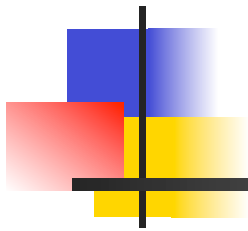


Programming Languages and Compilers (CS 421)



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Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha



Substitution

- Defined on α -equivalence classes of terms
- $P [N / x]$ means replace every free occurrence of x in P by N
 - P called *redex*; N called *residue*
- Provided that no variable free in N becomes bound in $P [N / x]$
 - Rename bound variables in P to avoid capturing free variables of N



Substitution

- $x [N / x] = N$
- $y [N / x] = y$ if $y \neq x$
- $(e_1 e_2) [N / x] = ((e_1 [N / x]) (e_2 [N / x]))$
- $(\lambda x. e) [N / x] = (\lambda x. e)$
- $(\lambda y. e) [N / x] = \lambda y. (e [N / x])$
provided $y \neq x$ and y not free in N
 - Rename y in redex if necessary



Example

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

- Problems?

- z in redex in scope of y binding
- y free in the residue

- $(\lambda y. y z) [(\lambda x. x y) / z] \xrightarrow{\alpha} (\lambda w. w z) [(\lambda x. x y) / z] = \lambda w. w (\lambda x. x y)$

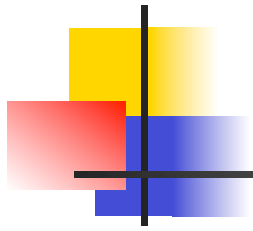


Example

- Only replace free occurrences
- $(\lambda y. y z (\lambda z. z)) [(\lambda x. x) / z] =$
 $\lambda y. y (\lambda x. x) (\lambda z. z)$

Not

$$\lambda y. y (\lambda x. x) (\lambda z. (\lambda x. x))$$



β reduction

- β Rule: $(\lambda x. P) N \xrightarrow{\beta} P [N / x]$
- Essence of computation in the lambda calculus
- Usually defined on α -equivalence classes of terms



Example

- $(\lambda z. (\lambda x. x y) z) (\lambda y. y z)$

$$\text{--}\beta\text{--}\rightarrow (\lambda x. x y) (\lambda y. y z)$$

$$\text{--}\beta\text{--}\rightarrow (\lambda y. y z) y \text{--}\beta\text{--}\rightarrow y z$$

- $(\lambda x. x x) (\lambda x. x x)$

$$\text{--}\beta\text{--}\rightarrow (\lambda x. x x) (\lambda x. x x)$$

$$\text{--}\beta\text{--}\rightarrow (\lambda x. x x) (\lambda x. x x) \text{--}\beta\text{--}\rightarrow \dots$$



α β Equivalence

- α β equivalence is the smallest congruence containing α equivalence and β reduction
- A term is in *normal form* if no subterm is α equivalent to a term that can be β reduced
- Hard fact (Church-Rosser): if e_1 and e_2 are $\alpha\beta$ -equivalent and both are normal forms, then they are α equivalent



Order of Evaluation

- Not all terms reduce to normal forms
- Not all reduction strategies will produce a normal form if one exists



Transition Semantics for λ -Calculus

$$\frac{E \rightarrow E''}{EE' \twoheadrightarrow E''E'}$$

- Application (version 1 - Lazy Evaluation)

$$(\lambda x. E) E' \twoheadrightarrow E[E'/x]$$

- Application (version 2 - Eager Evaluation)

$$\frac{E' \twoheadrightarrow E''}{(\lambda x. E) E' \twoheadrightarrow (\lambda x. E) E''}$$

$$\frac{}{(\lambda x. E) V \twoheadrightarrow E[V/x]}$$

V - variable or abstraction (value)



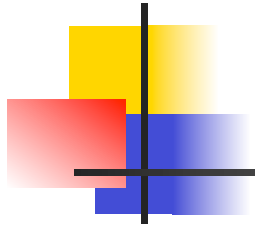
Lazy evaluation:

- Always reduce the left-most application in a top-most series of applications (i.e. Do not perform reduction inside an abstraction)
- Stop when term is not an application, or left-most application is not an application of an abstraction to a term



Example 1

- $(\lambda z. (\lambda x. x)) ((\lambda y. y y) (\lambda y. y y))$
- Lazy evaluation:
- Reduce the left-most application:
- $(\lambda z. (\lambda x. x)) ((\lambda y. y y) (\lambda y. y y))$
-- β --> $(\lambda x. x)$



