PLC type system

$$(\mathbf{var})\ \frac{}{\Gamma \vdash x : \tau} \text{ if } (x : \tau) \in \Gamma$$

$$(\mathbf{fn})\ \frac{\Gamma, x : \tau_1 \vdash M : \tau_2}{\Gamma \vdash \lambda x : \tau_1\ (M) : \tau_1 \to \tau_2} \text{ if } x \notin dom(\Gamma)$$

$$(\mathbf{app})\ \frac{\Gamma \vdash M : \tau_1 \to \tau_2 \qquad \Gamma \vdash M' : \tau_1}{\Gamma \vdash M\, M' : \tau_2}$$

$$(\mathbf{gen})\ \frac{\Gamma \vdash M : \tau}{\Gamma \vdash \Lambda\alpha\ (M) : \forall\alpha\ (\tau)} \text{ if } \alpha \notin ftv(\Gamma)$$

$$(\mathbf{spec})\ \frac{\Gamma \vdash M : \forall\alpha\ (\tau_1)}{\Gamma \vdash M\, \tau_2 : \tau_1[\tau_2/\alpha]}$$

Datatypes in PLC [Sect. 4.4]

- define a suitable PLC type for the data
- define suitable PLC expressions for values & operations on the data
- show PLC expressions have correct typings & computational behaviour

need to give PLC an operational semantics

Functions on types

In PLC, $\boxed{\Lambda\alpha\,(M)}$ is an anonymous notation for the function F mapping each type τ to the value of $M[\tau/\alpha]$ (of some particular type).

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Computation in PLC involves beta-reduction for such functions on types

$$(\Lambda\alpha\,(M))\,\tau \to M[\tau/\alpha]$$

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Computation in PLC involves beta-reduction for such functions on types

$$(\Lambda\alpha\,(M))\,\tau \to M[\tau/\alpha]$$

as well as the usual form of beta-reduction from λ-calculus

$$(\lambda x : \tau\,(M_1))\,M_2 \to M_1[M_2/x]$$

Beta-reduction of PLC expressions

M *beta-reduces to* M' *in one step*, $\boxed{M \to M'}$ means M' can be obtained from M (up to alpha-conversion, of course) by replacing a subexpression which is a *redex* by its corresponding *reduct*.
The redex-reduct pairs are of two forms:

$$(\lambda x : \tau\, (M_1))\, M_2 \to M_1[M_2/x]$$

$$(\Lambda \alpha\, (M))\, \tau \to M[\tau/\alpha]$$

$M_1[M_2/x]$ = result of substituting M_2 for all free occurrences of x in M_1 (avoiding capture of free vars & tyvars in M_2 by binders in M_1)

$M[\tau/\alpha]$ = result of substituting τ for all free occurrences of α in M (avoiding capture)

[p44]

$$(\lambda x : \alpha_1 \to \alpha_1\ (x\, y))\ ((\Lambda \alpha_2\, (\lambda z : \alpha_2\, (z)))(\alpha_1 \to \alpha_1))$$

[p44]

$$(\lambda x:\alpha_1\to\alpha_1\,(x\,y))\ \boxed{(\Lambda\alpha_2\,(\lambda z:\alpha_2\,(z)))(\alpha_1\to\alpha_1)}$$

$$(\lambda z:\alpha_1\to\alpha_1\,(z))$$

[p44]

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[p44]

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[p44]

$$(\lambda x:\alpha_1\to\alpha_1\,(x\,y))\;(\Lambda\alpha_2\,(\lambda z:\alpha_2\,(z)))(\alpha_1\to\alpha_1)$$

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[p44]

$$
\begin{tikzcd}[column sep=small]
& \boxed{(\lambda x:\alpha_1\to\alpha_1\,(xy))\ \boxed{(\Lambda\alpha_2(\lambda z:\alpha_2(z)))(\alpha_1\to\alpha_1)}} \arrow[dl] \arrow[dr] & \\
\boxed{(\Lambda\alpha_2(\lambda z:\alpha_2(z)))(\alpha_1\to\alpha_1)}\ y \arrow[dr] & & \boxed{(\lambda x:\alpha_1\to\alpha_1(xy))(\lambda z:\alpha_1\to\alpha_1(z))} \arrow[dl] \\
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\end{tikzcd}
$$

[p44]

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 & (\lambda z:\alpha_1\to\alpha_1\,(z))\,y \arrow[d] & \\
 & y &
\end{tikzcd}
$$

Beta-reduction of PLC expressions

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$M \to^* M'$ indicates a chain of finitely[†] many beta-reductions.

