Programming Language Theory

Untyped λ-Calculus

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Assessment guidelines

Deadline	17:00, 20 Aug
Assessment	**Assignment** (10% + 10% + 10%)
	Exam (100%)
Email	`liang.ting.chen.tw(at)gmail(dot)com`

Please follow the instructions for assignments below.

1. Write down your name and your student number.
2. Use A4 paper only in physical form or in *non-scanned* PDF.
3. Be brief but comprehensive.
4. Submit assignments in person or by email with

subject	`[FLOLAC] PL HW%x%`
attachment	`PL-HW%x% - %STDNO% - %NAME%.pdf`
body	(optional)

Untyped λ-Calculus: Statics

λ-calculus: Terms

Let $V := \{x, y, z, \ldots\}$ be a countably infinite set of *variables*.

Definition 1 (Syntax of λ-calculus)

The formation $M : \mathtt{Term}_\lambda$ is defined by

1. Variable: with the side condition that $x \in V$

$$\frac{}{x : \mathtt{Term}_\lambda}\ \text{(var)}$$

2. Function application of M to the argument N:

$$\frac{M : \mathtt{Term}_\lambda \qquad N : \mathtt{Term}_\lambda}{M\ N : \mathtt{Term}_\lambda}\ \text{(app)}$$

3. Function abstraction with an argument x and a function body M:

$$\frac{M : \mathtt{Term}_\lambda \qquad x \in V}{\lambda x. M : \mathtt{Term}_\lambda}\ \text{(abs)}$$

Examples and non-examples

1. $(x\ y)\ z$
2. $x\ (y\ z)$
3. $\lambda x.\, y$
4. $\lambda x.\, x$
5. $\lambda s.\, (\lambda z.\, (s\ z))$
6. $\lambda a.\, (\lambda b.\, (a\ (\lambda c.\, a\ b)))$
7. $(\lambda x.\, x)\ (\lambda y.\, y)$

The following are NOT examples

1. $\lambda(\lambda x.\, x).\, y$
2. $\lambda x.$
3. $\lambda.\, x$
4. $\ldots$

Conventions

Consecutive abstractions

$$\lambda x_1\, x_2\ \ldots x_n.\, M := \lambda x_1.\, (\lambda x_2.\, (\ldots (\lambda x_n.\, M) \ldots))$$

Consecutive applications

$$M_1\ M_2\ M_3\ \ \ldots\ \ M_n := (\ldots ((M_1\ M_2)\ M_3) \ldots)\ M_n$$

Function body extends as far right as possible

$$\lambda x.\, M\ N := \lambda x.\, (M\ N)$$

instead of $(\lambda x.\, M)\ N$.

For example, $\lambda x_1.\, (\lambda x_2.\, x_1) \equiv \lambda x_1\, x_2.\, x_1$ and $x\ y\ z$ means $(x\ y)\ z$.
Warning. We apply these rules in our *meta*-language.

Meta-language and object-language

- *Meta-language* is the language we use to describe the object of study. E.g. English, or naive set theory.
- *Object-language* is the object of study. E.g., arithmetic expressions and λ-terms.

Naming a function is not supported in λ-calculus, so the following

$$\texttt{id} := \lambda x.\, x$$

happens in the meta-language.

1. `id` is a symbol different from '$\lambda x.\, x$' in the meta-language.
2. `id` and $\lambda x.\, x$ are *syntactically equivalent* denoted by

   $$\texttt{id} \equiv \lambda x.\, x$$

   in the object language.

Example 2 (Identity function)

$$\texttt{id} := \lambda x.\, x$$

Example 3 (Projections)

$$\texttt{fst} := \lambda x.\, \lambda y.\, x \quad \text{and} \quad \texttt{snd} := \lambda x.\, \lambda y.\, y$$

Example 4 (Church encoding of Natural numbers)

$$\begin{aligned}
\texttt{c}_0 &:= \lambda f x.\, x \\
\texttt{c}_1 &:= \lambda f x.\, f x \\
\texttt{c}_2 &:= \lambda f x.\, f(f x) \\
\texttt{c}_3 &:= \lambda f x.\, f(f(f(x))) \\
&\vdots
\end{aligned}$$

α-equivalence, informally

Definition 5

Two terms M an N are α-equivalent

$$M =_\alpha N$$

if variables *bound* by abstractions can be renamed to derive the same term.

