Lambda Calculus: Reduction / Substitution

CIS352 — Spring 2023

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Last lecture: β−reduction, informally

$$((\lambda\ (x)\ E_0)\ E_1) \quad \rightarrow_{\beta} \quad E_0[x \leftarrow E_1]$$

redex

(**red**ucible **ex**pression)

replace every x in E_0 with E_1.

If you watch the **history of the lambda calculus discussion by Dana Scott**, I will award +.5% bonus (min 5-30):

https://www.youtube.com/watch?v=uS9InrmPIoc

How can we define beta reduction as a Racket function…?

```
(define (beta-reduce e)
  (match e
    [`((lambda (,x) ,e-body) ,e-arg) (subst x e-arg e-body)]
    [_ (error "beta-reduction cannot apply...")]))
```

Today: how do we define the **subst** function?

Variables are **challenging**

Semantics of the Lambda Calculus

Typical presentations of the lambda calculus define a **textual-reduction semantics**.

You can envision a "machine" where the machine's **state** is the *text* of the program as it evolves

```
((lambda (x) x) ((lambda (z) z) y))
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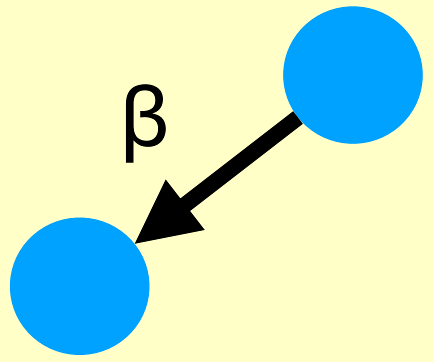


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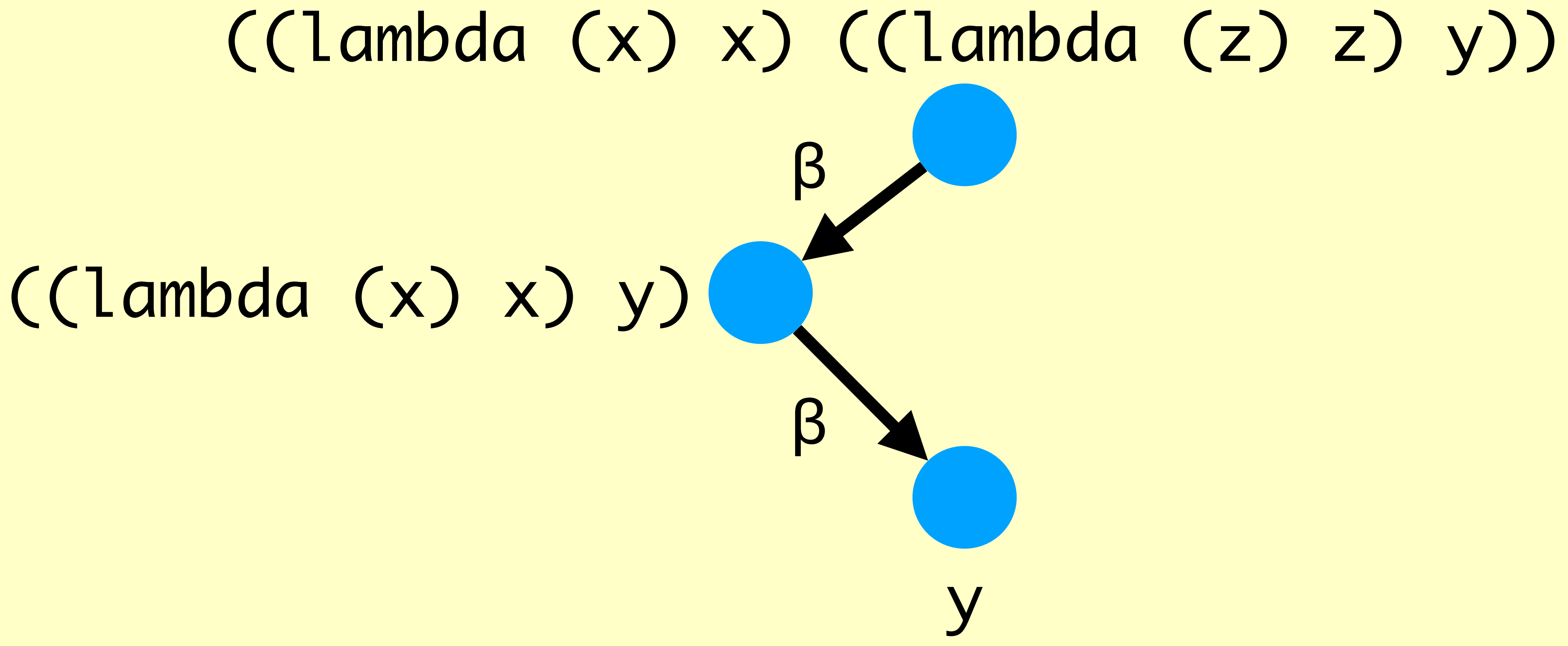
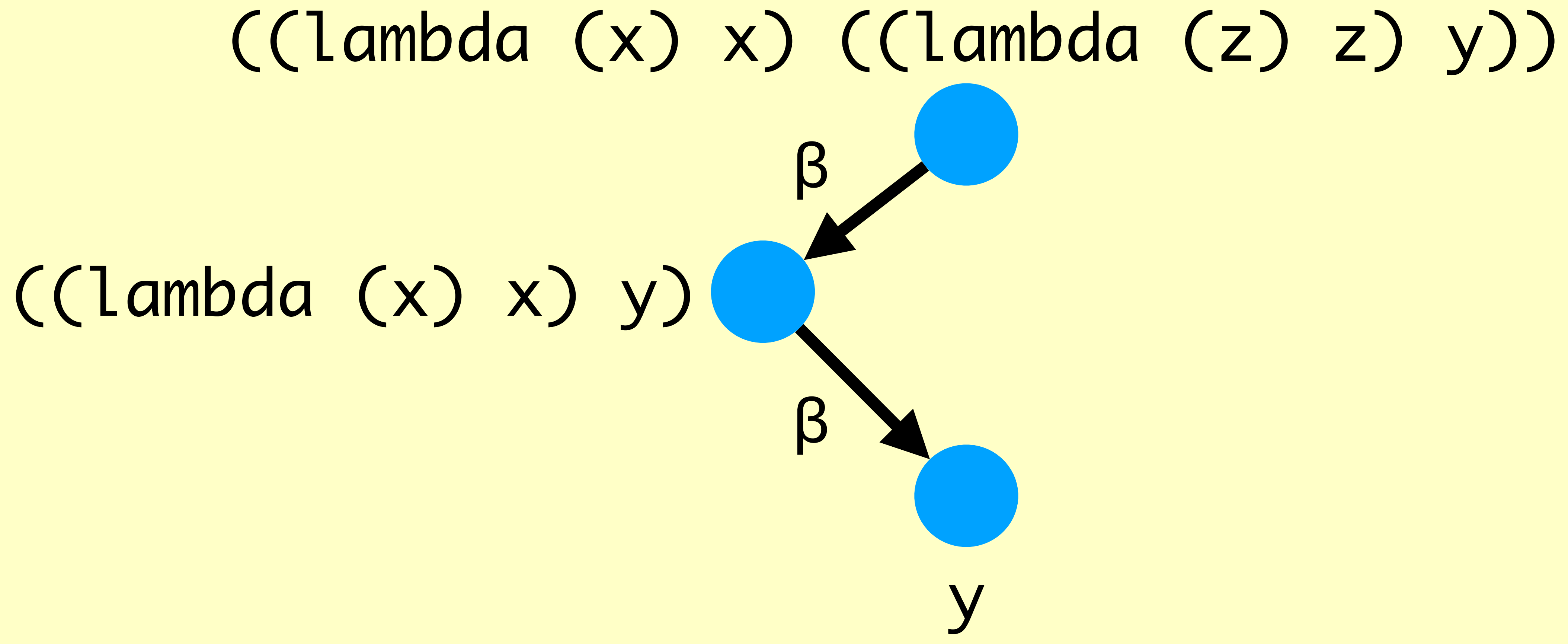


Semantics of the Lambda Calculus

Observe! Β-Reduction is nondeterministic

In general, a term may have **multiple** β redexes, and thus multiple β reductions

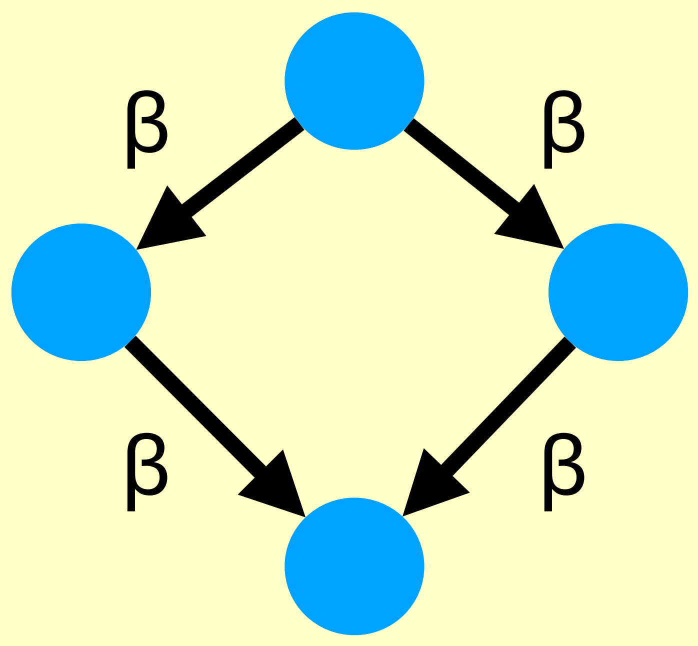


Semantics of the Lambda Calculus

This term has **two** beta redexes!

The outer one in **red**
The inner one in **blue**