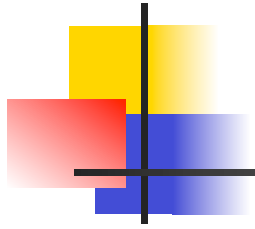
Eager evaluation

- (Eagerly) reduce left of top application to an abstraction
- Then (eagerly) reduce argument
- Then β -reduce the application



Example 1

- $(\lambda z. (\lambda x. x))((\lambda y. y y) (\lambda y. y y))$
- Eager evaluation:
- Reduce the rator of the top-most application to an abstraction: Done.
- Reduce the argument:
- $(\lambda z. (\lambda x. x))((\lambda y. y y) (\lambda y. y y))$
- β --> $(\lambda z. (\lambda x. x))((\lambda y. y y) (\lambda y. y y))$
- β --> $(\lambda z. (\lambda x. x))((\lambda y. y y) (\lambda y. y y))...$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta} \dots$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Lazy evaluation:

$(\lambda x. \boxed{x} \boxed{x})((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Lazy evaluation:

$(\lambda x. \boxed{x} \boxed{x})((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$\boxed{((\lambda y. y y) (\lambda z. z))} \boxed{((\lambda y. y y) (\lambda z. z))}$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. \boxed{y} \boxed{y}) \underline{(\lambda z. z)}) ((\lambda y. y y) (\lambda z. z))$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. \boxed{y} \boxed{y}) \underline{(\lambda z. z)}) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} (\boxed{(\lambda z. z)} \boxed{(\lambda z. z)})((\lambda y. y y) (\lambda z. z))$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \text{ --}\beta\text{--}\>$$
$$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$$
$$\text{--}\beta\text{--}\> ((\lambda z. z) (\lambda z. z))((\lambda y. y y) (\lambda z. z))$$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} ((\lambda z. \boxed{z}) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \text{ --}\beta\text{--}\rightarrow$

$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\text{--}\beta\text{--}\rightarrow ((\lambda z. \boxed{z}) (\lambda z. z))((\lambda y. y y) (\lambda z. z))$

$\text{--}\beta\text{--}\rightarrow \boxed{(\lambda z. z)} ((\lambda y. y y) (\lambda z. z))$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Lazy evaluation:

$$\begin{aligned} & (\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta} \\ & ((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z)) \\ & \xrightarrow{\beta} ((\lambda z. z) (\lambda z. z))((\lambda y. y y) (\lambda z. z)) \\ & \xrightarrow{\beta} (\lambda z. \boxed{z}) \underline{((\lambda y. y y) (\lambda z. z))} \xrightarrow{\beta} \\ & (\lambda y. y y) (\lambda z. z) \end{aligned}$$

Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

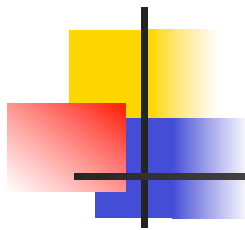
$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} ((\lambda z. z) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} (\lambda z. z) ((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$(\lambda y. y y) (\lambda z. z)$



Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$

- Lazy evaluation:

$(\lambda x. x x)((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$((\lambda y. y y) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} ((\lambda z. z) (\lambda z. z)) ((\lambda y. y y) (\lambda z. z))$

$\xrightarrow{\beta} (\lambda z. z) ((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta}$

$(\lambda y. y y) (\lambda z. z) \sim_{\beta} \lambda z. z$

Example 2

- $(\lambda x. x x)((\lambda y. y y) (\lambda z. z))$
- Eager evaluation:

$(\lambda x. x x) ((\lambda y. y y) (\lambda z. z)) \xrightarrow{\beta} (\lambda x. x x) ((\lambda z. z) (\lambda z. z)) \xrightarrow{\beta} (\lambda x. x x) (\lambda z. z) \xrightarrow{\beta} (\lambda z. z) (\lambda z. z) \xrightarrow{\beta} \lambda z. z$



Untyped λ -Calculus

- Only three kinds of expressions:
 - Variables: x, y, z, w, \dots
 - Abstraction: $\lambda x. e$
(Function creation)
 - Application: $e_1 e_2$



How to Represent (Free) Data Structures (First Pass - Enumeration Types)