Example 6

1. $\lambda x.\, x$ and $\lambda y.\, y$ are distinct λ-terms but $\lambda x.\, x =_\alpha \lambda y.\, y$.
2. $\lambda x.\, \lambda y.\, y =_\alpha \lambda z.\, \lambda y.\, y$.
3. $\lambda x.\, \lambda y.\, x \neq_\alpha \lambda x.\, \lambda y.\, y$.

α-equivalent terms are *programs of the same structure.*

Evaluation, informally

The evaluation of λ-calculus happens in this form

$$\underbrace{(\lambda x.\, M)\, N}_{\beta\text{-redex}} \longrightarrow \underbrace{M\,[N/x]}_{\text{substitution of } N \text{ for a free variable } x \text{ in } M}$$

For example, $(\lambda x.\, x + 1)\; 3 \to 3 + 1$.

How to evaluate the following terms?

1. $(\lambda x.x)\, z$
2. $(\lambda x\, y.\, x)\, y$
3. $(\lambda y\, y.\, y)\, x$

Free and bound variables

Definition 7

The set **FV** of free variables of a term M is defined by

$$\begin{aligned}\mathbf{FV}(x) &= \{x\}\\ \mathbf{FV}(\lambda x.\, M) &= \mathbf{FV}(M) - \{x\}\\ \mathbf{FV}(M\ N) &= \mathbf{FV}(M) \cup \mathbf{FV}(N)\end{aligned}$$

Definition 8

1. A variable y in M is free if $y \in \mathbf{FV}(M)$.
2. A λ-term M is *closed* if $\mathbf{FV}(M) = \emptyset$.

Exercise: free variables

$$\begin{aligned} \mathsf{FV}(x\ (\lambda y.\, y)\ z) &= \mathsf{FV}(x\ (\lambda y.\, y)) \cup \mathsf{FV}(z) \\ &= \mathsf{FV}(x) \cup (\mathsf{FV}(y) - \{y\}) \cup \{z\} \\ &= \{x\} \cup (\{y\} - \{y\}) \cup \{z\} \\ &= \{x, z\} \end{aligned}$$

Calculate the set of free variables of following terms:

1. $x\ (y\ z)$
2. $\lambda x.\, y$
3. $\lambda x.\, x$
4. $\lambda s\, z.\, (s\ z))$
5. $(\lambda x.\, x)\ \lambda y.\, y$

Exercise: bound variables

Define

- $\mathsf{Var}(M)$ the set of variables of a term M by structural recursion on Λ.
- $\mathsf{BV}(M)$ the set of bound variables.

Untyped λ-Calculus: Substitution

Substitution

A substitution is a process of replacing *free* variables by another terms (on the meta-level).

The name of a variable does not matter but the location does. So, …

1. bound variables should remain bound after substitution.
2. other free variables should remain free after substitution.

Concretely, we want to avoid …

1. $(\lambda y.\, y)[x/y] \equiv (\lambda y.\, x)$
2. $(\lambda y.\, x)[y/x] \equiv (\lambda y.\, y)$

Naive substitution I

Definition 9

For $x \in V$ and $L : \mathtt{Term}_\lambda$, the substitution of L for x is defined by

$$\begin{aligned} x[L/x] &= L \\ y[L/x] &= y && \text{if } x \neq y \\ (M\ N)[L/x] &= M[L/x]\ N[L/x] \\ (\lambda y.\, M)[L/x] &= \lambda y.\, M[L/x] \end{aligned}$$

A bound variable may become free.

