma \vdash M = \langle \rangle : 1}$$

More η-laws

η-law for `bool`, everything is `true` or `false`

$$\frac{\Gamma \vdash M : \texttt{bool} \quad \Gamma, \texttt{z} : \texttt{bool} \vdash N : C}{\begin{array}{l}\Gamma \vdash N[M/\texttt{z}] = \\ \quad \texttt{match}\ M\ \texttt{as}\ \{\texttt{true}.\, N[\texttt{true}/\texttt{z}],\ \texttt{false}.\, N[\texttt{false}/\texttt{z}]\} : C\end{array}}\ \texttt{z} \notin \Gamma$$

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η-law for $A + B$, everything is `inl` or `inr`

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η-law for 0, nothing exists

$$\frac{\Gamma \vdash M : 0 \quad \Gamma, \mathtt{z} : 0 \vdash N : C}{\Gamma \vdash N[M/\mathtt{z}] = \mathtt{match}\ M\ \mathtt{as}\ \{\ \}_C : C}\ \mathtt{z} \notin \Gamma$$

The $\beta\eta$-theory

We define $\Gamma \vdash M =_{\beta\eta} M' : A$ inductively as follows.

All the β- and η-laws are taken as axioms,

and it is a congruence i.e. an equivalence relation preserved by each term constructor. For example:

$$\frac{\Gamma, \mathtt{x} : A \vdash M = M' : B}{\Gamma \vdash \lambda \mathtt{x}_A.\, M = \lambda \mathtt{x}_A.\, M' : A \to B}$$

Properties of $=_{\beta\eta}$

Closure Theorems

- $=_{\beta\eta}$ is closed under weakening. But not conversely, e.g.

$$\begin{array}{rrcl} & \mathtt{z} : 0 & \vdash & \mathtt{true} =_{\beta\eta} \mathtt{false} : \mathtt{bool} \\ \text{but not} & & \vdash & \mathtt{true} =_{\beta\eta} \mathtt{false} : \mathtt{bool} \end{array}$$

- $=_{\beta\eta}$ is closed under substitution.

Soundness theorem

If $\Gamma \vdash M =_{\beta\eta} M' : A$ then $[\![M]\!] = [\![M']\!]$.

Follows from the weakening and substitution lemmas.

Reversible rule for $A \to B$

The connective $\to$ is rightist: it has a reversible rule

$$\frac{\Gamma, \mathtt{x} : A \vdash B}{\overline{\Gamma \vdash A \to B}}$$

natural in Γ—we'll skate over naturality.

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- Downwards, a term $\Gamma, \mathtt{x} : A \vdash M : B$ is sent to $\lambda \mathtt{x}_A .\, M$.
- Upwards, a term $\Gamma \vdash N : A \to B$ is sent to $N\,\mathtt{x}$.
- These are inverse up to $=_{\beta\eta}$.

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- Upwards, a term $\Gamma \vdash N : A \to B$ is sent to $N\,\mathtt{x}$.
- These are inverse up to $=_{\beta\eta}$.

$A \to B$ appears on the right of $\vdash$ in the conclusion.

Reversible rule for bool

The (nullary) connective bool is leftist.
That means: it has a reversible rule

$$\frac{\Gamma \vdash C \quad \Gamma \vdash C}{\Gamma, \mathtt{z} : \mathtt{bool} \vdash C}$$

natural in Γ and C—we'll skate over naturality.

- Downwards, a pair $\Gamma \vdash M : C$ and $\Gamma \vdash M' : C$ is sent to $\mathtt{match\ z\ as}\ \{\mathtt{true}.\, M,\ \mathtt{false}.\, M'\}$.
- Upwards, a term $\Gamma, \mathtt{z} : \mathtt{bool} \vdash N : C$ is sent to $N[\mathtt{true}/\mathtt{z}]$ and $N[\mathtt{false}/\mathtt{z}]$.
- These are inverse up to $=_{\beta\eta}$.

bool appears on the left of $\vdash$ in the conclusion.

Reversible rule for $A + B$

The connective $+$ is leftist, having a reversible rule

$$\frac{\Gamma, \mathtt{x} : A \vdash C \quad \Gamma, \mathtt{y} : B \vdash C}{\Gamma, \mathtt{z} : A + B \vdash C}$$

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Reversible rule for $A + B$

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natural in Γ and C.

The (nullary) connective 0 is leftist, having a reversible rule

$$\frac{}{\Gamma, \mathtt{z} : 0 \vdash C}$$

natural in Γ and C.

Bipartisan connectives

The connective $\times$ has a reversible rule

$$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \times B}$$

natural in Γ, so it's rightist.

Bipartisan connectives

The connective $\times$ has a reversible rule

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natural in Γ, so it's rightist.

It also has a reversible rule

$$\frac{\Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash C}{\Gamma, \mathtt{z} : A \times B \vdash C}$$

natural in Γ and C, so it's leftist.

Bipartisan connectives

The connective $\times$ has a reversible rule

$$\frac{\Gamma \vdash A \quad \Gamma \vdash B}{\Gamma \vdash A \times B}$$

natural in Γ, so it's rightist.

It also has a reversible rule

$$\frac{\Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash C}{\Gamma, \mathtt{z} : A \times B \vdash C}$$

natural in Γ and C, so it's leftist.

Bipartisan connectives

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natural in Γ, so it's rightist.

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$$\frac{\Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash C}{\Gamma, \mathtt{z} : A \times B \vdash C}$$

natural in Γ and C, so it's leftist.

In summary, the connective $\times$ is bipartisan.
Likewise the (nullary) connective 1.

Most general leftist connective

The variant tuple type $\boxed{\sum}\{^0 A, A';\ ^1 B, B', B''\}$ denotes a sum of products

$$(\llbracket A \rrbracket \times \llbracket A' \rrbracket) + (\llbracket B \rrbracket \times \llbracket B' \rrbracket \times \llbracket B'' \rrbracket)$$

This gives a leftist connective.

$$\frac{\Gamma, A, A' \vdash C \quad \Gamma, B, B', B'' \vdash C}{\Gamma, \boxed{\sum}\{^0 A, A';\ ^1 B, B', B''\} \vdash C}$$

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$$\frac{\Gamma, A, A' \vdash C \quad \Gamma, B, B', B'' \vdash C}{\Gamma, \boxed{\sum}\{^0 A, A';\ ^1 B, B', B''\} \vdash C}$$

Here is its term syntax:

$$\mathtt{in}_0(M, M')$$

$$\mathtt{in}_1(M, M', M'')$$

$$\mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{in}_0(\mathtt{x}, \mathtt{x}').\, N, \mathtt{in}_1(\mathtt{y}, \mathtt{y}', \mathtt{y}'').\, N'\}$$

Most general rightist connective

The variant function type $\boxed{\prod}\{^{0}\,A, A' \vdash B;\ ^{1}\,C, C', C' \vdash D\}$ denotes a product of multi-ary function types

$$((\llbracket A \rrbracket \times \llbracket A' \rrbracket) \to \llbracket B \rrbracket) \times ((\llbracket C \rrbracket \times \llbracket C' \rrbracket \times \llbracket C'' \rrbracket) \to \llbracket D \rrbracket)$$

This gives a rightist connective.

$$\frac{\Gamma, A, A' \vdash B \quad \Gamma, C, C', C'' \vdash D}{\Gamma \vdash \boxed{\prod}\{^{0}\,A, A' \vdash B;\ ^{1}\,C, C', C' \vdash D\}}$$

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This gives a rightist connective.

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Here is its term syntax:

$$\begin{array}{r} \lambda\{^0(\mathtt{x}, \mathtt{x}').M,^1 (\mathtt{y}, \mathtt{y}', \mathtt{y}'').M'\} \\ M\,^0(N, N') \\ M\,^1(N, N', N'') \end{array}$$

Jumbo λ-calculus

Type syntax

$$A \quad ::= \quad \boxed{\sum}\{\overrightarrow{A_i}\}_{i<n} \quad | \quad \boxed{\prod}\{\overrightarrow{A_i} \vdash B_i\}_{i<n} \qquad (n \in \mathbb{N} \text{ or } n = \infty)$$

Term syntax, with type annotations omitted

$$\begin{array}{rcl} M & ::= & \mathtt{x} \mid \mathtt{let}\ (\overrightarrow{\mathtt{x}\ \mathtt{be}\ M}).\ M \\ & & \mid \mathtt{in}_i(\overrightarrow{M}) \\ & & \mid \mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{in}_i(\overrightarrow{\mathtt{x}}).\ M_i\}_{i<n} \\ & & \mid \lambda\{^i(\overrightarrow{\mathtt{x}}).\ M_i\}_{i<n} \\ & & \mid M\,^i(\overrightarrow{M}) \end{array}$$

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Includes both pattern-match product $A \times B$
and projection product $A \,\Pi\, B$.

Jumbo vs non-jumbo

Jumbo λ-calculus is the most expressive form of simply typed λ-calculus:

it contains all leftist and rightist connectives as primitives.

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Modulo $=_{\beta\eta}$ it is no more expressive than the non-jumbo version.

Jumbo vs non-jumbo

Jumbo λ-calculus is the most expressive form of simply typed λ-calculus:

it contains all leftist and rightist connectives as primitives.

Modulo $=_{\beta\eta}$ it is no more expressive than the non-jumbo version.

But the β- and η-laws are not going to survive.

Evaluating terms

We want to evaluate every closed term $\vdash M : A$ to a terminal term.

We want $\lambda \mathtt{x}_A.\, M$ to be terminal, since M is not closed.

But there are many options.

Three decisions we must make

1. To evaluate $\texttt{let}\ (\texttt{x be}\ M,\ \texttt{y be}\ M').\ N$, do we
   - evaluate M to T and M' to T', then evaluate $N[T/\texttt{x}, T'/\texttt{y}]$?
   - just evaluate $N[M/\texttt{x}, M'/\texttt{y}]$?

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2. To evaluate $M\,N$, we must evaluate M to $\lambda\texttt{x}_A.\,P$. Do we
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3. Any terminal term of type $A + B$ must be $\texttt{inl}\ M$ or $\texttt{inr}\ M$. Do we
   - deem $\texttt{inl}\ T$ and $\texttt{inr}\ T$ terminal only if T is terminal?
   - always deem $\texttt{inl}\ M$ and $\texttt{inr}\ M$ terminal?

One fundamental decision

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Substituting unevaluated terms gives call-by-name.

Terminology: lazy and call-by-name

- "Lazy" evaluation usually means call-by-need, except in Abramsky's "lazy λ-calculus".
- In the untyped literature, "call-by-name" evaluation means reduction to head normal form.