```
((lambda (x) x) ((lambda (z) z) y))
```




```
((lambda (x) x) y)        ((lambda (z) z) y)
```

```
y
```

The two challenges for this lecture:

- How do we implement substitution
- How do we deal with nondeterminism in the semantics

Substitution seems conceptually simple, but it is surprisingly tricky. But consider this: substitution is fundamentally **where computation happens**!

```
(define (beta-reduce e)
  (match e
    [`((lambda (,x) ,e-body) ,e-arg) (subst x e-arg e-body)]
    [_ (error "beta-reduction cannot apply...")]))
```

If we have **subst**, we can easily define **beta-reduce**.

Free Variables

We define the free variables of a lambda expression via the function FV:

$$\mathbf{FV} : \mathbf{Exp} \rightarrow \mathscr{P}(\mathbf{Var})$$

$$\mathbf{FV}(x) \triangleq \{x\}$$

$$\mathbf{FV}((\lambda\ (x)\ e_b)) \triangleq \mathbf{FV}(e_b) \setminus \{x\}$$

$$\mathbf{FV}(e_f\ e_a)) \triangleq \mathbf{FV}(e_f)\ \cup\ \mathbf{FV}(e_a)$$

$$\mathbf{FV}((x\ \ y)) = \{x, y\}$$

$$\mathbf{FV}(((\lambda\ \ (x)\ \ x)\ \ y)) = \{y\}$$

$$\mathbf{FV}(((\lambda\ \ (x)\ \ x)\ \ x)) = \{x\}$$

$$\mathbf{FV}(((\lambda\ \ (y)\ \ ((\lambda\ \ (x)\ \ (z\ \ x))\ \ x)))) = \{z, x\}$$

$$\mathbf{FV}(\texttt{(x y)}) = \{x, y\}$$

$$\mathbf{FV}(\texttt{((}\lambda\texttt{ (x) x) y)}) = \{y\}$$

$$\mathbf{FV}(\texttt{((}\lambda\texttt{ (x) x) x)}) = \{x\}$$

$$\mathbf{FV}(\texttt{((}\lambda\texttt{ (y) ((}\lambda\texttt{ (x) (z x)) x)))}) = \{z, x\}$$

What are the free variables of each of the following terms?

```
((λ (x) x) y)

((λ (x) (x x)) (λ (x) (x x)))

((λ (x) (z y)) x)
```

What are the free variables of each of the following terms?