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

Naive substitution II

Definition 10

For $x \in V$ and $L : \mathtt{Term}_\lambda$, the substitution of L for x is defined by

$$\begin{aligned}
x[L/x] &= L \\
y[L/x] &= y && \text{if } x \neq y \\
(M\,N)[L/x] &= M[L/x]\;N[L/x] \\
(\lambda y.\,M)[L/x] &= \lambda y.\,M[L/x] && \text{if } x \neq y \\
(\lambda y.\,M)[L/x] &= \lambda y.\,M && \text{if } x = y
\end{aligned}$$

A variable may be captured by an abstraction.

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

Capture-avoiding substitution

Capture-avoiding substitution[1] of L for the free occurrences of x is a *partial* function $(\cdot)[L/x] \colon \mathtt{Term}_\lambda \to \mathtt{Term}_\lambda$ defined by

$$
\begin{aligned}
x[L/x] &= L \\
y[L/x] &= y && \text{if } x \neq y \\
(M\,N)[L/x] &= (M[L/x]\ N[L/x]) \\
(\lambda x.\,M)[L/x] &= \lambda x.\,M \\
(\lambda y.\,M)[L/x] &= \lambda y.\,M[L/x] && \text{if } x \neq y \text{ and } y \notin \mathbf{FV}(L)
\end{aligned}
$$

Definition 11 (Freshness)

A variable y is fresh for L if $y \notin \mathbf{FV}(L)$.

[1] Sign, this definition is nevertheless ill-defined.

Renaming of bound variables

If a variable y is *fresh* for M, the bound variable x of $\lambda x.\, M$ can be renamed to y without changing the meaning.

Definition 12 (α-conversion)

α-conversion is an judgement $M \to_\alpha N$ between two terms defined by

$$\frac{y \text{ is fresh for } M}{\lambda x.\, M \longrightarrow_\alpha \lambda y.\, M[y/x]}$$

Yet, $M\ (\lambda x.\, x) \longrightarrow_\alpha M\ (\lambda y.\, y)$ does not hold.

α-equivalence

Definition 13

$$\frac{(x \text{ is a variable})}{x =_\alpha x} \qquad \frac{M_1 =_\alpha M_2 \qquad N_1 =_\alpha N_2}{M_1\ N_1 =_\alpha M_2\ N_2}$$

$$\frac{M_1 \to_\alpha M_2}{M_1 =_\alpha M_2} \qquad \frac{M_1 =_\alpha M_2}{\lambda x.\, M_1 =_\alpha \lambda x.\, M_2}$$

Lemma 14

α-equivalence is an equivalence, i.e.

reflexivity *$M =_\alpha M$ for any term M;*

symmetry *$N =_\alpha M$ if $M =_\alpha N$;*

transitivity *$L =_\alpha N$ if $L =_\alpha M$ and $M =_\alpha N$.*

Proof of reflexivity

By induction on the formation of M.

1. $M = x$ for some $x \in V$. Then, by definition $x =_\alpha x$ holds.
2. $M = M_1\ M_2$. Then, by induction hypothesis, we have derivations D_1 and D_2 for $M_1 =_\alpha M_1$ and $M_2 =_\alpha M_2$ respectively. Therefore, we have the desired derivation

$$\dfrac{\dfrac{\vdots}{M_1 =_\alpha M_1}\,D_1 \qquad \dfrac{\vdots}{M_1 =_\alpha M_2}\,D_2}{M_1\ M_2 =_\alpha M_1\ M_2}$$

3. $M = \lambda x.\, M'$. By induction hypothesis, we have a derivation D for $M' =_\alpha M'$. Hence,

$$\dfrac{\dfrac{\vdots}{M' =_\alpha M'}\,D}{\lambda x.\, M' =_\alpha \lambda x.\, M'}$$

Proof of symmetry

By induction on the derivation D of $M =_\alpha N$. The only interesting case is that D is derived from an α-conversion, i.e.

$$\lambda x.\, M' \to_\alpha \lambda y.\, M'[y/x]$$

and y is fresh for M'. We know that $x \notin \mathsf{FV}(M'[y/x])$ since the substitution $[y/x]$ replaces[2] the free variable x by y. Therefore, we have $\lambda x.\, M'[y/x][x/y] \equiv \lambda x.\, M'$. It follows that

$$\lambda y.M'[y/x] \to_\alpha \lambda x.M'$$

Hence, $N =_\alpha M$.