Evaluation order for `let`

To evaluate `let` $(\mathtt{x}\ \mathtt{be}\ M,\ \mathtt{y}\ \mathtt{be}\ M').\ N$, do we

- evaluate M to T and M' to T', then evaluate $N[T/\mathtt{x}, T'/\mathtt{y}]$? Call-by-value
- just evaluate $N[M/\mathtt{x}, M'/\mathtt{y}]$? Call-by-name

Evaluation order for application

To evaluate $M\,N$, we must evaluate M to $\lambda \mathtt{x}_A.\,P$. Do we

- evaluate N to T (before or after evaluating M), then evaluate $P[T/\mathtt{x}]$? Call-by-value
- just evaluate $P[N/\mathtt{x}]$? Call-by-name

Terminal terms of type $A + B$

Any terminal term of type $A + B$ must be $\texttt{inl}\ M$ or $\texttt{inr}\ M$. Do we

- deem $\texttt{inl}\ T$ and $\texttt{inr}\ T$ terminal only if T is terminal? Call-by-value
- always deem $\texttt{inl}\ M$ and $\texttt{inr}\ M$ terminal? Call-by-name

Consider evaluation of $\texttt{match}\ P\ \texttt{as}\ \{\texttt{inl x}.\, N,\ \texttt{inr y}.\, N'\}$ to see this.

Definitional interpreter for call-by-value

CBV terminals $T ::= \ \mathtt{true} \mid \mathtt{false} \mid \mathtt{inl}\ T \mid \mathtt{inr}\ T \mid \lambda\mathtt{x}.M$

To evaluate

- $\mathtt{true}$: return $\mathtt{true}$.
- $M + N$: evaluate M. If this returns m, evaluate N. If this returns n, return $m + n$.
- $\lambda\mathtt{x}.M$: return $\lambda\mathtt{x}.M$.
- $\mathtt{inl}\ M$: evaluate M. If this returns T, return $\mathtt{inl}\ T$.
- $\mathtt{let}\ (\mathtt{x}\ \mathtt{be}\ M,\ \mathtt{y}\ \mathtt{be}\ M').\ N$: evaluate M. If this returns T, evaluate M'. If this returns T', evaluate $N[T/\mathtt{x}, T'/\mathtt{y}]$.
- $\mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{true}.\ N,\ \mathtt{false}.\ N'\}$: evaluate M. If this returns $\mathtt{true}$, evaluate N, but if it returns $\mathtt{false}$, evaluate N'.
- $\mathtt{match}\ M\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\ N,\ \mathtt{inr}\ \mathtt{x}.\ N'\}$: evaluate M. If this returns $\mathtt{inl}\ T$, evaluate $N[T/\mathtt{x}]$, but if it returns $\mathtt{inr}\ T$, evaluate $N'[T/\mathtt{x}]$.
- MN: evaluate M. If this returns $\lambda\mathtt{x}.P$, evaluate N. If this returns T, evaluate $P[T/\mathtt{x}]$.

Definitional interpreter for call-by-name

In CBN the terminals are $\texttt{true}, \texttt{false}, \texttt{inl}\ M, \texttt{inr}\ M, \lambda\texttt{x}.M$
To evaluate

- $\texttt{true}$: return $\texttt{true}$.
- $M + N$: evaluate M. If this returns m, evaluate N. If this returns n, return $m + n$.
- $\lambda\texttt{x}.M$: return $\lambda\texttt{x}.M$.
- $\texttt{inl}\ M$: return $\texttt{inl}\ M$.
- $\texttt{let}\ (\texttt{x be}\ M,\ \texttt{y be}\ M').\ N$: evaluate $N[M/\texttt{x}, M'/\texttt{y}]$.
- $\texttt{match}\ M\ \texttt{as}\ \{\texttt{true}.\ N,\ \texttt{false}.\ N'\}$: evaluate M. If this returns $\texttt{true}$, evaluate N, but if it returns $\texttt{false}$, evaluate N'.
- $\texttt{match}\ M\ \texttt{as}\ \{\texttt{inl x}.\ N,\ \texttt{inr x}.\ N'\}$: evaluate M. If this returns $\texttt{inl}\ P$, evaluate $N[P/\texttt{x}]$, but if it returns $\texttt{inr}\ P$, evaluate $N'[P/\texttt{x}]$.
- $M\,N$: evaluate M. If this returns $\lambda\texttt{x}.P$, evaluate $P[N/\texttt{x}]$.

Big-step semantics for call-by-value

We write $M \Downarrow T$ to mean that M evaluates to T.

This is defined inductively, for example

$$\frac{M \Downarrow \lambda \mathtt{x}_A.\, P \quad N \Downarrow T \quad P[T/\mathtt{x}] \Downarrow T'}{M\, N \Downarrow T'}$$

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If $\vdash M : A$ then $M \Downarrow T$ for unique T.

Moreover $\vdash T : A$ and $[\![M]\!] = [\![T]\!]$.

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Long story

The experiment

- Add effects to (jumbo) λ-calculus, with CBV or CBN evaluation.
- See what equations and isomorphisms survive.
- Seek a denotational semantics for each language.

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Analyzing CBV with a microscope

- Look closely at the CBV models: there's a pattern.
- CBV contains particles of meaning, constituting fine-grain call-by-value.

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Analyzing CBV with a microscope

- Look closely at the CBV models: there's a pattern.
- CBV contains particles of meaning, constituting fine-grain call-by-value.

Increasing the magnification

- Look very closely at the CBN and fine-grain CBV models: there's a pattern.
- Both contain tiny particles of meaning, constituting call-by-push-value.

The big picture

$$\begin{tikzcd}
\begin{array}{c}\text{Call-by-value}\\ \text{jumbo } \lambda\text{-calculus}\end{array} \arrow[d] & \begin{array}{c}\text{Call-by-name}\\ \text{jumbo } \lambda\text{-calculus}\end{array} \arrow[d] \\
\begin{array}{c}\text{Fine-grain call-by-value}\\ \text{jumbo } \lambda\text{-calculus}\end{array} \arrow[r] & \text{Call-by-push-value}
\end{tikzcd}$$

Both fine-grain call-by-value and call-by-push-value are obtained empirically, by observing particles of meaning within a range of denotational models.

Where this story comes from

- Plotkin: semantics of recursion for call-by-name (PCF) and call-by-value (FPC)
- Moggi: list of monads for denotational semantics
- Moggi: monadic metalanguage
- Power and Robinson: Freyd categories
- Plotkin and Felleisen: call-by-value continuation semantics
- Reynolds' Idealized Algol, a call-by-name language with state
- O'Hearn: semantics of type identifiers in such a language
- Streicher and Reus: call-by-name continuation semantics
- Filinski: Effect-PCF

Adding computational effects

Errors

Let $E = \{\mathrm{CRASH}, \mathrm{BANG}\}$ be a set of "errors". We add

$$\frac{}{\Gamma \vdash \texttt{error}^B\ e : B}\ e \in E$$

To evaluate $\texttt{error}^B\ e$: halt with error message e.

Printing

Let $\mathcal{A} = \{\mathrm{a}, \mathrm{b}, \mathrm{c}, \mathrm{d}, \mathrm{e}\}$ be a set of "characters". We add

$$\frac{\Gamma \vdash M : B}{\Gamma \vdash \texttt{print}\ c.\ M : B}\ c \in \mathcal{A}$$

To evaluate $\texttt{print}\ c.\ M$: print c and then evaluate M.

Exercises

1. Evaluate

$$\texttt{let}\ (\mathrm{x}\ \texttt{be}\ \texttt{error}\ \mathrm{CRASH}).\ 5$$

   in CBV and CBN.

2. Evaluate

$$(\lambda \mathrm{x}.(\mathrm{x}+\mathrm{x}))(\texttt{print}\ \texttt{"hello"}.\ 4)$$

   in CBV and CBN.

3. Evaluate

$$\begin{array}{l}\texttt{match}\ (\texttt{print}\ \texttt{"hello"}.\ \texttt{inr}\ \texttt{error}\ \mathrm{CRASH})\ \texttt{as} \\ \quad \{\texttt{inl}\ \mathrm{x}.\ \mathrm{x}+1,\ \texttt{inr}\ \mathrm{y}.\ 5\}\end{array}$$

   in CBV and CBN.

Big-step semantics for errors

For call-by-value, we inductively define two big-step relations:

- $M \Downarrow T$ means M evaluates to T.
- $M \lightning e$ means M raises error e.

Here are the rules for application:

$$\frac{M \lightning e}{M\ N \lightning e} \qquad \frac{M \Downarrow \lambda \mathtt{x}.\, P \quad N \lightning e}{M\ N \lightning e}$$

$$\frac{M \Downarrow \lambda \mathtt{x}.\, P \quad N \Downarrow T \quad P[T/\mathtt{x}] \lightning e}{M\ N \lightning e}$$

$$\frac{M \Downarrow \lambda \mathtt{x}.\, P \quad N \Downarrow T \quad P[T/\mathtt{x}] \Downarrow T'}{M\ N \Downarrow T'}$$

Likewise for call-by-name.

Observational equivalence

A program is a closed term of type `nat` or `bool`.

Two terms $\Gamma \vdash M, M' : B$ are observationally equivalent

when $\mathcal{C}[M]$ and $\mathcal{C}[M']$ have the same behaviour

for every program with a hole $\mathcal{C}[\cdot]$.

Same behaviour means: print the same string, raise the same error, return the same boolean.

We write $M \simeq_{\mathbf{CBV}} M'$ and $M \simeq_{\mathbf{CBN}} M'$.

The η-law for boolean type: has it survived?

η-law for bool

Any term $\Gamma, \mathtt{z} : \mathtt{bool} \vdash M : B$ can be expanded as

$$\mathtt{match}\ \mathtt{z}\ \mathtt{as}\ \{\mathtt{true}.\ M[\mathtt{true}/\mathtt{z}],\ \mathtt{false}.\ M[\mathtt{false}/\mathtt{z}]\}$$

Anything of boolean type is a boolean.

This holds in CBV, because `z` can only be replaced by `true` or `false`.

But it's broken in CBN, because `z` might raise an error. For example,

$$\mathtt{true} \not\simeq_{\mathbf{CBN}} \mathtt{match}\ \mathtt{z}\ \mathtt{as}\ \{\mathtt{true}.\ \mathtt{true},\ \mathtt{false}.\ \mathtt{true}\}$$

because we can apply the context

$$\mathtt{let}\ (\mathtt{z}\ \mathtt{be}\ \mathtt{error}\ \mathrm{CRASH}).\ [\cdot]$$

Similarly the η-law for sum types is valid in CBV but not in CBN.

