

CSC_51051_EP: Pure λ -calculus

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Part I

Introduction

Imperative programming

You are mostly used to **imperative** programming languages where programs consist in sequences of instructions and modify a state.

```
public long factorial(int n) {  
    int result = 1;  
    for (int i = 1; i <= n; i++) {  
        result = result * i;  
    }  
    return result;  
}
```

Functional programming

In **functional** programming, we manipulate functions, which can even be created on the fly:

```
let rec map f l =  
  match l with  
  | [] -> []  
  | x::l' -> (f x)::(map f l')
```

```
let double_list l =  
  map (fun x -> 2 * x) l
```

So that

```
# double_list [1; 2; 3];;  
- : int list = [2; 4; 6]
```

Functional programming

We can define the multiplication function by

```
let mult x y = x * y
```

and then define doubling with

```
let double = mult 2
```

this is thanks to Curryfication which allows partial application:

the above definition is equivalent to

```
let mult = fun x -> fun y -> x * y
```

We have seen how to describe the reduction for an imperative programming language.

How can we define this for functional programming languages?

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How can we define this for functional programming languages?

The λ -**calculus** is the core of a functional programming language:
we focus on the functional part.

It is a subject of study per se, but it can be mixed with imperative features
(e.g. OCaml).

Variable binding

When we define a function

$$f(x) = 2 \times x$$

the name of the variable x does not matter:

$$f(y) = 2 \times y$$

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We say that x is **bound** in the expression.

The relation which identifies two expressions differing only in renaming of bound variable is called α -conversion.

There are many places where this phenomenon occurs in mathematics:

$$\lim_{x \rightarrow \infty} \frac{y}{x}$$

$$\int_0^1 tx \, dt$$

$$\sum_{i=0}^n ix$$

Variable binding

This looks like a detail, but it is quite important: consider

$$f(y) = \lim_{x \rightarrow \infty} \frac{y}{x}$$

Clearly, if I replace y by any arbitrary expression t (say, $t = \ln(\sin(z))^{\sqrt{2}}$),

$$f(t) = \lim_{x \rightarrow \infty} \frac{t}{x} = 0$$

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In mathematics, this is generally implicit, but when implementing we have to explicitly take care of α -**conversion**: there is no easy way of automatically taking care of this.

Believe it or not, this is one of the most error prone issues to correctly handle.

The λ notation

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$$x \mapsto t$$

or the programming notation

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fun x -> t
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where x might occur in the term t , e.g.

$$\lambda x.(2 \times x)$$

Moreover, we will always write

$$f = \lambda x.t$$

instead of

$$f(x) = t$$

The “squaring” function can be defined as

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We can then apply the function to an argument

$$\text{square } 3$$

which will reduce to

$$3 \times 3$$

as expected.

We can also consider the function

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For this reason, application is always implicitly bracketed on the left:

$$\text{mult } 3 \ 4 = (\text{mult } 3) \ 4 \neq \text{mult } (3 \ 4)$$

We can also consider the function

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We expect $\text{mult } t$ to be multiplication by t .

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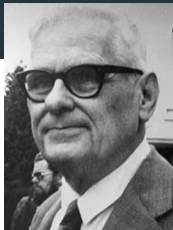
$$\text{mult } y \longrightarrow \lambda y. (y \times y)$$

but

$$\text{mult } y = (\lambda x. \lambda y. (x \times y))y = (\lambda x. \lambda z. (x \times z))y \longrightarrow \lambda z. (y \times z)$$

Part II

λ -calculus



This notation was invented by Church in the 1930s, looking for new foundations of mathematics based on functions instead of sets.

The set of λ -terms is defined by the following grammar:

$$t, u ::= x \mid t u \mid \lambda x. t$$

A λ -term is thus either

- a *variable* x ,
- an *application* $t u$,
- an *abstraction* $\lambda x. t$.

For instance,

$$\lambda x. x$$

$$(\lambda x. (xx))(\lambda y. (yx))$$

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

Conventions

By convention,

- application is associative on the left, i.e.

$$tuv = (tu)v$$

and not $t(uv)$,

- application binds more tightly than abstraction, i.e.

$$\lambda x.xy = \lambda x.(xy)$$

and not $(\lambda x.x)y$ (this says that abstraction extends as far as possible on the right),

- we sometimes group abstractions, i.e.

$$\lambda xyz.xz(yz) \quad \text{is read as} \quad \lambda x.\lambda y.\lambda z.xz(yz)$$

Bound and free variables

We write $FV(t)$ for the set of **free variables** of t , i.e. those which are not bound by a λ .