[2]We actually need to show that $x \notin \mathsf{FV}(M[y/x])$ whenever $\mathsf{FV}(M[y/x])$ is defined.

Proof of transitivity

By induction on the derivations D_1 and D_2 of $L =_\alpha M$ and $M =_\alpha N$ respectively. The interesting case is when D_i's are given by α-conversion

$$\lambda x.\, M' \to_\alpha \lambda y.\, M'[y/x] \to_\alpha \lambda z.\, M'[y/x][z/y].$$

It follows that

$$\lambda x.\, M' \to_\alpha \lambda z.\, M'[z/x]$$

where the freshness condition clearly holds (why?) and also that

$$M'[y/x][z/y] \equiv M'[z/x].$$

Hence, transitivity holds for this case.

Example 15

$$(\lambda y.\, y)\ (\lambda x.\, x) =_\alpha (\lambda x.\, x)\ (\lambda y.\, y)$$

Why? We use the fact that $=_\alpha$ is an equivalence!

Proof.

$$\dfrac{\dfrac{\dfrac{\lambda x.\, x \to_\alpha \lambda y.\, x[y/x]}{\lambda x.\, x =_\alpha \lambda y.\, y}}{(\lambda y.\, y)\ (\lambda x.\, x) =_\alpha (\lambda y.\, y)\ (\lambda y.\, y)} \qquad \dfrac{\dfrac{\lambda y.\, y \to_\alpha \lambda x.\, y[x/y]}{\lambda y.\, y =_\alpha \lambda x.\, x}}{(\lambda y.\, y)\ (\lambda y.\, y) =_\alpha (\lambda x.\, x)\ (\lambda y.\, y)}}{(\lambda y.\, y)\ (\lambda x.\, x) =_\alpha (\lambda x.\, x)\ (\lambda y.\, y)}$$

$\square$

Exercise

Which of the following pairs are α-equivalent? Why?

1. x and y
2. $\lambda x\, y.\, y$ and $\lambda z\, y.\, y$
3. $\lambda x\, y.\, x$ and $\lambda y\, x.\, y$
4. $\lambda x\, y.\, x$ and $\lambda x\, y.\, y$

Convention

Terms are equal up to α-equivalence of bound variables.

Feel free to rename any bound variable whenever convenient.

Untyped λ-Calculus: Dynamics

β-conversion

Definition 16 (β-conversion)

β-conversion is defined by

$$\underbrace{(\lambda x.\, M)\ N}_{\beta\text{-redex}} \longrightarrow_\beta M[N/x]$$

$$\begin{aligned} ((\lambda x.\, \lambda y.\, x)\ M) &\longrightarrow_\beta (\lambda y.\, x)[M/x] \\ &\equiv \lambda y.\, x[M/x] \equiv \lambda y.\, M \end{aligned}$$

$$((\lambda x\, y.\, x)\ M)\ N \longrightarrow_\beta ?$$

One-step full β-reduction

Definition 17

The one-step full β-reduction is defined by

$$\frac{}{(\lambda x.\, M)\ N \longrightarrow_{\beta 1} M[N/x]} \qquad \frac{M_1 \longrightarrow_{\beta 1} M_2}{M_1\ N \longrightarrow_{\beta 1} M_2\ N}$$

$$\frac{M_1 \longrightarrow_{\beta 1} M_2}{\lambda x.\, M_1 \longrightarrow_{\beta 1} \lambda x.\, M_2} \qquad \frac{N_1 \longrightarrow_{\beta 1} N_2}{M\ N_1 \longrightarrow_{\beta 1} M\ N_2}$$

$$\begin{aligned} ((\lambda x\, y.\, x)\ M)\ N &\longrightarrow_{\beta 1} (\lambda y.\, M)\ N \\ &\longrightarrow_{\beta 1} M[N/y] \end{aligned}$$