The η-law for functions: has it survived?

η-law for $A \to B$ and $A \Pi B$

Any term $\Gamma \vdash M : A \to B$ can be expanded as $\lambda \mathtt{x}.M\mathtt{x}$.
Any term $\Gamma \vdash M : A \Pi B$ can be expanded as $\lambda\{^{\mathtt{l}}.\, M^{\mathtt{l}},\ ^{\mathtt{r}}.\, M^{\mathtt{r}}\}$.

Although these fail in CBV, they hold in CBN. Consequences:

$$\begin{array}{rcl}
\mathtt{error}\ e & \simeq_{\mathbf{CBN}} & \lambda\mathtt{x}.\ \mathtt{error}\ e \\
\mathtt{error}\ e & \simeq_{\mathbf{CBN}} & \lambda\{^{\mathtt{l}}.\,\mathtt{error}\ e,\ ^{\mathtt{r}}.\,\mathtt{error}\ e\} \\
\mathtt{print}\ c.\ \lambda\mathtt{x}.\ M & \simeq_{\mathbf{CBN}} & \lambda\mathtt{x}.\ \mathtt{print}\ c.\ M \\
\mathtt{print}\ c.\ \lambda\{^{\mathtt{l}}.\,M,\ ^{\mathtt{r}}.\,N\} & \simeq_{\mathbf{CBN}} & \lambda\{^{\mathtt{l}}.\,\mathtt{print}\ c.\ M,\ ^{\mathtt{r}}.\,\mathtt{print}\ c.\ N\}
\end{array}$$

Yet the two sides have different operational behaviour! What's going on?

In CBN, a function gets evaluated only by being applied.

Summary

The pure λ-calculus satisfies all the β- and η-laws.

With computational effects,

- CBV satisfies η for leftist connectives (tuple types), but not rightist ones (function types)
- CBN satisfies η for rightist connectives (function types), but not leftist ones (tuple types).

Summary

The pure λ-calculus satisfies all the β- and η-laws.

With computational effects,

- CBV satisfies η for leftist connectives (tuple types), but not rightist ones (function types)
- CBN satisfies η for rightist connectives (function types), but not leftist ones (tuple types).

Similarly for isomorphisms:

- $(A + B) + C \cong A + (B + C)$ survives in CBV but not CBN.
- $A \times B \cong A \,\Pi\, B$ survives in neither CBV nor CBN.
- $A \to (B \to C) \cong (A \,\Pi\, B) \to C$ survives in CBN but not CBV.

Naive CBV semantics

Our first attempt.

Each type A denotes a set, a semantic domain for terms.

$$\begin{array}{rcl} [\![\mathtt{bool}]\!]_* & = & \mathbb{B} + E \\ [\![\mathtt{bool} + \mathtt{bool}]\!]_* & = & (\mathbb{B} + \mathbb{B}) + E \\ [\![\mathtt{bool} \times \mathtt{bool}]\!]_* & = & (\mathbb{B} \times \mathbb{B}) + E \end{array}$$

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Not easy to make this compositional, so we abandon it.

CBV denotational semantics

Each type denotes a set, a semantic domain for terminals.

$$\begin{array}{rcl} [\![\texttt{bool}]\!] & = & \mathbb{B} \\ [\![A + B]\!] & = & [\![A]\!] + [\![B]\!] \\ [\![A \to B]\!] & = & [\![A]\!] \to ([\![B]\!] + E) \\ [\![() \to B]\!] & = & [\![B]\!] + E \\ [\![\Gamma]\!] & = & \prod\limits_{(\mathtt{x}:A)\in\Gamma} [\![A]\!] \end{array}$$

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Each term $\Gamma \vdash M : B$ denotes a function $[\![M]\!] : [\![\Gamma]\!] \longrightarrow ([\![B]\!] + E)$.

Semantics of term constructors

$$\frac{\Gamma, \mathtt{x} : A \vdash M : B}{\Gamma \vdash \lambda \mathtt{x} \in A.\, M : A \to B}$$

$$[\![\lambda \mathtt{x}_A.\, M]\!] \;:\; \rho \longmapsto \mathsf{inl}\ \lambda a \in [\![A]\!].\, [\![M]\!](\rho, \mathtt{x} \mapsto a)$$

$$\frac{\Gamma \vdash M : A \to B \quad \Gamma \vdash N : A}{\Gamma \vdash M\, N : B}$$

$$[\![M\, N]\!] \;:\; \rho \longmapsto \mathsf{match}\ [\![M]\!]\rho\ \mathsf{as} \begin{cases} \mathsf{inl}\ f. & \mathsf{match}\ [\![N]\!]\rho\ \mathsf{as} \begin{cases} \mathsf{inl}\ x. & f(x) \\ \mathsf{inr}\ e. & \mathsf{inr}\ e \end{cases} \\ \mathsf{inr}\ e. & \mathsf{inr}\ e \end{cases}$$

More term constructors

$$\frac{\Gamma \vdash M : A}{\Gamma \vdash \mathtt{inl}^{A,B}\ M : A + B}$$

$$[\![\mathtt{inl}^{A,B}\ M]\!] \,:\, \rho \longmapsto \textsf{match } [\![M]\!]\rho \textsf{ as } \left\{ \begin{array}{ll} \textsf{inl } a. & \textsf{inl inl } a \\ \textsf{inr } e. & \textsf{inr } e \end{array} \right.$$

More term constructors

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$$[\![\mathtt{inl}^{A,B}\ M]\!]\ :\ \rho \longmapsto \text{match } [\![M]\!]\rho \text{ as } \begin{cases} \text{inl } a. & \text{inl inl } a \\ \text{inr } e. & \text{inr } e \end{cases}$$

To prove the soundness of the denotational semantics, we need a substitution lemma.

CBV Substitution Lemma: What Doesn't Work

Can we obtain $[\![N[M/\mathtt{x}]]\!]$ from $[\![M]\!]$ and $[\![N]\!]$?

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Example that rules out a general substitution lemma

Define $\vdash M : \mathtt{bool}$ and $\mathtt{x} : \mathtt{bool} \vdash N, N' : \mathtt{bool}$.

$$\begin{array}{rcl}
M & \stackrel{\text{def}}{=} & \mathtt{error}\ \mathrm{CRASH} \\
N & \stackrel{\text{def}}{=} & \mathtt{true} \\
N' & \stackrel{\text{def}}{=} & \mathtt{match}\ \mathtt{x}\ \mathtt{as}\ \{\mathtt{true}.\,\mathtt{true},\ \mathtt{false}.\,\mathtt{true}\} \\
[\![N]\!] & = & [\![N']\!] \qquad \text{because } N =_{\eta\,\mathtt{bool}} N' \\
[\![N[M/\mathtt{x}]]\!] & \neq & [\![N'[M/\mathtt{x}]]\!]
\end{array}$$

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Can we obtain $[\![N[M/\mathtt{x}]]\!]$ from $[\![M]\!]$ and $[\![N]\!]$? Not in CBV.

Example that rules out a general substitution lemma

Define $\vdash M : \mathtt{bool}$ and $\mathtt{x} : \mathtt{bool} \vdash N, N' : \mathtt{bool}$.

$$
\begin{array}{rcl}
M & \stackrel{\text{def}}{=} & \mathtt{error}\ \text{CRASH} \\
N & \stackrel{\text{def}}{=} & \mathtt{true} \\
N' & \stackrel{\text{def}}{=} & \mathtt{match}\ \mathtt{x}\ \mathtt{as}\ \{\mathtt{true}.\,\mathtt{true},\ \mathtt{false}.\,\mathtt{true}\} \\
[\![N]\!] & = & [\![N']\!] \qquad \text{because } N =_{\eta\,\mathtt{bool}} N' \\
[\![N[M/\mathtt{x}]]\!] & \neq & [\![N'[M/\mathtt{x}]]\!]
\end{array}
$$

But we can give a lemma for the substitution of values.

Values

The following terms are called values.

$$V \quad ::= \quad \texttt{true} \mid \texttt{false} \mid \texttt{inl}\ V \mid \texttt{inr}\ V \mid \lambda \mathrm{x}.M \mid \texttt{x}$$

The closed values are just the terminals:
we don't allow "complex values" such as

$$\texttt{match true as } \{\texttt{true}.\,\texttt{false},\ \texttt{false}.\,\texttt{true}\}$$

Denotational semantics of values

Each value $\Gamma \vdash V : A$ denotes a function $[\![V]\!]^{\mathsf{val}} : [\![\Gamma]\!] \longrightarrow [\![A]\!]$.

$$\begin{array}{lcccl}
[\![\mathtt{x}]\!]^{\mathsf{val}} & : & \rho & \longmapsto & \rho_{\mathtt{x}} \\
[\![\mathtt{true}]\!]^{\mathsf{val}} & : & \rho & \longmapsto & \mathsf{true} \\
[\![\mathtt{inl}\ V]\!]^{\mathsf{val}} & : & \rho & \longmapsto & \mathsf{inl}\ [\![V]\!]^{\mathsf{val}}\rho \\
[\![\lambda \mathtt{x}_A .\, M]\!]^{\mathsf{val}} & : & \rho & \longmapsto & \lambda a \in [\![A]\!].\, [\![M]\!](\rho, \mathtt{x} \mapsto [\![a]\!])
\end{array}$$

We can recover $[\![V]\!]$ from $[\![V]\!]^{\mathsf{val}}$.

$$[\![V]\!] : \rho \longmapsto \mathsf{inl}\ [\![V]\!]^{\mathsf{val}}\rho$$

Substitution Lemma For Values

Given values $\Gamma \vdash V : A$ and $\Gamma \vdash W : B$ and a term $\Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash M : C$ we can obtain $[\![M[V/\mathtt{x}, W/\mathtt{y}]]\!]$ from $[\![V]\!]^{\mathsf{val}}$ and $[\![W]\!]^{\mathsf{val}}$ and $[\![M]\!]$.

$$[\![M[V/\mathtt{x}, W/\mathtt{y}]]\!] \,:\, \rho \longmapsto [\![M]\!](\rho, \mathtt{x} \mapsto [\![V]\!]^{\mathsf{val}}\rho, \mathtt{y} \mapsto [\![W]\!]^{\mathsf{val}}\rho)$$

Likewise for substitution of values into values.

Soundness of CBV Denotational Semantics

- If $M \Downarrow V$ then $[\![M]\!]\varepsilon = \mathsf{inl}\ ([\![V]\!]^{\mathsf{val}}\varepsilon)$.
- If $M \lightning e$ then $[\![M]\!]\varepsilon = \mathsf{inr}\ e$.

Proof by induction, using the substitution lemma.

