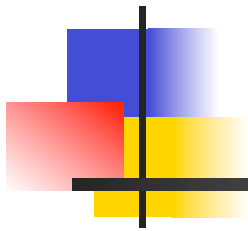


# Programming Languages and Compilers (CS 421)



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<http://www.cs.illinois.edu/class/cs421/>

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



# Untyped $\lambda$ -Calculus

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- 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  $\tau$  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

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- `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

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- 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<sub>bool</sub>  $x_1$   $x_2$  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:

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not b

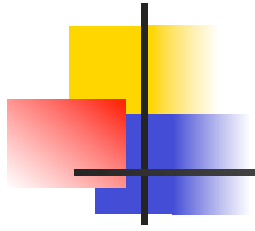
= match b with True -> False | False -> True

→ (match<sub>bool</sub>) False True b

= (λ x<sub>1</sub> x<sub>2</sub> b . b x<sub>1</sub> x<sub>2</sub>) (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  $\tau$  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  $\tau$  is a type with  $n$  constructors:

type  $\tau = C_1 t_{11} \dots t_{1k} \mid \dots \mid C_n t_{n1} \dots t_{nm},$

- 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

---

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



# Adding Church Numerals

---

- $\bar{n} \equiv \lambda f x. f^n x$     and     $m \equiv \lambda f x. f^m x$
- $\overline{n + m} = \lambda f x. f^{(n+m)} x$   
 $= \lambda f x. f^n (f^m x) = \lambda f x. \bar{n} f (\bar{m} f x)$
- $\overline{+} \equiv \lambda n m f x. n f (m f x)$
- Subtraction is harder



# Multiplying Church Numerals

---

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

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

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





# Predecessor

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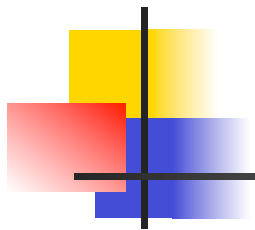
- let pred\_aux n =  
match n with 0 -> (0,0)  
| Suc m  
-> (Suc(fst(pred\_aux m)), fst(pred\_aux m))  
= fold ( $\lambda$  r. (Suc(fst r), fst r)) (0,0) n
- pred  $\equiv$   $\lambda$  n. snd (pred\_aux n) n =  
 $\lambda$  n. snd (fold ( $\lambda$  r.(Suc(fst r), fst r)) (0,0) n)



# Recursion

---

- Want a  $\lambda$ -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

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■ 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
- $I = \lambda x . x$
- $K = \lambda x . \lambda y . x$
- $K_* = \lambda x . \lambda y . y$
- $S = \lambda x . \lambda y . \lambda z . x z (y z)$