Multi-step full β-reduction

Definition 18

$$\frac{}{M \longrightarrow_{\beta *} M}\;(\text{0-step})$$

$$\frac{L \longrightarrow_{\beta 1} M \qquad M \longrightarrow_{\beta *} N}{L \longrightarrow_{\beta *} N}\;(n+1\text{-steps})$$

α-conversion during β-conversion

Renaming of bound variables may need to happen during reduction:

$$\begin{aligned}
(\lambda y.\, y\ y)\ (\lambda z\, x.\, z\ x) &\longrightarrow_{\beta 1} && (\lambda z\, x.\, z\ x)\ (\lambda z\, x.\, z\ x) \\
&\longrightarrow_{\beta 1} && \lambda x.\, (\lambda z\, x.\, z\ x)\ x \\
&=_{\alpha} && \lambda x.\, (\lambda z\, y.\, z\ y)\ x \\
&\longrightarrow_{\beta 1} && \lambda x.\, (\lambda y.\, x\ y)
\end{aligned}$$

Even worse, we actually need infinitely many variables:

$$(\lambda y.\, y\ s\ y)\ (\lambda t\, z\, x.\, z\ (t\ x)\ z)$$

Exercise

Evaluate the above term.

Computational meaning

Definition 19

M and N have the same *computational meaning* if $M =_\beta N$ where $=_\beta$ is defined inductively by

$$\frac{M \longrightarrow_{\beta 1} N}{M =_\beta N} \qquad \frac{M =_\beta N}{N =_\beta M}$$

$$\frac{}{M =_\beta M} \qquad \frac{L =_\beta M \qquad M =_\beta N}{L =_\beta N}$$

- $\mathbf{c}_2 =_\beta (\lambda x\, y.y)\ \mathbf{c}_1\ \mathbf{c}_2$
- $\lambda z.\,(\lambda x\, y.x)\ z =_\beta \lambda z\, y.\, z$

Equality, equality, equality!

So far, we have notions of equality and reduction.

- $1 + 1 \neq_{\alpha} 2$
- $1 + 1 \longrightarrow_{\beta *} 2$ but $2 \not\longrightarrow_{\beta *} 1 + 1$
- $1 + 1 =_{\beta} 2$

Each of above statements says the following.

- $1 + 1$ is a different expression from 2.
- $1 + 1$ reduces to 2, but 2 does not reduce to $1 + 1$.
- $1 + 1$ and 2 have the same computational meaning.

Programming in λ-Calculus

Church encoding of boolean values

Boolean and conditional can be encoded as combinators.

Boolean

$$\begin{aligned} \texttt{True} &:= \lambda x\, y.\, x \\ \texttt{False} &:= \lambda x\, y.\, y \end{aligned}$$

Conditional

$$\begin{aligned} \texttt{if} &:= \lambda b\, x\, y.\, b\, x\, y \\ \texttt{if}\ \texttt{True}\ M\ N &\longrightarrow_{\beta*} M \\ \texttt{if}\ \texttt{False}\ M\ N &\longrightarrow_{\beta*} N \end{aligned}$$

for any two λ-terms M and N.

Church Encoding of natural numbers i

Natural numbers can be encoded as λ-terms, so can arithmetic operations.

Church numerals

$$\begin{aligned}
\mathsf{c}_0 &:= \lambda f x.\, x \\
\mathsf{c}_1 &:= \lambda f x.\, f x \\
\mathsf{c}_2 &:= \lambda f x.\, f (f x) \\
\mathsf{c}_{n+1} &:= \lambda f x.\, f^{n+1}(x)
\end{aligned}$$

where $f^1(x) := f\,x$ and $f^{n+1}(x) := f\,(f^n(x))$.