```
((λ (x) x) y)
```

{y}

```
((λ (x) (x x)) (λ (x) (x x)))
```

{}

```
((λ (x) (z y)) x)
```

{x, y, z}

Closed Terms

A term is **closed** when it has no free variables:

- ((lambda (x) x) (lambda (y) y))
- (lambda (z) (lambda (x) (z (lambda (z) z)))

Sometimes we call these (closed terms) **combinators**

Some **open** terms…

- (lambda (x) ((lambda (z) z) **z**))
- ((lambda (x) x) (lambda (z) **x**))

Alpha-Renaming

α-renaming allows us to rename variables:

$$\frac{y \notin FV(e)}{(\lambda\,(x)\;\,e) \overset{\alpha}{\to} (\lambda\,(y)\;\,e[x \mapsto y])}$$

Still need to define substitution…

Important consequence: terms are unique **up to α equivalence**

$$e_0 \overset{\alpha}{\longleftrightarrow} e_1 \overset{\alpha}{\longleftrightarrow} e_2 \overset{\alpha}{\longleftrightarrow} e_3 \overset{\alpha}{\longleftrightarrow} e_4 \overset{\alpha}{\longleftrightarrow} e_5$$

```
(lambda (😋) 😋)
```

```
(lambda (x) x)
```

Every term has infinitely-many terms to which it is α equivalent

What breaks if the antecedent isn't enforced..?

$$\frac{y \notin FV(e)}{(\lambda\,(x)\ e) \xrightarrow{\alpha} (\lambda\,(y)\ e[x \mapsto y])}$$

Meaning of term changes! Someone might have an intention to **use** that free variable y

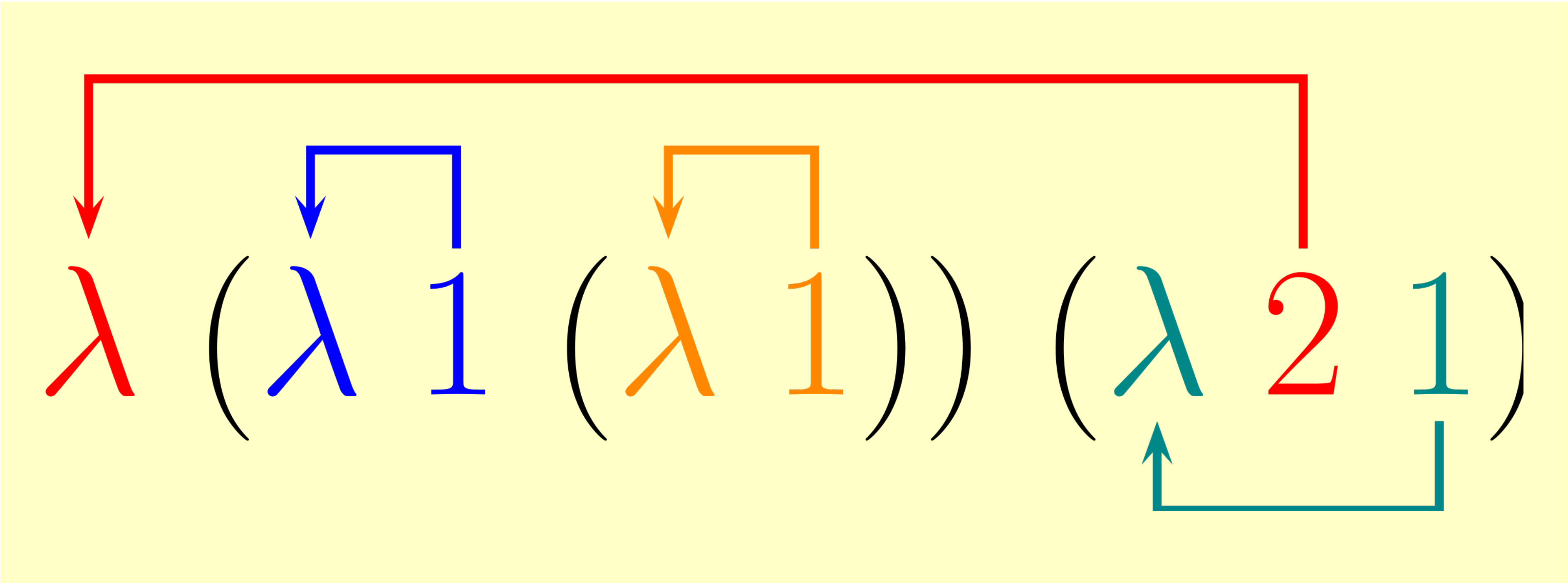
`(lambda (x) add1)` very different from `(lambda (x) x)`