Fine-Grain Call-By-Value

Fine-grain call-by-value has two judgements:

- A value $\Gamma \vdash^{\mathsf{v}} V : A$ denotes a function $[\![V]\!] : [\![\Gamma]\!] \longrightarrow [\![A]\!]$.
- A computation $\Gamma \vdash^{\mathsf{c}} M : A$ denotes a function $[\![M]\!] : [\![\Gamma]\!] \longrightarrow [\![A]\!] + E$.

Key typing rules

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{c}} \mathtt{return}\ V : A} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : A \quad \Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} N : B}{\Gamma \vdash^{\mathsf{c}} M\ \mathtt{to}\ \mathtt{x}.\ N : B}$$

Corresponds to Power and Robinson's notion of a Freyd category.

Semantics of returning and sequencing

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{c}} \texttt{return}\ V : A}$$

$$[\![\texttt{return}\ V]\!] \,:\, \rho \longmapsto \mathsf{inl}\ [\![V]\!]\rho$$

$$\frac{\Gamma \vdash^{\mathsf{c}} M : A \quad \Gamma, \texttt{x} : A \vdash^{\mathsf{c}} N : B}{\Gamma \vdash^{\mathsf{c}} M\ \texttt{to x.}\ N : B}$$

$$[\![M\ \texttt{to x.}\ N]\!] \,:\, \rho \longmapsto \mathsf{match}\ [\![M]\!]\rho\ \mathsf{as} \begin{cases} \mathsf{inl}\ a. & [\![N]\!](\rho, \texttt{x} \mapsto a) \\ \mathsf{inr}\ e. & \mathsf{inr}\ e \end{cases}$$

Syntax

For connectives $\texttt{bool}, +, \to$ the syntax is as follows.

$$
\begin{array}{rcl}
V & ::= & \texttt{x} \mid \texttt{true} \mid \texttt{false} \\
 & & \mid \texttt{inl}\ V \mid \texttt{inr}\ V \mid \lambda\texttt{x}.\,M \\
M & ::= & M\ \texttt{to}\ \texttt{x}.\ M \mid \texttt{return}\ V \\
 & & \mid \texttt{let}\ (\overrightarrow{\texttt{x}\ \mathsf{be}\ V}).\ M \mid V\,V \\
 & & \mid \texttt{match}\ V\ \mathsf{as}\ \{\texttt{true}.\,M,\ \texttt{false}.\,M\} \\
 & & \mid \texttt{match}\ V\ \mathsf{as}\ \{\texttt{inl}\ \texttt{x}.\,M,\ \texttt{inr}\ \texttt{x}.\,M\} \\
 & & \mid \texttt{error}\ e
\end{array}
$$

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For connectives $\texttt{bool}, +, \to$ the syntax is as follows.

$$
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 & & \mid \texttt{inl}\ V \mid \texttt{inr}\ V \mid \lambda\texttt{x}.\, M \\
M & ::= & M\ \texttt{to}\ \texttt{x}.\ M \mid \texttt{return}\ V \\
 & & \mid \texttt{let}\ (\overrightarrow{\texttt{x}\ \texttt{be}\ V}).\ M \mid V\,V \\
 & & \mid \texttt{match}\ V\ \texttt{as}\ \{\texttt{true}.\, M,\ \texttt{false}.\, M\} \\
 & & \mid \texttt{match}\ V\ \texttt{as}\ \{\texttt{inl}\ \texttt{x}.\, M,\ \texttt{inr}\ \texttt{x}.\, M\} \\
 & & \mid \texttt{error}\ e
\end{array}
$$

We don't allow "complex values" such as

$$\texttt{match true as}\ \{\texttt{true}.\,\texttt{false},\ \texttt{false}.\,\texttt{true}\}$$

These would complicate the operational semantics.

Definitional interpreter for fine-grain CBV

We evaluate a closed computation $\vdash^{\mathsf{c}} M : A$ to a closed value $\vdash^{\mathsf{v}} V : A$.
To evaluate

- $\texttt{return}\ V$: return V.
- $M\ \texttt{to x.}\ N$, evaluate M. If this returns V, evaluate $N[V/\texttt{x}]$.
- $\texttt{let}\ (\texttt{x be}\ V,\ \texttt{y be}\ W).\ M$, evaluate $M[V/\texttt{x}, W/\texttt{y}]$.
- $(\lambda\texttt{x}.\, M)\, V$, evaluate $M[V/\texttt{x}]$.
- $\texttt{match inl}\ V\ \texttt{as}\ \{\texttt{inl x.}\ N,\ \texttt{inr x.}\ N'\}$: evaluate $N[V/\texttt{x}]$.

Equational theory

β-laws

$$\begin{aligned} \mathtt{match}\ (\mathtt{inl}\ V)\ \mathtt{as}\ \{\mathtt{true}.\, M, \mathtt{false}.\, M'\} &= M[V/\mathtt{x}] \\ (\lambda \mathtt{x}.\, M)\, V &= M[V/\mathtt{x}] \\ \mathtt{let}\ (\mathtt{x}\ \mathtt{be}\ V,\ \mathtt{y}\ \mathtt{be}\ W).\ M &= M[V/\mathtt{x}, W/\mathtt{y}] \end{aligned}$$

η-laws

$$\begin{aligned} M[V/\mathtt{z}] &= \mathtt{match}\ V\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\, M[\mathtt{inl}\ \mathtt{x}/\mathtt{z}],\ \mathtt{inr}\ \mathtt{y}.\, M[\mathtt{inr}\ \mathtt{x}/\mathtt{z}]\} \\ V &= \lambda \mathtt{x}.\ V\mathtt{x} \end{aligned}$$

Sequencing laws

$$\begin{aligned} (\mathtt{return}\ V)\ \mathtt{to}\ \mathtt{x}.\ M &= M[V/\mathtt{x}] \\ M &= M\ \mathtt{to}\ \mathtt{x}.\ \mathtt{return}\ \mathtt{x} \\ (M\ \mathtt{to}\ \mathtt{x}.\ N)\ \mathtt{to}\ \mathtt{y}.\ P &= M\ \mathtt{to}\ \mathtt{x}.\ (N\ \mathtt{to}\ \mathtt{y}.\ P) \end{aligned}$$

CBV to fine-grain call-by-value

Term $\Gamma \vdash M : A$ to computation $\Gamma \vdash^{\mathsf{c}} \hat{M} : A$.

$$\begin{array}{rcl}
\mathtt{x} & \longmapsto & \mathtt{return\ x} \\
\lambda\mathtt{x}.\, M & \longmapsto & \mathtt{return}\ \lambda\mathtt{x}.\, \hat{M} \\
\mathtt{inl}\ M & \longmapsto & \hat{M}\ \mathtt{to\ x.\ return\ inl\ x} \\
M\, N & \longmapsto & \hat{M}\ \mathtt{to\ x.}\ \hat{N}\ \mathtt{to\ y.\ x\, y} \\
\mathtt{let}\ (\mathtt{x\ be}\ M,\ \mathtt{y\ be}\ M').\ N & \longmapsto & \hat{M}\ \mathtt{to\ x.}\ \hat{M}'\ \mathtt{to\ y.}\ \hat{N}
\end{array}$$

Value $\Gamma \vdash V : A$ to value $\Gamma \vdash^{\mathsf{v}} \check{V} : A$.

$$\begin{array}{rcl}
\mathtt{x} & \longmapsto & \mathtt{x} \\
\lambda\mathtt{x}.\, M & \longmapsto & \lambda\mathtt{x}.\, \hat{M} \\
\mathtt{inl}\ V & \longmapsto & \mathtt{inl}\ \check{V}
\end{array}$$

Nullary functions

Call-by-value programmers use nullary functions to delay evaluation, and call them thunks.

$$\begin{array}{rcl@{\qquad}rcl}
TA & \stackrel{\text{def}}{=} & () \to A & [\![TA]\!] & = & [\![A]\!] + E \\
\mathtt{thunk}\ M & \stackrel{\text{def}}{=} & \lambda().\, M & [\![\mathtt{thunk}\ M]\!] & = & [\![M]\!] \\
\mathtt{force}\ V & \stackrel{\text{def}}{=} & V\,() & [\![\mathtt{force}\ V]\!] & = & [\![V]\!]
\end{array}$$

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The type TA has a reversible rule $\dfrac{\Gamma \vdash^{\mathsf{c}} A}{\Gamma \vdash^{\mathsf{v}} TA}$

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The type TA has a reversible rule $\dfrac{\Gamma \vdash^{\mathsf{c}} A}{\Gamma \vdash^{\mathsf{v}} TA}$

Fine-grain CBV (unlike the monadic metalanguage) distinguishes computations from thunks.

Naive CBN semantics of errors

Each type denotes a set, a semantic domain for terms. For example:

$$\begin{aligned}
[\![\texttt{bool} \to (\texttt{bool} \to \texttt{bool})]\!]_* &= (\mathbb{B}+E) \to ((\mathbb{B}+E) \to (\mathbb{B}+E)) \\
[\![\texttt{bool} + \texttt{bool}]\!]_* &= ((\mathbb{B}+E) + (\mathbb{B}+E)) + E \\
[\![\texttt{bool} \,\Pi\, \texttt{bool}]\!]_* &= (\mathbb{B}+E) \times (\mathbb{B}+E)
\end{aligned}$$

Thus we define

$$\begin{aligned}
[\![\texttt{bool}]\!]_* &= \mathbb{B}+E \\
[\![A+B]\!]_* &= ([\![A]\!]_* + [\![B]\!]_*) + E \\
[\![A \to B]\!]_* &= [\![A]\!]_* \to [\![B]\!]_* \\
[\![A \,\Pi\, B]\!]_* &= [\![A]\!]_* \times [\![B]\!]_* \\
[\![\Gamma]\!] &= \prod_{(\mathtt{x}:A)\in\Gamma} [\![A]\!]_*
\end{aligned}$$

Each term $\Gamma \vdash M : B$ should denote a function $[\![M]\!] : [\![\Gamma]\!] \longrightarrow [\![B]\!]_*$.

Naive semantics: what goes wrong

$$\frac{}{\Gamma \vdash \texttt{error}\ \mathrm{CRASH} : B}$$

denotes $\rho \longmapsto$?

Naive semantics: what goes wrong

$$\frac{}{\Gamma \vdash \texttt{error}\ \mathrm{CRASH} : B} \qquad \text{denotes } \rho \longmapsto ?$$

Example:

- suppose $B = \texttt{bool} \to (\texttt{bool} \to \texttt{bool})$
- then B denotes $(\mathbb{B} + E) \to ((\mathbb{B} + E) \to (\mathbb{B} + E))$
- and $\texttt{error}\ \mathrm{CRASH} \simeq_{\mathbf{CBN}} \lambda\mathtt{x}.\ \lambda\mathtt{y}.\ \texttt{error}\ \mathrm{CRASH}$
- so the answer should be $\lambda x.\ \lambda y.\ \mathsf{inr}\ \mathrm{CRASH}.$

Intuition: go down through the function types until we hit a tuple type.

