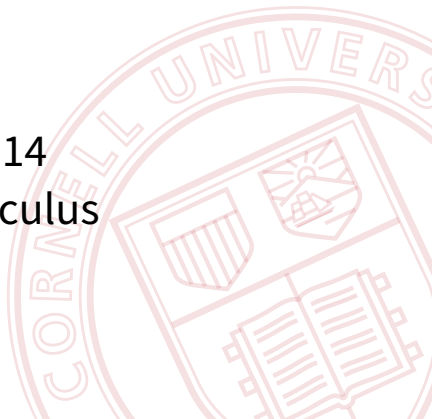


CS 4110

# Programming Languages & Logics

## Lecture 14 More $\lambda$ -calculus



# Review: $\lambda$ -calculus

## Syntax

$$\begin{aligned} e &::= x \mid e_1 e_2 \mid \lambda x. e \\ v &::= \lambda x. e \end{aligned}$$

## Semantics (call by value)

$$\frac{e_1 \rightarrow e'_1}{e_1 e_2 \rightarrow e'_1 e_2} \qquad \frac{e \rightarrow e'}{v e \rightarrow v e'}$$

$$\frac{}{(\lambda x. e) v \rightarrow e\{v/x\}} \beta$$

## Example: Twice

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We can abstract this pattern using a generic function:

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Now the functions above can be written as

$$\text{quadruple} = \text{twice double}$$

$$\text{octuple} = \text{twice quadruple}$$

$$\text{hexadecatuple} = \text{twice octuple} \\ \text{(or twice } (\lambda x. \text{twice } x))$$

# Evaluation

The essence of  $\lambda$ -calculus evaluation is the  $\beta$ -reduction rule, which says how to apply a function to an argument.

$$\frac{}{(\lambda x. e) v \rightarrow e\{v/x\}} \beta\text{-REDUCTION}$$

But there are many different evaluation strategies, each corresponding to particular ways of using  $\beta$ -reduction:

- Call-by-value
- Call-by-name
- “Full”  $\beta$ -reduction
- ...

# Call by value

$$\frac{e_1 \rightarrow e'_1}{e_1 e_2 \rightarrow e'_1 e_2} \quad \frac{e_2 \rightarrow e'_2}{v_1 e_2 \rightarrow v_1 e'_2}$$

$$\frac{}{(\lambda x. e_1) v_2 \rightarrow e_1 \{v_2/x\}} \beta$$

Key characteristics:

- Arguments evaluated fully before they are supplied to functions
- Evaluation goes from left to right (in this presentation)
- We don't evaluate "under a  $\lambda$ "

# Call by name

$$\frac{e_1 \rightarrow e'_1}{e_1 e_2 \rightarrow e'_1 e_2}$$

$$\frac{}{(\lambda x. e_1) e_2 \rightarrow e_1 \{e_2/x\}} \beta$$

Key characteristics:

- Arguments supplied immediately to functions
- Evaluation still goes from left to right (in this presentation)
- We still don't evaluate "under a  $\lambda$ "

# Full $\beta$ reduction

$$\frac{e_1 \rightarrow e'_1}{e_1 e_2 \rightarrow e'_1 e_2} \qquad \frac{e_2 \rightarrow e'_2}{e_1 e_2 \rightarrow e_1 e'_2}$$

$$\frac{e \rightarrow e'}{\lambda x. e \rightarrow \lambda x. e'}$$

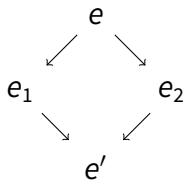
$$\overline{(\lambda x. e_1) e_2 \rightarrow e_1 \{e_2/x\}}^{\beta}$$

Key characteristics:

- Use the  $\beta$  rule anywhere...
- ...including “under a  $\lambda$ ”...
- ...nondeterministically.

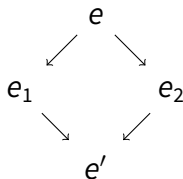
# Confluence

Full  $\beta$  reduction has this property:



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## Theorem (Confluence)

*If  $e \rightarrow^* e_1$  and  $e \rightarrow^* e_2$  then  $e_1 \rightarrow^* e'$  and  $e_2 \rightarrow^* e'$  for some  $e'$ .*

# Substitution

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The main workhorse in the  $\beta$  rule is **substitution**, which replaces free occurrences of a variable  $x$  with a term  $e$ .

However, defining substitution  $e_1\{e_2/x\}$  correctly is tricky...



# “Substitution”

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As a first attempt, consider:

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What's wrong with this definition?

It substitutes bound variables too!

$$(\lambda y.y)\{3/y\}$$

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What's wrong with this definition?

It substitutes bound variables too!

$$(\lambda y.y)\{3/y\} = (\lambda y.3)$$

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Okay... let's avoid rewriting bound variables by relying on  $\alpha$ -equivalence. We'll require that abstractions don't use  $x$ , the variable we're substituting.

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$$\begin{aligned}y\{e/x\} &= \begin{cases} e & \text{if } y = x \\ y & \text{otherwise} \end{cases} \\(e_1 \ e_2)\{e/x\} &= (e_1\{e/x\}) (e_2\{e/x\})\end{aligned}$$



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We *assume away* abstractions over  $x$ . (Thanks,  $\alpha$ -equivalence!)

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It leads to variable capture!

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# Real Substitution

The correct definition is *capture-avoiding substitution*:

$$\begin{aligned}y\{e/x\} &= \begin{cases} e & \text{if } y = x \\ y & \text{otherwise} \end{cases} \\(e_1 e_2)\{e/x\} &= (e_1\{e/x\}) (e_2\{e/x\}) \\(\lambda y. e_1)\{e/x\} &= \lambda y. (e_1\{e/x\}) \quad \text{where } y \neq x \text{ and } y \notin \text{fv}(e)\end{aligned}$$

where  $\text{fv}(e)$  is the *free variables* of a term  $e$ .