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Beta-reduction of PLC expressions

M *beta-reduces to M' in one step*, $\boxed{M \rightarrow M'}$ means M' can be obtained from M (up to alpha-conversion, of course) by replacing a subexpression which is a *redex* by its corresponding *reduct*.
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$$(\lambda x : \tau\,(M_1))\, M_2 \rightarrow M_1[M_2/x]$$

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$M \rightarrow^* M'$ indicates a chain of finitely† many beta-reductions.

($\dagger$ possibly zero – which just means M and M' are alpha-convertible).

M is in *beta-normal form* if it contains no redexes.

Properties of PLC beta-reduction on typeable expressions

Suppose $\Gamma \vdash M : \tau$ is provable in the PLC type system. Then the following properties hold:

Subject Reduction. If $M \to M'$, then $\Gamma \vdash M' : \tau$ is also a provable typing.

Subject reduction: if $\Gamma \vdash M : \tau$ & $M \to M'$, then $\Gamma \vdash M' : \tau$

$$\dfrac{\dfrac{\Gamma, x : \tau' \vdash M : \tau}{\Gamma \vdash \lambda x : \tau'(M) : \tau' \to \tau} \qquad \Gamma \vdash M' : \tau'}{\Gamma \vdash (\lambda x : \tau'(M))\, M' : \tau}$$

$$\dfrac{\dfrac{\Gamma, x : \tau' \vdash M : \tau}{\Gamma \vdash \lambda x : \tau'(M) : \tau' \to \tau} \qquad \Gamma \vdash M' : \tau'}{\Gamma \vdash (\lambda x : \tau'(M))\, M' : \tau}$$

$$\downarrow_{\beta}$$

$$M[M'/x]$$

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$$\downarrow_{\beta}$$

$$M[M'/x]$$

$\leftarrow$ to see that this has type τ, need to prove a <u>Substitution Lemma</u>

If $\Gamma, x : \tau' \vdash M : \tau$

and $\Gamma \vdash M' : \tau'$

then

$$\Gamma \vdash M[M'/x] : \tau$$

<u>Substitution Lemma</u>

(proved by induction on structure of M)

Subject reduction: if $\Gamma \vdash M : \tau$ & $M \to M'$, then $\Gamma \vdash M' : \tau$

$$\dfrac{\dfrac{\Gamma \vdash M : \tau}{\Gamma \vdash \Lambda\alpha(M) : \forall\alpha(\tau)}\ \alpha \notin ftv(\Gamma)}{\Gamma \vdash (\Lambda\alpha(M))\tau' : \tau[\tau'/\alpha]}$$

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$$\downarrow_\beta$$

$$M[\tau'/\alpha]$$

to see ~~that~~ ~~this~~ has type $\tau[\tau'/\alpha]$, need to prove a substitution lemma

If $\Gamma \vdash M : \tau$ & $\alpha \notin ftv(\Gamma)$

then

$\Gamma \vdash M[\tau'/\alpha] : \tau[\tau'/\alpha]$

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<u>Substitution lemma</u>

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[p44]

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Properties of PLC beta-reduction on typeable expressions

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Strong Normalisation Property. There is no infinite chain $M \to M_1 \to M_2 \to \ldots$ of beta-reductions starting from M.