Naive semantics: what goes wrong

$$\frac{}{\Gamma \vdash \texttt{error}\ \mathrm{CRASH} : B} \qquad \text{denotes } \rho \longmapsto ?$$

Example:

- suppose $B = \texttt{bool} \to (\texttt{bool} \to \texttt{bool})$
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- and $\texttt{error}\ \mathrm{CRASH} \simeq_{\mathbf{CBN}} \lambda\mathrm{x}.\ \lambda\mathrm{y}.\ \texttt{error}\ \mathrm{CRASH}$
- so the answer should be $\lambda x.\ \lambda y.\ \mathsf{inr}\ \mathrm{CRASH}$.

Intuition: go down through the function types until we hit a tuple type.

A similar problem arises with `match`.

Solution: E-pointed sets

Definition

An E-pointed set is a set X with two distinguished elements $c, b \in X$.

A type should denote an E-pointed set, a semantic domain for terms.

Solution: E-pointed sets

Definition

An E-pointed set is a set X with two distinguished elements $c, b \in X$.

A type should denote an E-pointed set, a semantic domain for terms.
Examples:

$$\begin{array}{rcl}
[\![\texttt{bool} \to (\texttt{bool} \to \texttt{bool})]\!] & = & ((\mathbb{B} + E) \to ((\mathbb{B} + E) \to (\mathbb{B} + E)), \\
& & \lambda \mathsf{x}.\lambda \mathsf{y}.\mathsf{inr}\ \mathrm{CRASH}, \\
& & \lambda \mathsf{x}.\lambda \mathsf{y}.\mathsf{inr}\ \mathrm{BANG}) \\
[\![\texttt{bool} + \texttt{bool}]\!] & = & (((\mathbb{B} + E) + (\mathbb{B} + E)) + E, \\
& & \mathsf{inr}\ \mathrm{CRASH}, \\
& & \mathsf{inr}\ \mathrm{BANG}) \\
[\![\texttt{bool}\ \Pi\ \texttt{bool}]\!] & = & ((\mathbb{B} + E) \times (\mathbb{B} + E), \\
& & (\mathsf{inr}\ \mathrm{CRASH}, \mathsf{inr}\ \mathrm{CRASH}), \\
& & (\mathsf{inr}\ \mathrm{BANG}, \mathsf{inr}\ \mathrm{BANG}))
\end{array}$$

CBN semantics of errors

$$[\![\texttt{bool}]\!] = (\mathbb{B} + E, \mathsf{inr}\ \mathrm{CRASH}, \mathsf{inr}\ \mathrm{BANG})$$

If $[\![A]\!] = (X, c, b)$ and $[\![B]\!] = (Y, c', b')$

$$\begin{array}{lrcl} \text{then} & [\![A + B]\!] & = & ((X + Y) + E, \mathsf{inr}\ \mathrm{CRASH}, \mathsf{inr}\ \mathrm{BANG}) \\ \text{and} & [\![A \to B]\!] & = & (X \to Y, \lambda x.\, c', \lambda x.\, b') \\ \text{and} & [\![A \,\Pi\, B]\!] & = & (X \times Y, (c, c'), (b, b')) \end{array}$$

CBN semantics of errors

$$[\![\texttt{bool}]\!] \quad = \quad (\mathbb{B} + E, \textsf{inr}\ \mathrm{CRASH}, \textsf{inr}\ \mathrm{BANG})$$

If $[\![A]\!] = (X, c, b)$ and $[\![B]\!] = (Y, c', b')$

then $[\![A + B]\!] = ((X + Y) + E, \textsf{inr}\ \mathrm{CRASH}, \textsf{inr}\ \mathrm{BANG})$

and $[\![A \to B]\!] = (X \to Y, \lambda x.\, c', \lambda x.\, b')$

and $[\![A \,\Pi\, B]\!] = (X \times Y, (c, c'), (b, b'))$

$$[\![\Gamma]\!] \quad = \quad \prod_{\substack{(\mathtt{x}:A)\in\Gamma \\ [\![A]\!]=(X,c,b)}} X$$

A term $\Gamma \vdash M : B$ denotes a function $[\![M]\!] : [\![\Gamma]\!] \longrightarrow [\![B]\!]$.

Semantics of term constructors

$$\frac{}{\Gamma \vdash \texttt{true} : \texttt{bool}}$$

$$[\![\texttt{true}]\!] \ : \ \rho \longmapsto \mathsf{inl\ true}$$

$$\frac{\Gamma \vdash M : \texttt{bool} \quad \Gamma \vdash N : B \quad \Gamma \vdash N' : B}{\Gamma \vdash \texttt{match}\ M\ \texttt{as}\ \{\texttt{true}.\ N,\ \texttt{false}.\ N'\} : B}$$

$$[\![\texttt{match}\ M\ \texttt{as}\ \{\texttt{true}.\ N,\ \texttt{false}.\ N'\}]\!] \ : \ \rho \quad \longmapsto$$

$$\mathsf{match}\ [\![M]\!]\rho\ \mathsf{as} \begin{cases} \mathsf{inl\ true.} & [\![N]\!]\rho \\ \mathsf{inl\ false.} & [\![N']\!]\rho \\ \mathsf{inr}\ \mathrm{CRASH.} & c \\ \mathsf{inr}\ \mathrm{BANG.} & b \end{cases} \qquad \text{where } [\![B]\!] = (Y, c, b)$$

More term constructors

$$
\begin{array}{lcccl}
[\![\lambda \mathtt{x}.M]\!] & : & \rho & \longmapsto & \lambda a.\,[\![M]\!](\rho, \mathtt{x} \mapsto a) \\
[\![M\;N]\!] & : & \rho & \longmapsto & [\![M]\!]\,[\![N]\!] \\
[\![\mathtt{x}]\!] & : & \rho & \longmapsto & \rho_{\mathtt{x}} \\
\mathtt{error}\ \mathrm{CRASH} & : & \rho & \longmapsto & c
\end{array}
$$

Soundness/adequacy

- If $M \Downarrow T$ then $[\![M]\!]\varepsilon = [\![T]\!]\varepsilon$.
- If $M \lightning \mathrm{CRASH}$ then $[\![M]\!]\varepsilon = c$.
- If $M \lightning \mathrm{BANG}$ then $[\![M]\!]\varepsilon = b$.

Proved by induction, using the substitution lemma.

Notation for E-pointed sets

- Free E-pointed set on a set X.

$$F^E X \quad \stackrel{\text{def}}{=} \quad (X + E, \mathsf{inr}\ \mathrm{CRASH}, \mathsf{inr}\ \mathrm{BANG})$$

- Product of two E-pointed sets.

$$(X, c, b)\, \Pi\, (Y, c', b') \quad \stackrel{\text{def}}{=} \quad (X \times Y, (c, c'), (b, b'))$$

- Unit E-pointed set. $\qquad 1_\Pi \quad \stackrel{\text{def}}{=} \quad (1, (\,), (\,))$
- Product of a family of E-pointed sets.

$$\prod_{i \in I}(X_i, c_i, b_i) \quad \stackrel{\text{def}}{=} \quad (\prod_{i \in I} X_i, \lambda i.\, c_i, \lambda i.\, b_i)$$

- Exponential E-pointed set.

$$\begin{aligned} X \to (Y, c, b) \quad &\stackrel{\text{def}}{=} \quad \prod_{x \in X}(Y, c, b) \\ &= \quad (X \to Y, \lambda x.\, c, \lambda x.\, b) \end{aligned}$$

- Carrier of an E-pointed set. $\qquad U^E(X, c, b) \stackrel{\text{def}}{=} X$

Summary of call-by-name semantics

A type denotes an E-pointed set.

$$\begin{array}{rcl}
[\![\texttt{bool}]\!] & = & F^E(1+1) \\
[\![A+B]\!] & = & F^E(U^E[\![A]\!] + U^E[\![B]\!]) \\
[\![A \to B]\!] & = & U^E[\![A]\!] \to [\![B]\!] \\
[\![A \,\Pi\, B]\!] & = & [\![A]\!] \,\Pi\, [\![B]\!]
\end{array}$$

A typing context denotes a set.

$$[\![\Gamma]\!] \quad = \quad \prod_{(\mathtt{x}:A)\in\Gamma} U^E[\![A]\!]$$

A term $\Gamma \vdash M : B$ denotes a function $[\![\Gamma]\!] \longrightarrow [\![B]\!]$.

Summary of call-by-value semantics

A type denotes a set.

$$\begin{array}{rcl} [\![\texttt{bool}]\!] & = & 1+1 \\ [\![A+B]\!] & = & [\![A]\!]+[\![B]\!] \\ [\![A \to B]\!] & = & U^E([\![A]\!] \to F^E[\![B]\!]) \\ [\![TB]\!] & = & U^E F^E [\![B]\!] \end{array}$$

A typing context denotes a set.

$$[\![\Gamma]\!] \quad = \quad \prod_{(\mathtt{x}:A)\in\Gamma} [\![A]\!]$$

A computation $\Gamma \vdash^{\mathsf{c}} M : B$ denotes a function $[\![\Gamma]\!] \longrightarrow F^E[\![B]\!]$.

Call-By-Push-Value Types

Two kinds of type:

- A value type denotes a set.
- A computation type denotes an E-pointed set.

Call-By-Push-Value Types

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- A value type denotes a set.
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value type	$A ::= \quad U\underline{B} \mid 1 \mid A \times A \mid 0 \mid A + A \mid \sum_{i\in\mathbb{N}} A_i$
computation type	$\underline{B} ::= \quad FA \mid A \to \underline{B} \mid 1_\Pi \mid \underline{B} \,\Pi\, \underline{B} \mid \prod_{i\in\mathbb{N}} \underline{B}_i$

Call-By-Push-Value Types

Two kinds of type:

- A value type denotes a set.
- A computation type denotes an E-pointed set.

$$\text{value type} \quad A ::= \; U\underline{B} \mid 1 \mid A \times A \mid 0 \mid A + A \mid \sum_{i \in \mathbb{N}} A_i$$

$$\text{computation type} \quad \underline{B} ::= \; FA \mid A \to \underline{B} \mid 1_\Pi \mid \underline{B} \,\Pi\, \underline{B} \mid \prod_{i \in \mathbb{N}} \underline{B}_i$$

Strangely function types are computation types, and $\lambda \mathrm{x}.M$ is a computation.