For instance,

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

$$FV((\lambda x. x)x) =$$

$$FV((\lambda x. x)(\lambda y. y)) =$$

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Formally,

$$FV(x) =$$

$$FV(t u) =$$

$$FV(\lambda x. t) =$$

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Formally,

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$$FV(\lambda x. t) = FV(t) \setminus \{x\}$$

Two terms are α -**equivalent** when they only differ by renaming of bound variables.

In a subterm, of the form $\lambda x.t$, we can rename x to y only if $y \notin FV(t)$.

For instance,

$$(\lambda x.xxy)t \equiv_{\alpha} (\lambda z.zzy)t \not\equiv_{\alpha} (\lambda y.yyy)t$$

In the following terms are always considered up to α -equivalence.

Substitution

Substitution

We write $t[u/x]$ for the term t where all *free* occurrences of x have been replaced by u .

$$x[u/x] = u$$

$$y[u/x] = y$$

if $y \neq x$

$$(t_1 t_2)[u/x] = (t_1[u/x]) (t_2[u/x])$$

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

For instance,

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

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$$(\lambda x. t)[u/x] = \lambda x. t$$

(simple but useful optimization)

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For instance,

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β -reduction

The notion of “execution” for λ -terms is given by β -reduction.

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- Reduction can create β -redexes:

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- Reduction can duplicate β -redexes:

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

- Reduction can erase β -redexes:

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

- Reduction can create β -redexes:

$$(\lambda x.xx)(\lambda y.y) \longrightarrow_{\beta} (\lambda y.y)(\lambda y.y)$$

- Reduction can duplicate β -redexes:

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

- Reduction can erase β -redexes:

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

- Some terms cannot reduce, **normal forms**:

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

- Some terms cannot reduce, **normal forms**:

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

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- Some terms reduce in multiple ways:

$$\beta \longleftarrow (\lambda xy. y)((\lambda x. x)(\lambda x. x)) \longrightarrow_{\beta}$$

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A β -reduction path is a sequence of β -reduction steps:

$$t \xrightarrow{*}_{\beta} u \quad = \quad t \longrightarrow_{\beta} t_1 \longrightarrow_{\beta} t_2 \longrightarrow_{\beta} \dots \longrightarrow_{\beta} u$$

(by which we mean that there exists terms t_i with the above reductions)

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The number of β -reduction steps is called the **length** of the path.

A reasonable programming language should be “deterministic”
or at least “reasonably predictable”.

How can we formalize this property?

Confluence

A fundamental property of β -reduction is that we can always make two reductions from the same term converge.

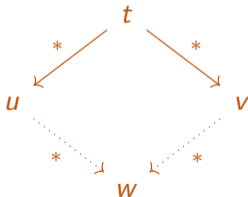
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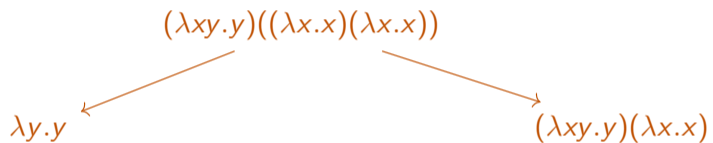
Theorem (Confluence)

Given a term t such that $t \xrightarrow{*}_{\beta} u$ and $t \xrightarrow{*}_{\beta} v$

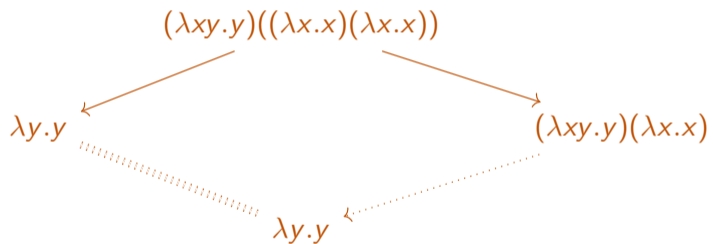
there exists a term w such that $u \xrightarrow{*}_{\beta} w$ and $v \xrightarrow{*}_{\beta} w$:



For instance,



For instance,



β -equivalence

The β -equivalence \equiv_{β} is the smallest equivalence relation containing \rightarrow_{β} .