$\Omega \triangleq (\lambda x : \alpha\,(x\,x))(\lambda x : \alpha\,(x\,x))$ satisfies $\Omega \to \Omega \to \Omega \to \cdots$

but it's not typeable (nor is the fixpoint combinator, Y)

Theorem 15: [p46]

> Church Rosser (CR) + Strong Normalization (SN)
> $\Rightarrow$ exist unique beta-normal forms for typeable PLC expressions

Existence: start from M & reduce any old way … must eventually stop by SN

Uniqueness: if

$$\begin{tikzcd} & N_1 \arrow[r, "/" marking] & {} \\ M \arrow[ur, "*"] \arrow[dr, "*"'] & & \\ & N_2 \arrow[r, "/" marking] & {} \end{tikzcd}$$

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so

$$N_1 = M' = N_2$$

α-equiv

PLC beta-conversion, $=_\beta$

By definition, $\boxed{M =_\beta M'}$ holds if there is a finite chain

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where each $-$ is either $\to$ or $\leftarrow$, i.e. a beta-reduction in one direction or the other.

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By definition, $\boxed{M =_\beta M'}$ holds if there is a finite chain

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where each $-$ is either $\to$ or $\leftarrow$, i.e. a beta-reduction in one direction or the other. (A chain of length zero is allowed—in which case M and M' are equal, up to alpha-conversion, of course.)

So $=_\beta$ is the smallest equivalence relation containing $\to$

PLC beta-conversion, $=_\beta$

By definition, $\boxed{M =_\beta M'}$ holds if there is a finite chain

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where each $-$ is either $\rightarrow$ or $\leftarrow$, i.e. a beta-reduction in one direction or the other. (A chain of length zero is allowed—in which case M and M' are equal, up to alpha-conversion, of course.)

Church Rosser + Strong Normalisation properties imply that, for typeable PLC expressions, $M =_\beta M'$ holds if and only if there is some beta-normal form N with

$$M \rightarrow^* N \; {}^*\!\!\leftarrow M'$$

Datatypes in PLC [Sect. 4.4]

- define a suitable PLC type for the data
- define suitable PLC expressions for values & operations on the data
- show PLC expressions have correct typings & computational behaviour

Polymorphic booleans

$$bool \triangleq \forall\alpha\,(\alpha \to (\alpha \to \alpha))$$

PLC operator association

$M_1 M_2 M_3$ means $(M_1 M_2) M_3$

$M_1 M_2 \tau$ means $(M_1 M_2) \tau$, etc.

$\forall \alpha_1, \alpha_2 (\tau)$ means $\forall \alpha_1 (\forall \alpha_2 (\tau))$

$\lambda x_1 : \tau_1, x_2 : \tau_2 (M)$ means $\lambda x_1 : \tau_1 (\lambda x_2 : \tau_2 (M))$

$\Lambda \alpha_1, \alpha_2 (M)$ means $\Lambda \alpha_1 (\Lambda \alpha_2 (M))$

Polymorphic booleans

$$\mathit{bool} \triangleq \forall \alpha\,(\alpha \to (\alpha \to \alpha))$$

$$\mathit{True} \triangleq \Lambda \alpha\,(\lambda x_1 : \alpha, x_2 : \alpha\,(x_1))$$

$$\mathit{False} \triangleq \Lambda \alpha\,(\lambda x_1 : \alpha, x_2 : \alpha\,(x_2))$$

$\{\} \vdash True : bool$

$\{\} \vdash False : bool$

Polymorphic booleans

$$bool \triangleq \forall\alpha\,(\alpha \to (\alpha \to \alpha))$$

$$True \triangleq \Lambda\alpha\,(\lambda x_1 : \alpha, x_2 : \alpha\,(x_1))$$

$$False \triangleq \Lambda\alpha\,(\lambda x_1 : \alpha, x_2 : \alpha\,(x_2))$$

$$if \triangleq \Lambda\alpha\,(\lambda b : bool, x_1 : \alpha, x_2 : \alpha\,(b\,\alpha\,x_1\,x_2))$$

$$\{\} \vdash if : \forall\alpha\,(bool \to (\alpha \to (\alpha \to \alpha)))$$

If $\begin{cases} M_1 \to^* \text{True} \\ M_2 \to^* N \end{cases}$, then

$$\text{if}\,\tau\, M_1\, M_2\, M_3 \to^* \text{if}\,\tau\, \text{True}\, M_2\, M_3$$