- Suppose τ is a type with n constructors:
 C_1, \dots, C_n (no arguments)
- Represent each term as an abstraction:
- Let $C_i \rightarrow \lambda x_1 \dots x_n. x_i$
- Think: you give me what to return in each case (think match statement) and I'll return the case for the i 'th constructor



How to Represent Booleans

- `bool = True | False`
- `True` $\rightarrow \lambda x_1. \lambda x_2. x_1 \equiv_{\alpha} \lambda x. \lambda y. x$
- `False` $\rightarrow \lambda x_1. \lambda x_2. x_2 \equiv_{\alpha} \lambda x. \lambda y. y$

- Notation

- Will write

$\lambda x_1 \dots x_n. e$ for $\lambda x_1. \dots \lambda x_n. e$

$e_1 e_2 \dots e_n$ for $(\dots (e_1 e_2) \dots e_n)$



Functions over Enumeration Types

- Write a “match” function

- match e with $C_1 \rightarrow x_1$

| ...

| $C_n \rightarrow x_n$

$\rightarrow \lambda x_1 \dots x_n e. e x_1 \dots x_n$

- Think: give me what to do in each case and give me a case, and I'll apply that case



Functions over Enumeration Types

- type $\tau = C_1 | \dots | C_n$
- match e with $C_1 \rightarrow x_1$
| ...
| $C_n \rightarrow x_n$
- $match\tau = \lambda x_1 \dots x_n e. e\ x_1 \dots x_n$
- $e =$ expression (single constructor)
 x_i is returned if $e = C_i$



match for Booleans

- `bool = True | False`
- `True` $\rightarrow \lambda x_1 x_2. x_1 \equiv_{\alpha} \lambda x y. x$
- `False` $\rightarrow \lambda x_1 x_2. x_2 \equiv_{\alpha} \lambda x y. y$

- `matchbool = ?`



match for Booleans

- $\text{bool} = \text{True} \mid \text{False}$
- $\text{True} \rightarrow \lambda x_1 x_2. x_1 \equiv_{\alpha} \lambda x y. x$
- $\text{False} \rightarrow \lambda x_1 x_2. x_2 \equiv_{\alpha} \lambda x y. y$

- $\text{match}_{\text{bool}} = \lambda x_1 x_2 e. e x_1 x_2$
 $\equiv_{\alpha} \lambda x y b. b x y$



How to Write Functions over Booleans

- if b then x_1 else $x_2 \rightarrow$
- if_then_else b x_1 $x_2 = b$ x_1 x_2
- if_then_else $\equiv \lambda$ b x_1 $x_2 . b$ x_1 x_2



How to Write Functions over Booleans

- Alternately:
- if b then x_1 else $x_2 =$
match b with True $\rightarrow x_1$ | False $\rightarrow x_2 \rightarrow$
match_{bool} x_1 x_2 b =
 $(\lambda x_1 x_2 b . b x_1 x_2) x_1 x_2 b = b x_1 x_2$
- if_then_else
 $\equiv \lambda b x_1 x_2 . (\text{match}_{\text{bool}} x_1 x_2 b)$
 $= \lambda b x_1 x_2 . (\lambda x_1 x_2 b . b x_1 x_2) x_1 x_2 b$
 $= \lambda b x_1 x_2 . b x_1 x_2$



Example:

not b

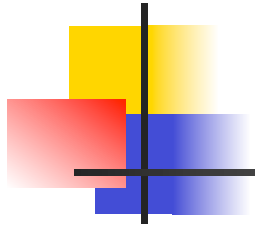
= match b with True -> False | False -> True

→ (match_{bool}) False True b

= (λ x₁ x₂ b . b x₁ x₂) (λ x y. y) (λ x y. x) b

= b (λ x y. y)(λ x y. x)

- not ≡ λ b. b (λ x y. y)(λ x y. x)
- Try and, or



and

or



How to Represent (Free) Data Structures (Second Pass - Union Types)

- Suppose τ is a type with n constructors:
type $\tau = C_1 t_{11} \dots t_{1k} \mid \dots \mid C_n t_{n1} \dots t_{nm}$,
- Represent each term as an abstraction:
- $C_i t_{i1} \dots t_{ij} \rightarrow \lambda x_1 \dots x_n. x_i t_{i1} \dots t_{ij}$,
- $C_i \rightarrow \lambda t_{i1} \dots t_{ij}. x_1 \dots x_n. x_i t_{i1} \dots t_{ij}$,
- Think: you need to give each constructor its arguments first