```
(((Lambda (x) add1) (lambda (y) y)) 2)
!=
(((Lambda (x) x) (lambda (y) y)) 2)
```

Can we define lambda calculi without explicit variables? (**Yes**!)

- De-Bruin Indices (variables are numbers indicating to which binder they belong)
- Combinatory logic uses bases of fully-closed terms. Always possible to rewrite any LC term to use only several closed combinators

We won't study either of these



We define **capture-avoiding substitution**, in which we are careful to avoid places where variables would become **captured** by a substitution.

The problem with (naive) textual substitution

```
((λ (a) (λ (a) a)) (λ (b) b))

        │ β
        ↓

 (λ (a) a)[a ← (λ (b) b)]
```

The problem with (naive) textual substitution

```
((λ (a) (λ (a) a)) (λ (b) b))
```

↓ β

```
(λ (a) (λ (b) b))
```

✗

Capture-avoiding substitution

$E_0[x \leftarrow E_1]$

$$x[x \leftarrow E] = E$$

$$y[x \leftarrow E] = y \quad \text{where} \quad y \neq x$$

$$x[x \leftarrow E] = E$$

$$y[x \leftarrow E] = y \quad \text{where} \quad y \neq x$$

$$(E_0\ \ E_1)[x \leftarrow E] = (E_0[x \leftarrow E]\ \ E_1[x \leftarrow E])$$

$$x[x \leftarrow E] = E$$

$$y[x \leftarrow E] = y \quad \text{where} \quad y \neq x$$

$$(E_0 \ E_1)[x \leftarrow E] = (E_0[x \leftarrow E] \ E_1[x \leftarrow E])$$

$$(\lambda \ (x) \ E_0)[x \leftarrow E] = (\lambda \ (x) \ E_0)$$

$$x[x \leftarrow E] = E$$

$$y[x \leftarrow E] = y \quad \text{where } y \neq x$$

$$(E_0\ E_1)[x \leftarrow E] = (E_0[x \leftarrow E]\ E_1[x \leftarrow E])$$

$$(\lambda\ (x)\ E_0)[x \leftarrow E] = (\lambda\ (x)\ E_0)$$

$$(\lambda\ (y)\ E_0)[x \leftarrow E] = (\lambda\ (y)\ E_0[x \leftarrow E])$$

$$\text{where } y \neq x \text{ and } y \notin FV(E)$$

β-reduction cannot occur when $y \in FV(E)$

How can you beta-reduce the following expression using capture-avoiding substitution?

```
((λ (y)
    ((λ (z) (λ (y) (z y))) y))
 (λ (x) x))
```

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((λ (y)
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```

$\downarrow \beta$

```
((λ (z) (λ (y) (z y))) (λ (x) x))
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How can you beta-reduce the following expression using capture-avoiding substitution?

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(λ (y) ((λ (z) (λ (y) z)) (λ (x) y)))
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```
(λ (y) ((λ (z) (λ (y) z)) (λ (x) y)))
```

You **cannot!** This redex would require:

```
(λ (y) z)[z ← (λ (x) y)]
```

(y is free here, so it would be captured)

How can you beta-reduce the following expression using capture-avoiding substitution?

```
(λ (y) ((λ (z) (λ (y) z)) (λ (x) y)))

→α (λ (y) ((λ (z) (λ (w) z)) (λ (x) y)))