Judgements

An identifier gets bound to a value, so it has value type.

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A context Γ is a finite set of identifiers with associated value type

$$\mathtt{x}_0 : A_0, \ldots, \mathtt{x}_{m-1} : A_{m-1}$$

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Two judgements:

- A value $\Gamma \vdash^{\mathsf{v}} V : A$ denotes a function $[\![V]\!] : [\![\Gamma]\!] \longrightarrow [\![A]\!]$.
- A computation $\Gamma \vdash^{\mathsf{c}} M : \underline{B}$ denotes a function $[\![M]\!] : [\![\Gamma]\!] \longrightarrow [\![\underline{B}]\!]$.

The type FA

A computation in FA aims to return a value in A.

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{c}} \mathtt{return}\ V : FA} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : FA \quad \Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} N : \underline{B}}{\Gamma \vdash^{\mathsf{c}} M\ \mathtt{to}\ \mathtt{x}.\ N : \underline{B}}$$

Sequencing in the style of Filinski's "Effect-PCF".

The type FA

A computation in FA aims to return a value in A.

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{c}} \texttt{return}\ V : FA} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : FA \quad \Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} N : \underline{B}}{\Gamma \vdash^{\mathsf{c}} M\ \texttt{to x.}\ N : \underline{B}}$$

Sequencing in the style of Filinski's "Effect-PCF".

$$\begin{array}{lcll} [\![\texttt{return}\ V]\!] & : & \rho & \longmapsto \quad \mathsf{inl}\ [\![V]\!]\rho \\ [\![M\ \texttt{to x.}\ N]\!] & : & \rho & \longmapsto \end{array}$$

$$\mathsf{match}\ [\![M]\!]\rho\ \mathsf{as} \begin{cases} \mathsf{inl}\ a. & [\![N]\!](\rho, \mathtt{x} \mapsto a) \\ \mathsf{inr}\ \mathrm{CRASH}. & c \\ \mathsf{inr}\ \mathrm{BANG}. & b \end{cases}$$

$$\text{where } [\![\underline{B}]\!] = (Y, c, b)$$

The type $U\underline{B}$

A value in $U\underline{B}$ is a thunk of a computation in $\underline{B}$.

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B}}{\Gamma \vdash^{\mathsf{v}} \texttt{thunk}\ M : U\underline{B}} \qquad \frac{\Gamma \vdash^{\mathsf{v}} V : U\underline{B}}{\Gamma \vdash^{\mathsf{c}} \texttt{force}\ V : \underline{B}}$$

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$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B}}{\Gamma \vdash^{\mathsf{v}} \texttt{thunk}\ M : U\underline{B}} \qquad \frac{\Gamma \vdash^{\mathsf{v}} V : U\underline{B}}{\Gamma \vdash^{\mathsf{c}} \texttt{force}\ V : \underline{B}}$$

$$[\![\texttt{thunk}\ M]\!] = [\![M]\!]$$

$$[\![\texttt{force}\ V]\!] = [\![V]\!]$$

Identifiers

An identifier is a value.

$$\frac{}{\Gamma \vdash^{\mathsf{v}} \mathtt{x} : A}\ (\mathtt{x} : A) \in \Gamma$$

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A \quad \Gamma \vdash^{\mathsf{v}} W : B \quad \Gamma, \mathtt{x} : A, \mathtt{y} : B \vdash^{\mathsf{c}} M : \underline{C}}{\Gamma \vdash^{\mathsf{c}} \mathtt{let}\ (\mathtt{x}\ \mathtt{be}\ V, \mathtt{y}\ \mathtt{be}\ W).\ M : \underline{C}}$$

Tuples

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{v}} \mathtt{inl}\ V : A + A'} \qquad \frac{\Gamma \vdash^{\mathsf{v}} V : A'}{\Gamma \vdash^{\mathsf{v}} \mathtt{inr}\ V : A + A'}$$

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A + A' \quad \Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} M : \underline{B} \quad \Gamma, \mathtt{y} : A \vdash^{\mathsf{c}} M' : \underline{B}}{\Gamma \vdash^{\mathsf{c}} \mathtt{match}\ V\ \mathtt{as}\ \{\mathtt{inl}\ \mathtt{x}.\, M, \mathtt{inr}\ \mathtt{y}.\, M'\} : \underline{B}}$$

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A \quad \Gamma \vdash^{\mathsf{v}} V' : A'}{\Gamma \vdash^{\mathsf{v}} \langle V, V' \rangle : A \times A'} \qquad \frac{\Gamma \vdash^{\mathsf{v}} V : A \times A' \quad \Gamma, \mathtt{x} : A, \mathtt{y} : A' \vdash^{\mathsf{c}} M : \underline{B}}{\Gamma \vdash^{\mathsf{c}} \mathtt{match}\ V\ \mathtt{as}\ \langle \mathtt{x}, \mathtt{y} \rangle . M : \underline{B}}$$

The rules for 1 are similar.

Functions

$$\frac{\Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} M : \underline{B}}{\Gamma \vdash^{\mathsf{c}} \lambda \mathtt{x}.M : A \to \underline{B}} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : A \to \underline{B} \quad \Gamma \vdash^{\mathsf{v}} V : A}{\Gamma \vdash^{\mathsf{c}} MV : \underline{B}}$$

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \quad \Gamma \vdash^{\mathsf{c}} M' : \underline{B}'}{\Gamma \vdash^{\mathsf{c}} \lambda\{^{\mathtt{l}}.\, M,\ ^{\mathtt{r}}.\, M'\} : \underline{B} \,\Pi\, \underline{B}'}$$

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \,\Pi\, \underline{B}'}{\Gamma \vdash^{\mathsf{c}} M^{\mathtt{l}} : \underline{B}} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \,\Pi\, \underline{B}'}{\Gamma \vdash^{\mathsf{c}} M^{\mathtt{r}} : \underline{B}'}$$

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$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \,\Pi\, \underline{B}'}{\Gamma \vdash^{\mathsf{c}} M^{\mathtt{l}} : \underline{B}} \qquad \frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \,\Pi\, \underline{B}'}{\Gamma \vdash^{\mathsf{c}} M^{\mathtt{r}} : \underline{B}'}$$

It is often convenient to write applications operand-first, as $V`M$ and $^{\mathtt{l}}`M$ and $^{\mathtt{r}}`M$.

Definitional interpreter for call-by-push-value

The terminals are computations: $\quad \texttt{return}\, V \qquad \lambda\texttt{x}.M \qquad \lambda\{\texttt{l}.\, M,\ \texttt{r}.\, M'\}$

Definitional interpreter for call-by-push-value

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To evaluate

- $\texttt{return}\ V$: return $\texttt{return}\ V$.
- $M\ \texttt{to}\ \texttt{x}.\ N$: evaluate M. If this returns $\texttt{return}\ V$, then evaluate $N[V/\texttt{x}]$.
- $\lambda\texttt{x}.N$: return $\lambda\texttt{x}.N$.
- MV: evaluate M. If this returns $\lambda\texttt{x}.N$, evaluate $N[V/\texttt{x}]$.
- $\lambda\{\texttt{l}.\, M,\ \texttt{r}.\, M'\}$: return $\lambda\{\texttt{l}.\, M,\ \texttt{r}.\, M'\}$.
- $M\,\texttt{l}$: evaluate M. If this returns $\lambda\{\texttt{l}.\, N,\ \texttt{r}.\, N'\}$, evaluate N.
- $\texttt{let}\ (\texttt{x}\ \texttt{be}\ V,\ \texttt{y}\ \texttt{be}\ W).\ M$: evaluate $M[V/\texttt{x}, W/\texttt{y}]$.
- $\texttt{force}\ \texttt{thunk}\ M$: evaluate M.
- $\texttt{match}\ \texttt{inl}\ V\ \texttt{as}\ \{\texttt{inl}\ \texttt{x}.\, M, \texttt{inr}\ \texttt{y}.\, M'\}$: evaluate $M[V/\texttt{x}]$.
- $\texttt{match}\ \langle V, V'\rangle\ \texttt{as}\ \langle\texttt{x},\texttt{y}\rangle.M$: evaluate $M[V/\texttt{x}, V'/\texttt{y}]$.
- $\texttt{error}\ e$, print error message e and stop.

Equational theory

β-laws

$$\begin{array}{rcl}
\texttt{force thunk } M & = & M \\
\texttt{match } (\texttt{inl } V) \texttt{ as } \{\texttt{true}. M, \texttt{false}. M'\} & = & M[V/\texttt{x}] \\
(\lambda \texttt{x}. M)\, V & = & M[V/\texttt{x}] \\
\texttt{let } (\texttt{x be } V,\ \texttt{y be } W).\ M & = & M[V/\texttt{x}, W/\texttt{y}]
\end{array}$$

η-laws

$$\begin{array}{rcl}
V & = & \texttt{thunk force } V \\
M[V/\texttt{z}] & = & \texttt{match } V \texttt{ as } \{\texttt{inl x}. M[\texttt{inl x}/\texttt{z}],\ \texttt{inr y}. M[\texttt{inr x}/\texttt{z}]\} \\
M & = & \lambda \texttt{x}.\ M \texttt{x}
\end{array}$$

Sequencing laws

$$\begin{array}{rcl}
(\texttt{return } V) \texttt{ to x}.\ M & = & M[V/\texttt{x}] \\
M & = & M \texttt{ to x. return x} \\
(M \texttt{ to x}.\ N) \texttt{ to y}.\ P & = & M \texttt{ to x}.\ (N \texttt{ to y}.\ P)
\end{array}$$

Decomposing CBV into CBPV

A CBV type translates into a value type.

$$\begin{array}{rcl} A \to B & \longmapsto & U(A \to FB) \\ TB & \longmapsto & UFB \end{array}$$

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A fine-grain CBV computation $\mathtt{x} : A, \mathtt{y} : B \vdash^{\mathsf{c}} M : C$
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$$\begin{array}{rcl} \lambda\mathtt{x}.\, M & \longmapsto & \mathtt{thunk}\ \lambda\mathtt{x}.\, M \\ V\,W & \longmapsto & (\mathtt{force}\ V)\,W \end{array}$$

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Therefore a CBV term $\mathtt{x} : A, \mathtt{y} : B \vdash M : C$
translates as $\mathtt{x} : A, \mathtt{y} : B \vdash^{\mathsf{c}} M : FC$

$$\begin{array}{rcl} \mathtt{x} & \longmapsto & \mathtt{return}\ \mathtt{x} \\ \lambda\mathtt{x}.\ M & \longmapsto & \mathtt{return}\ \mathtt{thunk}\ \lambda\mathtt{x}.\ M \\ M\ \ N & \longmapsto & M\ \mathtt{to}\ \mathtt{f}.\ N\ \mathtt{to}\ \mathtt{y}.\ ((\mathtt{force}\ \mathtt{f})\ \mathtt{y}) \end{array}$$