If $\begin{cases} M_1 \to^* \mathrm{True} \\ M_2 \to^* N \end{cases}$, then

$$\mathrm{if}\ \tau\ M_1\ M_2\ M_3 \to^* \mathrm{if}\ \tau\ \mathrm{True}\ M_2\ M_3$$

$$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad || $$

$$\Lambda\alpha(\ldots)\ \tau\ \mathrm{True}\ M_2\ M_3$$

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$$\| $$

$$\boxed{\Lambda\alpha(\ldots)\ \tau}\ \mathrm{True}\ M_2\ M_3$$

$$\downarrow$$

$$(\lambda b{:}\mathrm{bool}, x_1{:}\tau, x_2{:}\tau\,(b\ \tau\ x_1\ x_2))\ \mathrm{True}\ M_2\ M_3$$

If $\begin{cases} M_1 \to^* \mathrm{True} \\ M_2 \to^* N \end{cases}$, then

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$$\begin{aligned} &\quad \| \\ &\Lambda\alpha(\ldots)\ \tau\ \mathrm{True}\ M_2\ M_3 \\ &\quad \downarrow \\ &(\lambda b:\mathrm{bool}, x_1:\tau, x_2:\tau\,(b\ \tau\ x_1\ x_2))\ \mathrm{True}\ M_2\ M_3 \\ &\quad \downarrow^* \\ &\mathrm{True}\ \tau\ M_2\ M_3 \end{aligned}$$

If $\begin{cases} M_1 \to^* \mathrm{True} \\ M_2 \to^* N \end{cases}$, then

$$
\begin{aligned}
&\mathrm{if}\ \tau\ M_1\ M_2\ M_3 \to^* \mathrm{if}\ \tau\ \mathrm{True}\ M_2\ M_3 \\
&\qquad = \Lambda\alpha(\ldots)\ \tau\ \mathrm{True}\ M_2\ M_3 \\
&\qquad \to (\lambda b{:}\mathrm{bool}, x_1{:}\tau, x_2{:}\tau\,(b\ \tau\ x_1\ x_2))\ \mathrm{True}\ M_2\ M_3 \\
&\qquad \to^* \mathrm{True}\ \tau\ M_2\ M_3 \\
&\qquad = \Lambda\alpha\,(\lambda x_1{:}\alpha, x_2{:}\alpha\,(x_1))\ \tau\ M_2\ M_3
\end{aligned}
$$

If $\begin{cases} M_1 \to^* \mathrm{True} \\ M_2 \to^* N \end{cases}$, then

$$\mathrm{if}\ \tau\ M_1\ M_2\ M_3 \to^* \mathrm{if}\ \tau\ \mathrm{True}\ M_2\ M_3$$

$$= \Lambda\alpha(\dots)\ \tau\ \mathrm{True}\ M_2\ M_3$$

$$\to (\lambda b:\mathrm{bool}, x_1:\tau, x_2:\tau\,(b\ \tau\ x_1\ x_2))\ \mathrm{True}\ M_2\ M_3$$

$$\to^* \mathrm{True}\ \tau\ M_2\ M_3$$

$$= \Lambda\alpha\,(\lambda x_1:\alpha, x_2:\alpha\,(x_1))\ \tau\ M_2\ M_3$$

$$\to^* M_2 \to^* N$$

FACT: $\text{True} \triangleq \Lambda\alpha(\lambda x_1, x_2 : \alpha\,(x_1))$

$\text{False} \triangleq \Lambda\alpha(\lambda x_1, x_2 : \alpha\,(x_2))$

are the only closed expressions in β-normal form of type $\text{bool} \triangleq \forall\alpha(\alpha \to (\alpha \to \alpha))$.