Church Encoding of natural numbers ii

Successor

$$\begin{aligned} \texttt{succ} &:= \lambda n.\, \lambda f x.\, f\,(n\, f\, x) \\ \texttt{succ}\ \mathtt{c}_n &\longrightarrow_{\beta *} \mathtt{c}_{n+1} \end{aligned}$$

for any natural number $n \in \mathbb{N}$.

Addition

$$\begin{aligned} \texttt{add} &:= \lambda n\, m.\, \lambda f x.\ n\ f\ (m\ f\ x) \\ \texttt{add}\ \mathtt{c}_n\ \mathtt{c}_m &\longrightarrow_{\beta *} \mathtt{c}_{n+m} \end{aligned}$$

Church Encoding of natural numbers iii

Conditional

$$\begin{aligned}
\texttt{ifz} &:= \lambda n\,x\,y.\ n\ (\lambda z.\ y)\ x \\
\texttt{ifz}\ \mathtt{c}_0\ M\ N &\longrightarrow_{\beta *} M \\
\texttt{ifz}\ \mathtt{c}_{n+1}\ M\ N &\longrightarrow_{\beta *} N
\end{aligned}$$

Predecessor

$$\begin{aligned}
\texttt{pred} &:= \lambda n.\,\lambda f x.\,? \\
\texttt{pred}\ \mathtt{c}_0 &\longrightarrow_{\beta *} \mathtt{c}_0 \\
\texttt{pred}\ \mathtt{c}_{n+1} &\longrightarrow_{\beta *} \mathtt{c}_n
\end{aligned}$$

Exercise

1. Define the *flip* operation, i.e. a λ-term `flip` such that

$$\texttt{flip}\ M\ N\ P =_\beta M\ P\ N$$

2. Define Boolean operations `not`, `and`, and `or`.
3. Evaluate `succ` c_0 and `add` c_1 c_2.
4. Define the multiplication `mult` over Church numerals.
5. (Hard) Define `pred` so that `pred` $\mathsf{c}_0 =_\beta \mathsf{c}_0$ and `pred` $\mathsf{c}_{n+1} =_\beta \mathsf{c}_n$.

General Recursion, informally

The summation $\sum_{i=0}^{n} i$ for $n \in \mathbb{N}$ *can be* defined as

$$\texttt{sum}(n) = \begin{cases} 0 & \text{if } n = 0 \\ n + \texttt{sum}(n-1) & \text{otherwise.} \end{cases}$$

We cannot define recursion via self-reference in λ-calculus, can we avoid it? Consider the function $G\colon (\mathbb{N} \to \mathbb{N}) \to (\mathbb{N} \to \mathbb{N})$ defined by

$$(Gf)(n) := \begin{cases} 0 & \text{if } n = 0 \\ n + f(n-1) & \text{otherwise.} \end{cases} \tag{1}$$

If there exists $\texttt{sum}'$ with $G(\texttt{sum}') = \texttt{sum}'$, then $\texttt{sum}' = \texttt{sum}$.

Curry's paradoxical combinator

Proposition 20

Define

$$\mathsf{Y} := \lambda f.\,(\lambda x.\,f\,(x\,x))\,(\lambda x.\,f\,(x\,x)).$$

Then,

$$\begin{aligned}\mathsf{Y}F &\longrightarrow_{\beta 1} (\lambda x.\,F\,(x\,x))\,(\lambda x.\,F\,(x\,x)) \\ &\longrightarrow_{\beta 1} F\,((\lambda x.\,F\,(x\,x))\,(\lambda x.\,F\,(x\,x)))\end{aligned}$$

for every λ-term F.