Decomposing CBN into CBPV

A CBN type translates into a computation type.

$$\begin{array}{rcl} \texttt{bool} & \longmapsto & F(1+1) \\ \underline{A} + \underline{B} & \longmapsto & F(U\underline{A} + U\underline{B}) \\ \underline{A} \to \underline{B} & \longmapsto & U\underline{A} \to \underline{B} \end{array}$$

Decomposing CBN into CBPV

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A CBN term $\mathtt{x} : \underline{A}, \mathtt{y} : \underline{B} \vdash M : \underline{C}$ translates as $\mathtt{x} : U\underline{A}, \mathtt{y} : U\underline{B} \vdash^{\mathsf{c}} M : \underline{C}$.

$$\begin{array}{rcl} \mathtt{x} & \longmapsto & \mathtt{force}\,\mathtt{x} \\ \mathtt{let}\,(\mathtt{x}\ \mathtt{be}\ M,\ \mathtt{y}\ \mathtt{be}\ M').\,N & \longmapsto & \mathtt{let}\,(\mathtt{x}\ \mathtt{be}\ \mathtt{thunk}\ M,\ \mathtt{y}\ \mathtt{be}\ \mathtt{thunk}\ M').\,N \\ \lambda\mathtt{x}.\ M & \longmapsto & \lambda\mathtt{x}.\ M \\ M\ N & \longmapsto & M\ (\mathtt{thunk}\ N) \\ \mathtt{inl}\ M & \longmapsto & \mathtt{return}\ \mathtt{inl}\ \mathtt{thunk}\ M \end{array}$$

Summary

We've seen

- the call-by-push-value calculus
- its operational semantics
- denotational semantics for errors.

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We've seen

- the call-by-push-value calculus
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Moggi's TA is UFA.

But

- our error semantics makes `thunk` and `force` invisible
- we still don't understand why a function is a computation.

CK-machine

An operational semantics due to Felleisen and Friedman (1986).
And Landin, Krivine, Streicher and Reus, Bierman, Pitts, . . .

It is suitable for sequential languages whether CBV, CBN or CBPV.

At any time, there's a computation (C) and a stack of contexts (K).

Initially, K is empty.

Some authors make K into a single context, called an "evaluation context".

Transitions for sequencing

To evaluate M `to x.` N: evaluate M. If this returns `return` V, then evaluate $N[V/\mathtt{x}]$.

$$\boxed{\begin{array}{lll} M \ \mathtt{to\ x.}\ N & \quad\quad\quad\quad\quad K & \leadsto \\ M & \mathtt{to\ x.}\ N :: K & \end{array}}$$

$$\boxed{\begin{array}{lll} \mathtt{return}\ V & \mathtt{to\ x.}\ N :: K & \leadsto \\ N[V/\mathtt{x}] & \quad\quad\quad\quad\quad K & \end{array}}$$

Transitions for application

To evaluate $V`M$: evaluate M. If this returns $\lambda\mathtt{x}.N$, evaluate $N[V/\mathtt{x}]$.

$$\boxed{\begin{array}{lrl} V`M & K & \leadsto \\ M & V :: K & \end{array}}$$

$$\boxed{\begin{array}{lrl} \lambda\mathtt{x}.N & V :: K & \leadsto \\ N[V/\mathtt{x}] & K & \end{array}}$$

Those function rules again

$$\boxed{\begin{array}{lrr} V`M & K & \leadsto \\ M & V :: K & \end{array}}$$

$$\boxed{\begin{array}{lrr} \lambda \mathtt{x}.N & V :: K & \leadsto \\ N[V/\mathtt{x}] & K & \end{array}}$$

Those function rules again

$$\boxed{\begin{array}{lll} V`M & K & \rightsquigarrow \\ M & V :: K & \end{array}}$$

$$\boxed{\begin{array}{lll} \lambda \mathtt{x}.N & V :: K & \rightsquigarrow \\ N[V/\mathtt{x}] & K & \end{array}}$$

We can read $V`$ as an instruction "push V".

We can read $\lambda\mathtt{x}$ as an instruction "pop $\mathtt{x}$".

Those function rules again

$$\boxed{\begin{array}{lll} V\text{`}M & K & \rightsquigarrow \\ M & V :: K & \end{array}}$$

$$\boxed{\begin{array}{lll} \lambda\mathtt{x}.N & V :: K & \rightsquigarrow \\ N[V/\mathtt{x}] & K & \end{array}}$$

We can read V‘ as an instruction “push V”.

We can read $\lambda\mathtt{x}$ as an instruction “pop $\mathtt{x}$”.

Revisiting some equations:

$$\begin{array}{rcll} V \text{ ` } \lambda\mathtt{x}.\ M & = & M[V/\mathtt{x}] & \\ M & = & \lambda\mathtt{x}.\ \mathtt{x} \text{ ` } M & (\mathtt{x}\text{ fresh}) \\ \mathtt{error}\ e & = & \lambda\mathtt{x}.\ \mathtt{error}\ e & \\ \mathtt{print}\ c.\ \lambda\mathtt{x}.M & = & \lambda\mathtt{x}.\ \mathtt{print}\ c.\ M & \end{array}$$

Values and Computations

A value is, a computation does.

- A value of type $U\underline{B}$ is a thunk of a computation of type $\underline{B}$.
- A value of type $A + A'$ is a tagged value $\mathtt{inl}\ V$ or $\mathtt{inr}\ V$.
- A value of type $A \times A'$ is a pair $\langle V, V' \rangle$.
- A computation of type FA aims to return a value of type A.
- A computation of type $A \to \underline{B}$ aims
  to pop a value of type A and then behave in $\underline{B}$.
- A computation of type $\underline{B} \sqcap \underline{B}'$ aims
  to pop the tag $\mathtt{l}$ and then behave in $\underline{B}$
  or pop the tag $\mathtt{r}$ and then behave in $\underline{B}'$.

What's in a stack?

A stack consists of

- arguments that are values
- arguments that are tags
- frames taking the form $\mathtt{to}\ \mathtt{x}.\ N$.

Example program of type $F\,\mathtt{nat}$ (with complex values)

```
print "hello0".
let (x be 3,
     y be thunk (
          print "hello1".
          λz.
          print "we just popped " + z.
          return x + z
     )).
print "hello2".
( print "hello3".
  7‘
  print "we just pushed 7".
  force y
) to w.
print "w is bound to " + w.
return w + 5
```

Typing the CK-machine

Initial configuration to evaluate $\Gamma \vdash^{\mathsf{c}} P : \underline{C}$

Γ	P	$\underline{C}$	$\mathtt{nil}$	$\underline{C}$	

Transitions

Γ	$M\ \mathtt{to\ x.}\ N$	$\underline{B}$	K	$\underline{C}$	$\leadsto$
Γ	M	FA	$\mathtt{to\ x.}\ N :: K$	$\underline{C}$	

Γ	$\mathtt{return}\ V$	FA	$\mathtt{to\ x.}\ N :: K$	$\underline{C}$	$\leadsto$
Γ	$N[V/\mathtt{x}]$	$\underline{B}$	K	$\underline{C}$	

Typically Γ would be empty and $\underline{C} = F\,\mathtt{bool}$.

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Γ	P	$\underline{C}$	$\mathtt{nil}$	$\underline{C}$

Transitions

Γ	$M\ \mathtt{to}\ \mathtt{x}.\ N$	$\underline{B}$	K	$\underline{C}$	$\leadsto$
Γ	M	FA	$\mathtt{to}\ \mathtt{x}.\ N :: K$	$\underline{C}$	

Γ	$\mathtt{return}\ V$	FA	$\mathtt{to}\ \mathtt{x}.\ N :: K$	$\underline{C}$	$\leadsto$
Γ	$N[V/\mathtt{x}]$	$\underline{B}$	K	$\underline{C}$	

Typically Γ would be empty and $\underline{C} = F\,\mathtt{bool}$.

We write $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$ to mean that K can accompany a computation of type $\underline{B}$ during evaluation.

Typing rules, read off from the CK-machine

Typing a stack

$$\frac{}{\Gamma \vdash^{\mathsf{k}} \mathtt{nil} : \underline{C} \Longrightarrow \underline{C}} \qquad \frac{\Gamma, \mathtt{x} : A \vdash^{\mathsf{c}} M : \underline{B} \qquad \Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{k}} \mathtt{to\ x.}\ M :: K : FA \Longrightarrow \underline{C}}$$

$$\frac{\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{k}} \mathtt{1} :: K : \underline{B} \,\Pi\, \underline{B}' \Longrightarrow \underline{C}} \qquad \frac{\Gamma \vdash^{\mathsf{v}} V : A \qquad \Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{k}} V :: K : A \to \underline{B} \Longrightarrow \underline{C}}$$

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$$\frac{\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{k}} \texttt{l} :: K : \underline{B} \,\Pi\, \underline{B}' \Longrightarrow \underline{C}}$$

$$\frac{\Gamma \vdash^{\mathsf{v}} V : A \qquad \Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{k}} V :: K : A \to \underline{B} \Longrightarrow \underline{C}}$$

Typing a CK-configuration

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \qquad \Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}}{\Gamma \vdash^{\mathsf{ck}} (M, K) : \underline{C}}$$

Operations on Stacks

1. Given a stack $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$, we can weaken it or substitute values.

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2. A stack $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$ can be dismantled onto a computation $\Gamma \vdash^{\mathsf{c}} M : \underline{B}$, giving a computation $\Gamma \vdash^{\mathsf{c}} M \bullet K : \underline{C}$.

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3. Stacks $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$ and $\Gamma \vdash^{\mathsf{k}} L : \underline{C} \Longrightarrow \underline{D}$ can be concatenated to give $\Gamma \vdash^{\mathsf{k}} K +\!\!+ L : \underline{B} \Longrightarrow \underline{D}$.

Special Stacks

Continuations

A continuation is a stack from an F type, e.g. $\texttt{to x.}\ M :: K$.
It describes everything that will happen once a value is supplied.

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Top-Level Stack

The top-level stack is $\Gamma \vdash^{\mathsf{k}} \texttt{nil} : \underline{C} \Longrightarrow \underline{C}$.
The top-level type is $\underline{C}$.

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Top-Level Stack

The top-level stack is $\Gamma \vdash^{\mathsf{k}} \mathtt{nil} : \underline{C} \Longrightarrow \underline{C}$.
The top-level type is $\underline{C}$.