Two terms t and u are β -equivalent if there exists a sequence of reductions

$$t \equiv_{\beta} u \quad = \quad t \xleftarrow{*} t_1 \xrightarrow{*} t_2 \xleftarrow{*} t_3 \xrightarrow{*} t_4 \xleftarrow{*} \dots \xrightarrow{*} u$$

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Two terms t and u are β -equivalent iff

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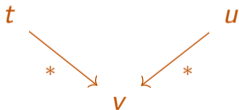
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From confluence,

Theorem (Church-Rosser)

Two terms t and u are β -equivalent iff there exists v such that $t \xrightarrow{*}_{\beta} v$ and $u \xrightarrow{*}_{\beta} v$:



Another equivalence

This is not the only interesting notion of equivalence.

The η -equivalence \equiv_{η} is the smallest congruence such that, for every term t ,

$$t \equiv_{\eta} \lambda x. t x$$

when $x \notin \text{FV}(t)$.

For instance, in OCaml

$$\text{sin} \equiv_{\eta} \text{fun } x \text{ -> sin } x$$

We will not insist much on it in the following, but we will see that two such functions can behave differently in languages such as OCaml (but not in λ -calculus).

How difficult is it to decide whether two terms are β -equivalent?

Part III

Expressive power

Let's see what we can compute
within
the pure λ -calculus.

We define the **identity** by

$$I =$$

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$$I = \lambda x.x$$

Identity

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It satisfies

$$I t \longrightarrow_{\beta} t$$

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Booleans

The **booleans** can be encoded as the two projections

$$T = \lambda xy.x$$

$$F = \lambda xy.y$$

Conditional branching can be encoded as

$$\text{if} =$$

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$$\mathbf{if} = \lambda bxy.b x y$$

Namely,

$$\mathbf{if} \mathbf{T} t u \xrightarrow{*} \beta$$

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There are other possible implementations, e.g.

$$\text{and} = \lambda xy.x \ y \ x$$

(not β -equivalent, note that behavior is only specified on booleans)

Pairs

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pair =

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$$\text{pair } t \ u \xrightarrow{*}_{\beta} \lambda b.\text{if } b \ t \ u$$

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It is not much more difficult to encode tuples.

Natural numbers

The n -th Church numeral is the λ -term

$$\underline{n} = \lambda fx.f^n x = \lambda fx.f(f(\dots(fx)))$$

so that

$$\underline{0} = \lambda fx.x \quad \underline{1} = \lambda fx.fx \quad \underline{2} = \lambda fx.f(fx) \quad \underline{3} = \lambda fx.f(f(fx)) \quad \dots$$

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mul =

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and the test at zero:

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We can also program the predecessor

pred =

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We can also program the predecessor

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(see in TD) and thus subtraction by

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In order to be able to program more full-fledged programs, we need to be able to define recursive functions.

For instance,

```
let rec fact n =  
  if n = 0 then 1 else n * fact (n-1)
```

Fixpoints

In mathematics, a **fixpoint** of a function $f : A \rightarrow A$ is an element $a \in A$ such that

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A distinguishing feature of λ -calculus is that

- every program admits a fixpoint,
- this fixpoint can be computed within λ -calculus.

This means that there is a term Y such that

$$t(Y t) \equiv_{\beta} Y t$$

This can be used to program recursive functions!

How do we program a fixpoint operator in OCaml?

$$t(Y t) \quad \equiv_{\beta} \quad Y t$$

How do we program a fixpoint operator in OCaml?

$$Y t \longrightarrow_{\beta} t (Y t)$$

How do we program a fixpoint operator in OCaml?

```
fix t = t (fix t)
```

Fixpoints

In OCaml, we can program a fixpoint operator with (by definition)

```
let rec fix f = f (fix f)
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fix fact_fun 0
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fact_fun (fix fact_fun) 0
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Fixpoints

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let rec fix f = f (fix f)
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For instance `fact 0` is

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For instance `fact 1` is

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1 * fix fact_fun 0
```

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```
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Problem solved:

```
# fact 5;;  
- : int = 120
```

(by an η -expansion!...)

Fixpoints

This translates directly as

$$\text{fact} = Y(\lambda fn. \text{if } (\text{iszero } n) \underline{1} (\text{mul } n (f (\text{pred } n))))$$

The factorial of 2 computes as

$$\begin{aligned} \text{fact } \underline{2} &= (YF) \underline{2} \\ &\xrightarrow{*}_{\beta} F (YF) \underline{2} \\ &\xrightarrow{*}_{\beta} \text{if } (\text{iszero } \underline{2}) \underline{1} (\text{mul } \underline{2} ((YF) (\text{pred } \underline{2}))) \\ &\xrightarrow{*}_{\beta} \text{if } \text{false } \underline{1} (\text{mul } \underline{2} ((YF) (\text{pred } \underline{2}))) \\ &\xrightarrow{*}_{\beta} \text{mul } \underline{2} ((YF) (\text{pred } \underline{2})) \\ &\xrightarrow{*}_{\beta} \text{mul } \underline{2} ((YF) \underline{1}) \\ &\vdots \\ &\xrightarrow{*}_{\beta} \text{mul } \underline{2} (\text{mul } \underline{1} \underline{1}) \xrightarrow{*}_{\beta} \underline{2} \end{aligned}$$