→β (λ (y) (λ (w) (λ (x) y)))
```

Instead we alpha-convert first.

To formally define the semantics of the lambda calculus via reduction, we also need rules that will let us apply reductions **inside of** rules:

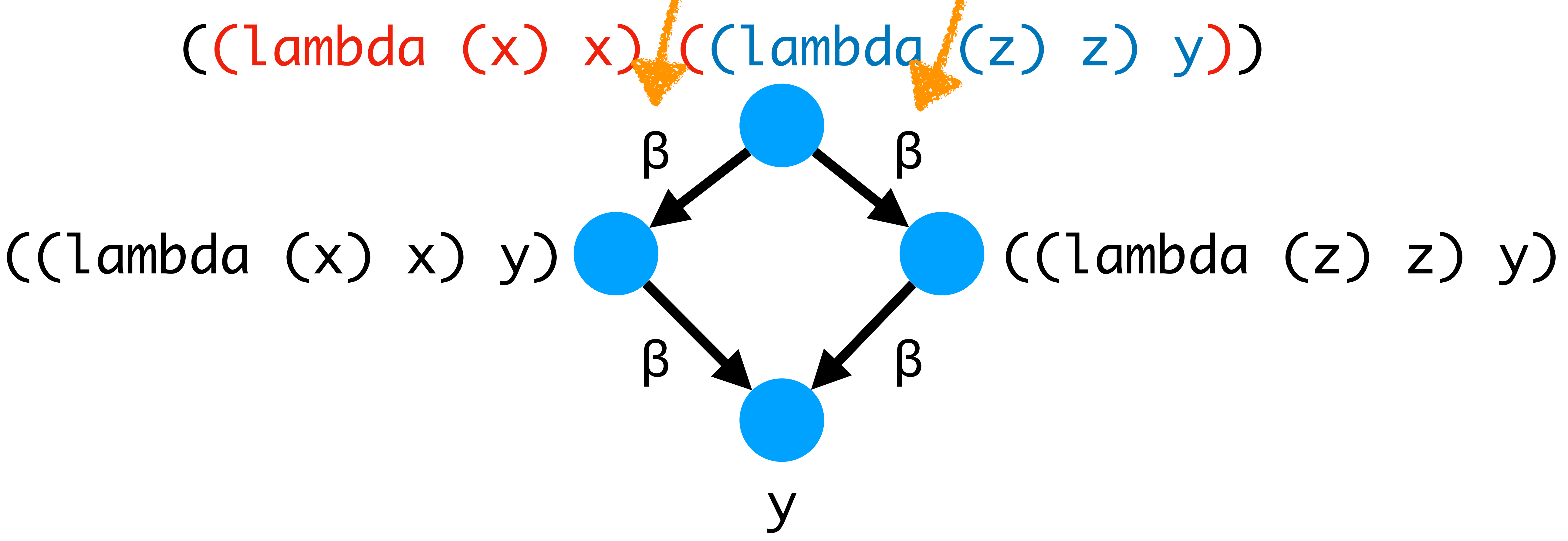
$$\alpha\ \frac{y \notin FV(e)}{(\lambda\,(x)\ e) \overset{\alpha}{\rightarrow} (\lambda\,(y)\ e[x \mapsto y])} \qquad \beta\ \frac{e' = e_b\,[x \mapsto e_1]}{\big((\lambda\,(x)\ e_b)\ e_1\big) \overset{\beta}{\rightarrow} e'}$$

$$\beta_{\mathbf{0}}\ \frac{e_0 \overset{\beta\alpha}{\rightarrow} e'}{(e_0\ e_1) \rightarrow (e'\ e_1)} \qquad \beta_{\mathbf{1}}\ \frac{e_1 \overset{\beta\alpha}{\rightarrow} e'}{(e_0\ e_1) \rightarrow (e_0\ e')}$$

$$\alpha\ \frac{y \notin FV(e)}{(\lambda\,(x)\ e) \xrightarrow{\alpha} (\lambda\,(y)\ e[x \mapsto y])} \qquad \beta\ \frac{e' = e_b\,[x \mapsto e_1]}{\big((\lambda\,(x)\ e_b)\ e_1\big) \xrightarrow{\beta} e'}$$

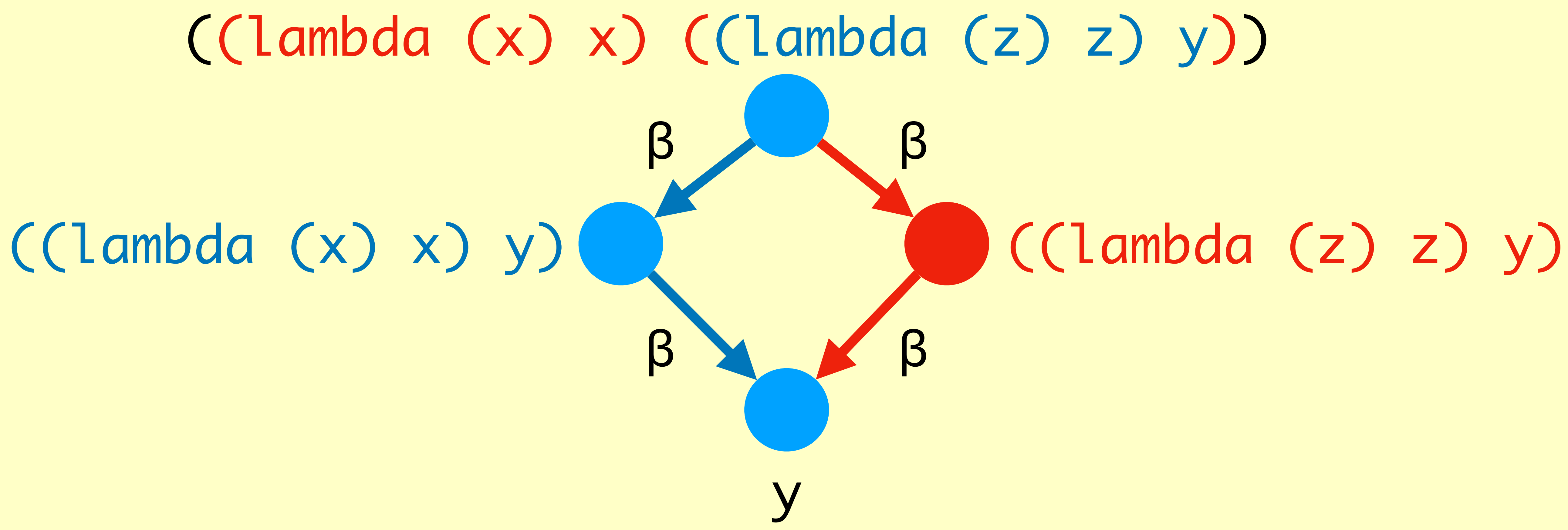
$$\beta_0\ \frac{e_0 \xrightarrow{\beta\alpha} e'}{(e_0\ e_1) \rightarrow (e'\ e_1)} \qquad \beta_1\ \frac{e_1 \xrightarrow{\beta\alpha} e'}{(e_0\ e_1) \rightarrow (e_0\ e')}$$

Recall: a term may have **multiple redexes**!



Because β and α reduction are inherently nondeterministic, we use a **reduction strategy**, which is system that tells us which reduction to apply:

- **Normal Order — Leftmost (outermost) application**
- **Applicative Order — Innermost application**