How to Represent Pairs

- Pair has one constructor (comma) that takes two arguments
- $\text{type } (\alpha, \beta)\text{pair} = (,) \alpha \beta$
- $(a , b) \text{ --> } \lambda x . x a b$
- $(_ , _) \text{ --> } \lambda a b x . x a b$



Functions over Union Types

- Write a “match” function
- match e with $C_1 y_1 \dots y_{m_1} \rightarrow f_1 y_1 \dots y_{m_1}$
| ...
| $C_n y_1 \dots y_{m_n} \rightarrow f_n y_1 \dots y_{m_n}$
- $match_{\tau} \rightarrow \lambda f_1 \dots f_n e. e f_1 \dots f_n$
- Think: give me a function for each case and give me a case, and I'll apply that case to the appropriate function with the data in that case



Functions over Pairs

- $\text{match}_{\text{pair}} = \lambda f p. p f$
- $\text{fst } p = \text{match } p \text{ with } (x,y) \rightarrow x$
- $\text{fst} \rightarrow \lambda p. \text{match}_{\text{pair}} (\lambda x y. x)$
 $= (\lambda f p. p f) (\lambda x y. x) = \lambda p. p (\lambda x y. x)$
- $\text{snd} \rightarrow \lambda p. p (\lambda x y. y)$



How to Represent (Free) Data Structures (Third Pass - Recursive Types)

- Suppose τ is a type with n constructors:

$$\text{type } \tau = C_1 t_{11} \dots t_{1k} \mid \dots \mid C_n t_{n1} \dots t_{nm},$$
- Suppose $t_{ih} : \tau$ (ie. is recursive)
- In place of a value t_{ih} have a function to compute the recursive value $r_{ih} x_1 \dots x_n$
- $C_i t_{i1} \dots r_{ih} \dots t_{ij} \rightarrow \lambda x_1 \dots x_n . x_i t_{i1} \dots (r_{ih} x_1 \dots x_n) \dots t_{ij}$
- $C_i \rightarrow \lambda t_{i1} \dots r_{ih} \dots t_{ij} x_1 \dots x_n . x_i t_{i1} \dots (r_{ih} x_1 \dots x_n) \dots t_{ij},$



How to Represent Natural Numbers

- $\text{nat} = \text{Suc nat} \mid 0$
- $\text{Suc} = \lambda n f x. f (n f x)$
- $\text{Suc } n = \lambda f x. f (n f x)$
- $0 = \lambda f x. x$
- Such representation called *Church Numerals*



Some Church Numerals

- Suc 0 = $(\lambda n f x. f (n f x)) (\lambda f x. x) \rightarrow$
 $\lambda f x. f ((\lambda f x. x) f x) \rightarrow$
 $\lambda f x. f ((\lambda x. x) x) \rightarrow \lambda f x. f x$

Apply a function to its argument once



Some Church Numerals

■ $\text{Suc}(\text{Suc } 0) = (\lambda n f x. f (n f x)) (\text{Suc } 0) \rightarrow$
 $(\lambda n f x. f (n f x)) (\lambda f x. f x) \rightarrow$
 $\lambda f x. f ((\lambda f x. f x) f x) \rightarrow$
 $\lambda f x. f ((\lambda x. f x) x) \rightarrow \lambda f x. f (f x)$

Apply a function twice

In general $\overline{n} = \lambda f x. f (\dots (f x) \dots)$ with n applications of f



Primitive Recursive Functions

- Write a “fold” function

- fold $f_1 \dots f_n = \text{match } e$

with $C_1 y_1 \dots y_{m1} \rightarrow f_1 y_1 \dots y_{m1}$

| ...

| $C_i y_1 \dots r_{ij} \dots y_{in} \rightarrow f_n y_1 \dots (\text{fold } f_1 \dots f_n r_{ij}) \dots y_{mn}$

| ...