Summation, formally

Using the combinators we have known so far, the equation (1) can be defined as λ-terms:

$$\begin{aligned} G &:= \lambda f\, n.\, \texttt{ifz}\ n\ \mathtt{c}_0\ (\texttt{add}\ n\ (f\ (\texttt{pred}\ n))) \\ \texttt{sum} &:= \mathsf{Y} G \end{aligned}$$

For example

$$\begin{aligned} \texttt{sum}\ \mathtt{c}_1 &\equiv (\mathsf{Y}G)\ \mathtt{c}_1 \\ &\longrightarrow_{\beta 1} G'\ \mathtt{c}_1 \\ &\longrightarrow_{\beta 1} G\ G'\ \mathtt{c}_1 \\ &\longrightarrow_{\beta 1} (\lambda n.\, \texttt{ifz}\ n\ \mathtt{c}_0\ (\texttt{add}\ n\ (G'\ (\texttt{pred}\ n))))\ \mathtt{c}_1 \\ &\longrightarrow_{\beta 1} \texttt{ifz}\ \mathtt{c}_1\ \mathtt{c}_0\ (\texttt{add}\ \mathtt{c}_1\ (G'\ (\texttt{pred}\ \mathtt{c}_1))) \\ &\longrightarrow_{\beta 1} \cdots \end{aligned}$$

where $G' := ((\lambda x.\, G\ (x\ x))\ (\lambda x.\, G\ (x\ x)))$.

Turing's fixed-point combinator

Here is a fixed-point operator such that $\Theta F \longrightarrow_{\beta *} F(\Theta F)$.

Proposition 21

Define

$$\Theta := (\lambda x f.\, f(x x f))\ (\lambda x f.\, f(x x f))$$

Then,

$$\Theta F \longrightarrow_{\beta *} F(\Theta F)$$

Try Turing's fixed-point combinator with G to define $\sum_{i=0}^{n} i$.

$$\begin{aligned} G &:= \lambda f n.\, \mathtt{ifz}\ n\ \mathtt{c}_0\ (\mathtt{add}\ n\ (f(\mathtt{pred}\ n))) \\ \mathtt{sum} &:= \Theta\, G \end{aligned}$$

Exercise

1. Evaluate `sum` c_1 to its normal form in detail.
2. Define the factorial $n!$ on Church numerals with Turing's fixed-point combinator.

Properties of λ-Calculus

Example 22

Suppose $M : \texttt{Term}_\lambda$ and $y \notin \mathtt{FV}(M)$. Then, consider

$$(\lambda y.\, M)\, ((\lambda x.\, x\, x)(\lambda x.\, x\, x))$$

Observations:

- Some evaluation may diverge while some may converge.
- Full β-reduction lacks for determinacy.

Question:

- Does every path give the same evaluation?

Confluence

Theorem 23 (Church-Rosser)

Given N_1 and N_2 with $M \longrightarrow_{\beta*} N_1$ and $M \longrightarrow_{\beta*} N_2$, there is L such that $N_1 \longrightarrow_{\beta*} L$ and $N_2 \longrightarrow_{\beta*} L$.

$$\begin{tikzcd}
 & M \arrow[dl, "\beta*"'] \arrow[dr, "\beta*"] & \\
N_1 \arrow[dr, dashed, "\beta*"'] & & N_2 \arrow[dl, dashed, "\beta*"] \\
 & L &
\end{tikzcd}$$

Normal form

We say that M is *in normal form* if $M \not\longrightarrow_{\beta 1}$.

Lemma 24

Suppose that M is in normal form. Then

$M \longrightarrow_{\beta *} N \implies M =_\alpha N.$

Corollary 25 (Uniqueness of normal forms)

Suppose that N_1 and N_2 are in normal form. Then,

$$\begin{tikzcd}
 & M \arrow[dl, "\beta *"'] \arrow[dr, "\beta *"] & \\
N_1 \arrow[r, phantom, "=_\alpha"] & N \arrow[r, phantom, "=_\alpha"] & N_2
\end{tikzcd}$$

Computationally equal terms have a confluent term

Corollary 26

If $M =_\beta N$, then there exists L satisfying

$$\begin{tikzcd}
M \arrow[rr, phantom, "=_\beta"] \arrow[dr, dashed, "\beta*"'] & & N \arrow[dl, dashed, "\beta*"] \\
& L &
\end{tikzcd}$$

Proof sketch.