If $\underline{C}$ is $F\mathtt{bool}$ (the usual situation),
then `nil` is the top-level continuation:
it receives a boolean and returns it to the user.

Stacks denote homomorphisms

Consider a stack $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$

where $[\![\underline{B}]\!] = (X, c, b)$ and $[\![\underline{C}]\!] = (Y, c', b')$.

What should K denote?

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So we want $\quad [\![K]\!] : [\![\Gamma]\!] \times X \longrightarrow Y$.

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This function should be homomorphic in its second argument:

$$\begin{array}{rcl} [\![K]\!](\rho, c) & = & c' \\ [\![K]\!](\rho, b) & = & b' \end{array}$$

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We assume there's no exception handling.

Operations on stacks

We define $\llbracket K \rrbracket$ by induction on K.

Then we prove

- a weakening lemma
- a substitution lemma
- a dismantling lemma
- a concatenation lemma

providing a semantic counterpart for each operation on stacks.

Soundness of CK-machine

What should a CK-configuration $\Gamma \vdash^{\mathsf{ck}} (M, K) : \underline{C}$ denote?

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What should a CK-configuration $\Gamma \vdash^{\mathsf{ck}} (M, K) : \underline{C}$ denote?

$$\begin{array}{rcccl} [\![(M,K)]\!] & : & [\![\Gamma]\!] & \longrightarrow & [\![\underline{C}]\!] \\ & & \rho & \longmapsto & [\![K]\!](\rho, [\![M]\!]\rho) \end{array}$$

Properties:

1. If $(M, K) \leadsto (M', K')$ then $[\![(M,K)]\!] = [\![(M',K')]\!]$.
2. $[\![(\mathtt{error}\ \mathrm{CRASH}, K)]\!]\rho = c'$.
3. $[\![(\mathtt{error}\ \mathrm{BANG}, K)]\!]\rho = b'$.

Adjunction between values and stacks

We have an adjunction between the category of values (sets and functions) and the category of stacks (E-pointed sets and homomorphisms).

$$\begin{tikzcd} \mathbf{Set} \arrow[r, shift left, "F^E"] \arrow[r, phantom, "\perp"] & E/\mathbf{Set} \arrow[l, shift left, "U^E"] \end{tikzcd}$$

This resolves the exception monad $X \longmapsto X + E$ on $\mathbf{Set}$.

State

Consider CBPV extended with two storage cells:
$\mathtt{l}$ stores a natural number, and $\mathtt{l}'$ stores a boolean.

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A state is $\mathtt{l} \mapsto n, \mathtt{l}' \mapsto b$.

The set of states is $S \cong \mathbb{N} \times \mathbb{B}$.

Big-step semantics for state

The big-step semantics takes the form $s, M \Downarrow s', T$.

A pair (s, M) is called an SC-configuration.

We can type these using

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B}}{\Gamma \vdash^{\mathsf{sc}} (s, M) : \underline{B}}\ s \in S$$

Denotational semantics of state

How can we give a denotational semantics for call-by-push-value with state?

- Algebra semantics.
- Intrinsic semantics.

Algebra semantics for state (briefly)

Moggi's monad for state is $S \to (S \times -)$.
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We complete the story with an adequacy theorem:

$$\text{If } s, M \Downarrow s', T \text{ then } [\![s, M]\!]\varepsilon = [\![s', T]\!]\varepsilon$$

This requires an SC-configuration to have a denotation.

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The behaviour of an SC-configuration $\Gamma \vdash^{\mathsf{sc}} (s, M) : \underline{B}$ depends on the environment:

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The behaviour of a computation $\Gamma \vdash^{\mathsf{c}} M : \underline{B}$ depends on the state and environment:

$$[\![M]\!] \; : \; S \times [\![\Gamma]\!] \longrightarrow [\![\underline{B}]\!]$$

State: semantics of types

An SC-configuration of type FA will terminate as $s, \mathtt{return}\ V$.

$$[\![FA]\!] = S \times [\![A]\!]$$

An SC-configuration of type $A \to \underline{B}$ will pop $\mathtt{x} : A$ and then behave in $\underline{B}$.

$$[\![A \to \underline{B}]\!] = [\![A]\!] \to [\![\underline{B}]\!]$$

An SC-configuration of type $\underline{B} \,\Pi\, \underline{B}'$ will pop $\mathtt{l}$ and then behave in $\underline{B}$, or pop $\mathtt{r}$ and then behave in $\underline{B}'$.

$$[\![\underline{B} \,\Pi\, \underline{B}']\!] = [\![\underline{B}]\!] \times [\![\underline{B}']\!]$$

A value $\Gamma \vdash^{\mathsf{v}} V : U\underline{B}$ can be forced in any state s, giving an SC-configuration $s, \mathtt{force}\ V$.

$$[\![U\underline{B}]\!] = S \to [\![\underline{B}]\!]$$

State: the value/stack adjunction

Consider a stack $\Gamma \vdash^{\mathsf{k}} K : \underline{B} \Longrightarrow \underline{C}$

What should K denote?

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So we want $\llbracket K \rrbracket : \llbracket \Gamma \rrbracket \times \llbracket \underline{B} \rrbracket \longrightarrow \llbracket \underline{C} \rrbracket$.

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This gives an adjunction

$$\begin{tikzcd} \mathbf{Set} \arrow[r, shift left, "S\times -"] \arrow[r, phantom, "\perp"] & \mathbf{Set} \arrow[l, shift left, "S\to -"] \end{tikzcd}$$

between values and stacks.

State in call-by-value and call-by-name

For call-by-value we recover

$$\begin{aligned} [\![\texttt{bool}_{\mathbf{CBV}}]\!] &= 1+1 \\ [\![A \to_{\mathbf{CBV}} B]\!] &= [\![U(A \to FB)]\!] \\ &= S \to ([\![A]\!] \to (S \times [\![B]\!])) \end{aligned}$$

This is standard.

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For call-by-name we recover

$$\begin{array}{rcl} [\![\texttt{bool}_{\mathbf{CBN}}]\!] & = & [\![F(1+1)]\!] \\ & = & S \times (1+1) \\ [\![\underline{A} \to_{\mathbf{CBN}} \underline{B}]\!] & = & [\![U\underline{A} \to \underline{B}]\!] \\ & = & (S \to [\![\underline{A}]\!]) \to [\![\underline{B}]\!] \end{array}$$

This is O'Hearn's semantics of types for a stateful CBN language.

Naming and changing the current stack

Extend the language with two instructions:

- `letstk` α means let α be the current stack.
- `changestk` α means change the current stack to α.

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Execution takes places in a bigger language.

Γ	$\texttt{letstk}\ \alpha.\ M$	$\underline{B}$	K	$\underline{C} \mid \Delta$	$\leadsto$
Γ	$M[K/\alpha]$	$\underline{B}$	K	$\underline{C} \mid \Delta$	

Γ	$\texttt{changestk}\ K.\ M$	$\underline{B}'$	L	$\underline{C} \mid \Delta$	$\leadsto$
Γ	M	$\underline{B}$	K	$\underline{C} \mid \Delta$	

Similar to Crolard's syntax. Numerous variations in the literature.

Typing judgements for control

We have typing judgements:

$$\Gamma \vdash^{\mathsf{v}} V : A \mid \Delta \qquad\qquad \Gamma \vdash^{\mathsf{c}} M : \underline{B} \mid \Delta$$

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Example typing rules

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \;\mid \Delta, \alpha : \underline{B}}{\Gamma \vdash^{\mathsf{c}} \texttt{letstk}\ \alpha.\ M \;\mid \Delta}$$

$$\frac{\Gamma \vdash^{\mathsf{c}} M : \underline{B} \;\mid \Delta}{\Gamma \vdash^{\mathsf{c}} \texttt{changestk}\ \alpha.\ M : \underline{B}' \;\mid \Delta}\ (\alpha : \underline{B}) \in \Delta$$

Typing judgements for execution language

During execution, the top-level type $\underline{C}$ must be indicated:

$$\Gamma \vdash^{\mathsf{v}} V : A\ [\underline{C}]\ \Delta \qquad \Gamma \vdash^{\mathsf{c}} M : \underline{B}\ [\underline{C}]\ \Delta$$
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Typically Γ and Δ would be empty and $\underline{C} = F\,\texttt{bool}$.

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Example typing rules

$$\frac{}{\Gamma \vdash^{\mathsf{k}} \alpha : \underline{B} \Longrightarrow \underline{C} \mid \Delta}\ (\alpha : \underline{B}) \in \Delta$$

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Algebra semantics of control

Fix a set R, the semantic domain for CK-configurations.

That means: a hypothetical extremely closed CK-configuration,
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Maybe we can build a denotational semantics
where a computation type $\underline{B}$ denotes an Eilenberg-Moore algebra $[\![\underline{B}]\!]_{\mathsf{alg}}$,
a semantic domain for computations.

Intrinsic semantics of control

The denotation of $\underline{B}$ is a semantic domain for stacks from $\underline{B}$.

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The behaviour of a computation $\Gamma \vdash^{\mathsf{c}} M : \underline{B} \mid \Delta$ depends on the environment, current stack and stack environment:

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A value $\Gamma \vdash^{\mathsf{v}} V : A \mid \Delta$ denotes

$$[\![V]\!] : [\![\Gamma]\!] \times [\![\Delta]\!] \longrightarrow [\![A]\!]$$

Control: semantics of types

A stack from FA receives a value $\mathtt{x} : A$ and then behaves as a configuration.

$$[\![FA]\!] = [\![A]\!] \to R$$

A stack from $A \to \underline{B}$ is a pair $V :: K$.

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A stack from $\underline{B} \sqcap \underline{B}'$ is a tagged stack $^{\mathtt{l}} :: K$ or $^{\mathtt{r}} :: K$.

$$[\![\underline{B} \sqcap \underline{B}']\!] = [\![\underline{B}]\!] + [\![\underline{B}']\!]$$

A value of type $U\underline{B}$ can be forced alongside any stack K, giving a configuration.

$$[\![U\underline{B}]\!] = [\![\underline{B}]\!] \to R$$

Semantics of the execution language

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That gives an adjunction

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This is Streicher and Reus' semantics
for a CBN language with control operators.

Summary: adjunctions between values and stacks

For a set E, the adjunction
$$\begin{tikzcd} \mathbf{Set} \arrow[r, shift left=2, "F^E"] \arrow[r, phantom, "\perp"] & E/\mathbf{Set} \arrow[l, shift left=2, "U^E"] \end{tikzcd}$$
models call-by-push-value with errors.

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