Fixpoints

```
((λf.(λx.(f (x x))) (λx.(f (x x)))) (λf.(λn.(((λb.(λx.(λy.((b x) y))) ((λn.(λx.(λy.((n (λz.y)) x))) n))
→ (λf.(λx.(f x))) (((λm.(λn.(λf.(λx.((m (n f)) x)))) n) (f ((λn.((λp.(p (λx.(λy.x)))) (n
→ (λp.(((λx.(λy.(λb.(((λb.(λx.(λy.((b x) y))) b) x) y))) ((λp.(p (λx.(λy.y)))) p)) ((λn.(λf.(λx.((n f) (f x))))
→ ((λp.(p (λx.(λy.y)))) p)))) ((λx.(λy.(λb.(((λb.(λx.(λy.((b x) y))) b) x) y))) (λf.(λx.x)) (λf.(λx.x))))))
→ n)))))) (λf.(λx.(f (f x))))
-> (((λx.((λf.(λn.(((λb.(λx.(λy.((b x) y))) ((λn.(λx.(λy.((n (λz.y)) x))) n)) (λf.(λx.(f x))))
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→ (((λx.(λy.(λb.(((λb.(λx.(λy.((b x) y))) b) x) y))) (λf.(λx.x)) (λf.(λx.x)))) n)))))) (x x))
→ (λx.((λf.(λn.(((λb.(λx.(λy.((b x) y))) ((λn.(λx.(λy.((n (λz.y)) x))) n)) (λf.(λx.(f x)))) ((λm.(λn.(λf.(λx.((m
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.
.
.
-> (λf.(λx.(f (((λx.x) (λf.(λx.(f x))) f) x))))
-> (λf.(λx.(f (((λf.(λx.(f x))) f) x))))
-> (λf.(λx.(f ((λx.(f x)) x)))
-> (λf.(λx.(f (f x))))
333 steps
```

We can also write unbounded loops:

```
let rec min_from p n =  
  if p n then n else min_from p (n+1)
```

```
let min p = min_from p 0
```

```
let x = min (fun n -> n - 10 = 0)
```

Fixpoints

We can also write unbounded loops:

```
let min_from_fun f p n =  
  if p n then n else f p (n+1)
```

```
let min_from = fix min_from_fun
```

```
let min p = min_from p 0
```

```
let x = min (fun n -> n - 10 = 0)
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We thus have

- natural numbers,
- the successor function,
- tuples and projections,
- composition,
- conditional branching with test to zero,
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We thus have **recursive functions!**

This should convince you that the λ -calculus is **Turing complete**.

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Theorem

The following decision problems are undecidable:

- *whether two λ -terms are β -equivalent,*
- *whether a λ -term can reduce to a normal form.*

... excepting

... excepting that we have not explained how to define a **fixpoint combinator** Y yet.

Fixpoints

...excepting that we have not explained how to define a **fixpoint combinator** Y yet.

The OCaml implementation

```
let rec fix f x = f (fix f) x
```

does not translate to λ -calculus because it is not an anonymous function:

```
let fix = fun f -> ???
```

Any guess?

Fixpoints

We can start by recalling that we had a non-terminating term:

$$\Omega = (\lambda x.xx)(\lambda x.xx) \longrightarrow_{\beta} (\lambda x.xx)(\lambda x.xx) \longrightarrow_{\beta} \dots$$

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\uparrow
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i.e.

$$Y f \equiv_{\beta} f(Y f)$$

Fixpoints

Note that computing fixpoints can loop:

$$Y f \xrightarrow{*} \beta f (Y f) \xrightarrow{*} \beta f (f (Y f)) \xrightarrow{*} \beta \dots$$

So that our implementation of factorial can loop
(this is what was happening in OCaml).

However, programming languages implement a **reduction strategy**, i.e. a particular way of β -reducing programs.

If we choose a decent one, the factorial will compute the factorial.

Fixpoints

Does this work in practice (= OCaml)?

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```

Namely, `x x` means that

- `x` is a function: of type `'a -> 'b`,
- that `'a = 'a -> 'b`

i.e. the type of `x` should be