We'll talk more about these **next time**. They relate to the computational notions of **call-by-name (normal)** and **call-by-value (applicative)** η-reduction / expansion capture a property akin to extensionality

`(λ (x) (E0 x))` $\rightarrow_\eta$ `E0` where $x \notin FV(E_0)$

`E0` $\rightarrow_\eta$ `(λ (x) (E0 x))` where $x \notin FV(E_0)$

We do not use η-reduction/expansion in computation (unlike β), but it helps us establish certain equalities in lambda theories

When unambiguous, we refer to **reduction** in the lambda calculus as the application of a beta, alpha, or eta reduction:

$$(\rightarrow) = (\rightarrow_\beta) \cup (\rightarrow_\alpha) \cup (\rightarrow_\eta)$$

$$(\rightarrow^*)$$

(When necessary for exams, we will clarify…)

It is often helpful to think of applying a sequence of reductions to arrive at some final "result."

In the lambda calculus, we call these results / values "normal forms."

$$E_0 \xrightarrow{*} E_8 \xrightarrow{*} \,?$$

A **normal form** is a form that has no more possible applications of some kind of reduction…

$$E_0 \xrightarrow{*}$$

`(λ (x) … (λ (z) ((a …) …)))`

In **beta *normal form***, no function position can be a lambda; this is to say: *there are no unreduced redexes left*!

We covered a lot of material!

- Free variables
- Alpha renaming
- Beta reduction
- Eta reduction / expansion
- Capture-avoiding substitution
- Applicative / normal order

Next time: **reduction strategies and more normal forms…**