| $C_n y_1 \dots y_{mn} \rightarrow f_n y_1 \dots y_{mn}$

- $\text{fold}\tau \rightarrow \lambda f_1 \dots f_n e. e f_1 \dots f_n$

- Match in non recursive case a degenerate version of fold



Primitive Recursion over Nat

- $\text{fold } f \ z \ n =$
- $\text{match } n \text{ with } 0 \rightarrow z$
- $\quad \quad \quad | \text{Suc } m \rightarrow f (\text{fold } f \ z \ m)$
- $\overline{\text{fold}} \equiv \lambda f \ z \ n. n \ f \ z$
- $\overline{\text{is_zero}} \ n = \overline{\text{fold}} (\lambda r. \overline{\text{False}}) \overline{\text{True}} \ n$
- $= (\lambda f \ x. f^n \ x) (\lambda r. \overline{\text{False}}) \overline{\text{True}}$
- $= ((\lambda r. \overline{\text{False}})^n) \overline{\text{True}}$
- $\equiv \text{if } n = 0 \text{ then True else False}$



Adding Church Numerals

- $\bar{n} \equiv \lambda f x. f^n x$ and $m \equiv \lambda f x. f^m x$

- $\overline{n + m} = \lambda f x. f^{(n+m)} x$
 $= \lambda f x. f^n (f^m x) = \lambda f x. \bar{n} f (\bar{m} f x)$

- $\bar{+} \equiv \lambda n m f x. n f (m f x)$

- Subtraction is harder



Multiplying Church Numerals

- $\bar{n} \equiv \lambda f x. f^n x$ and $m \equiv \lambda f x. f^m x$

- $\overline{n * m} = \lambda f x. (f^{n * m}) x = \lambda f x. (f^m)^n x$
 $= \lambda f x. \bar{n} (\bar{m} f) x$

$$\bar{*} \equiv \lambda n m f x. n (m f) x$$



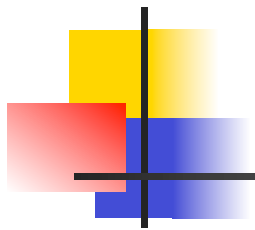
Predecessor

- let pred_aux n =
 match n with 0 -> (0,0)
 | Suc m
 -> (Suc(fst(pred_aux m)), fst(pred_aux m))
 = fold (λ r. (Suc(fst r), fst r)) (0,0) n
- pred \equiv λ n. snd (pred_aux n) n =
 λ n. snd (fold (λ r.(Suc(fst r), fst r)) (0,0) n)



Recursion

- Want a λ -term Y such that for all term R we have
- $Y R = R (Y R)$
- Y needs to have replication to “remember” a copy of R
- $Y = \lambda y. (\lambda x. y(x x)) (\lambda x. y(x x))$
- $Y R = (\lambda x. R(x x)) (\lambda x. R(x x))$
 $= R ((\lambda x. R(x x)) (\lambda x. R(x x)))$
- Notice: Requires lazy evaluation



Factorial

■ Let $F = \lambda f n. \text{if } n = 0 \text{ then } 1 \text{ else } n * f (n - 1)$

$$Y F 3 = F (Y F) 3$$

$$= \text{if } 3 = 0 \text{ then } 1 \text{ else } 3 * ((Y F)(3 - 1))$$

$$= 3 * (Y F) 2 = 3 * (F(Y F) 2)$$

$$= 3 * (\text{if } 2 = 0 \text{ then } 1 \text{ else } 2 * (Y F)(2 - 1))$$

$$= 3 * (2 * (Y F)(1)) = 3 * (2 * (F(Y F) 1)) = \dots$$

$$= 3 * 2 * 1 * (\text{if } 0 = 0 \text{ then } 1 \text{ else } 0 * (Y F)(0 - 1))$$

$$= 3 * 2 * 1 * 1 = 6$$



Y in OCaml

```
# let rec y f = f (y f);;
val y : ('a -> 'a) -> 'a = <fun>
# let mk_fact =
  fun f n -> if n = 0 then 1 else n * f(n-1);;
val mk_fact : (int -> int) -> int -> int = <fun>
# y mk_fact;;
Stack overflow during evaluation (looping
recursion?).
```



Eager Eval Y in Ocaml

```
# let rec y f x = f (y f) x;;
```

```
val y : (('a -> 'b) -> 'a -> 'b) -> 'a -> 'b =  
  <fun>
```

```
# y mk_fact;;
```

```
- : int -> int = <fun>
```

```
# y mk_fact 5;;
```

```
- : int = 120
```

- Use recursion to get recursion



Some Other Combinators

- For your general exposure
- $I = \lambda x . x$
- $K = \lambda x . \lambda y . x$
- $K_* = \lambda x . \lambda y . y$
- $S = \lambda x . \lambda y . \lambda z . x z (y z)$