By induction on the derivation of $M =_\beta N$.

For example, if $M \longrightarrow_{\beta 1} N$, then choose L as N. □

Evaluation strategies i

An evaluation strategy is a procedure of selecting β-redexes to reduce. It is a subset $\longrightarrow_{\mathrm{ev}}$ of the full β-reduction $\longrightarrow_{\beta 1}$.

Innermost β-redex does not contain any β-redex.

Outermost β-redex is not contained in any other β-redex.

Evaluation strategies ii

the leftmost-outermost (*normal order*) strategy reduces the leftmost outermost β-redex in a term first. For example,

$$\begin{aligned}
& \underline{(\lambda x.\,(\lambda y.\,y)\,x)} \quad \underline{(\lambda x.\,(\lambda y.\,y\,y)\,x)} \\
\longrightarrow_{\beta 1} & \underline{(\lambda y.\,y)} \quad \underline{(\lambda x.\,(\lambda y.\,y\,y)\,x)} \\
\longrightarrow_{\beta 1} & \lambda x.\,\underline{(\lambda y.\,y\,y)} \quad \underline{x} \\
\longrightarrow_{\beta 1} & (\lambda x.\,x\,x) \\
\not\longrightarrow_{\beta 1} &
\end{aligned}$$

Evaluation strategies iii

the leftmost-innermost strategy reduces the leftmost innermost β-redex in a term first. For example,

$$\begin{aligned}
& (\lambda x.\, \underline{(\lambda y.\, y)\ \ x})\,(\lambda x.\,(\lambda y.\, y\, y)\, x) \\
\longrightarrow_{\beta 1} & (\lambda x.\, x)\ (\lambda x.\, \underline{(\lambda y.\, y\, y)\ \ x}) \\
\longrightarrow_{\beta 1} & \underline{(\lambda x.\, x)\ \ (\lambda x.\, x\, x)} \\
\longrightarrow_{\beta 1} & (\lambda x.\, x\, x) \\
\not\longrightarrow_{\beta 1} &
\end{aligned}$$

the rightmost-innermost/outermost strategy are defined similarly where terms are reduced from right to left instead.

CBV versus CBN

Call-by-value strategy rightmost-outermost but not under any abstraction

Call-by-name strategy leftmost-outermost but not under any abstraction

Proposition 27 (Determinacy)

Each of evaluation strategies is deterministic, i.e. if $M \longrightarrow_{\beta 1} N_1$ *and* $M \longrightarrow_{\beta 1} N_2$ *then* $N_1 = N_2$.

Exercise

Define following terms

$$\Omega := (\lambda x.\, x\, x)\ (\lambda x.\, x\, x)$$
$$\mathsf{K}_1 := \lambda x\, y.\ x$$

Evaluate

$$\mathsf{K}_1\ z\ \Omega$$

using the call-by-value and the call-by-name strategy respectively.

Normalisation

Definition 28

1. M is in *normal form* if $M \not\longrightarrow_{\beta 1} N$ for any N.
2. M is *weakly normalising* if $M \longrightarrow_{\beta *} N$ for some N in normal form.

1. Ω is not weakly normalising.
2. K_1 is normal and thus weakly normalising.
3. $\mathsf{K}_1\ z\ \Omega$ is weakly normalising.

Theorem 29

The normal order strategy reduces every weakly normalising term to a normal form.

Homework

1. (25%) Show that $\longrightarrow_{\beta*}$ is transitive, i.e. $L \longrightarrow_{\beta*} N$ whenever $L \longrightarrow_{\beta*} M$ and $M \longrightarrow_{\beta*} N$. **Hint**. By induction on $L \longrightarrow_{\beta*} M$.
2. (25%) Show Lemma 24
3. (25%) Show Corollary 25
4. (25%) Show Corollary 26.