```
... -> 'b -> 'b -> 'b -> 'b
```

Fixpoints

There are ways to get around this, one being to use the option `-rectypes` of OCaml (which allows types such as `('a -> 'b) as 'a`):

```
let fix = fun f -> (fun x -> f (x x) ) (fun x -> f (x x) )
```

has type

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('a -> 'a) -> 'a
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Problem:

Stack overflow during evaluation (looping recursion?).

We can use the same trick as before.

Fixpoints

There are ways to get around this, one being to use the option `-rectypes` of OCaml (which allows types such as `('a -> 'b) as 'a`):

```
let fix = fun f -> (fun x y -> f (x x) y) (fun x y -> f (x x) y)
```

has type

```
(('a -> 'b) -> 'a -> 'b) -> 'a -> 'b
```

and we define

```
let fact_fun f n = if n = 0 then 1 else n * f (n - 1)
```

```
let fact = fix fact_fun
```

Problem solved:

```
# fact 5;;
```

```
- : int = 120
```

Fixpoints

If you (understandably) don't feel comfortable with `-rectypes`:

```
type 'a t = Arr of ('a t -> 'a)
```

```
let arr (Arr f) = f
```

```
let fix = fun f -> (fun x y -> f (arr x x) y)  
                (Arr (fun x y -> f (arr x x) y))
```

```
let fact_fun f n = if n = 0 then 1 else n * f (n - 1)
```

```
let fact = fix fact_fun
```

```
let n = fact 5
```


More primitives: products

In practice (= OCaml), one does not encode everything in *pure* λ -calculus, but rather adds more primitives. For instance, **products** can be added with

$$t, u ::= x \mid t u \mid \lambda x. t \mid \langle t, u \rangle \mid \pi_l \mid \pi_r$$

with additional reduction rules

$$\pi_l \langle t, u \rangle \longrightarrow_{\beta} t$$

$$\pi_r \langle t, u \rangle \longrightarrow_{\beta} u$$

and similarly for other constructions.

Reduction strategies

We have seen that the way reduction is implemented has an influence.

The main choice roughly is, for

$$(\lambda x.t)u$$

to either

- reduce u to \hat{u} and then reduce $t[\hat{u}/x]$ (*call-by-value*):
- reduce $t[u/x]$ (*call-by-name*):

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- reduce u to \hat{u} and then reduce $t[\hat{u}/x]$ (*call-by-value*):
more efficient since we compute arguments once,
- reduce $t[u/x]$ (*call-by-name*):
not sensitive to divergence of arguments, e.g. $(\lambda xy.y)\Omega!$.

Part IV

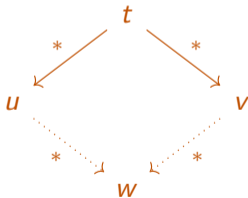
Confluence

We have announced the confluence theorem:

Theorem (Confluence)

Given a term t such that $t \xrightarrow{*}_{\beta} u$ and $t \xrightarrow{*}_{\beta} v$

there exists a term w such that $u \xrightarrow{*}_{\beta} w$ and $v \xrightarrow{*}_{\beta} w$:

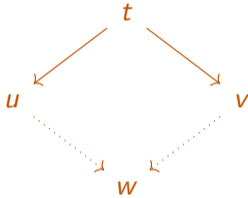


What could be a proof strategy to show confluence?

(clearly, we cannot consider all coinital pairs of reduction paths)

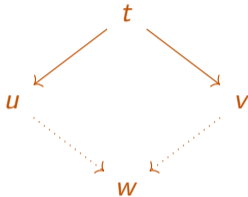
Showing confluence: the diamond property

Maybe we can show that has the **diamond property**:

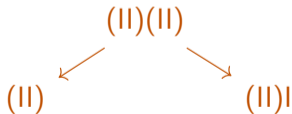


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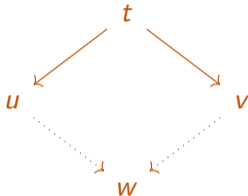


For instance,

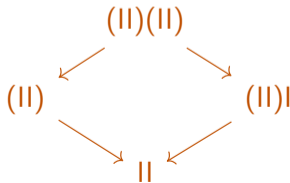


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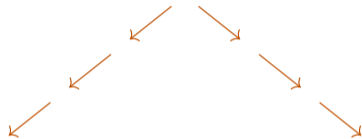


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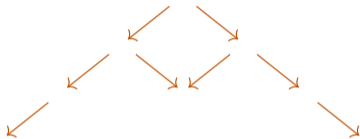
We can then easily conclude to confluence:



Note that this is done by using two recurrences.

Showing confluence: the diamond property

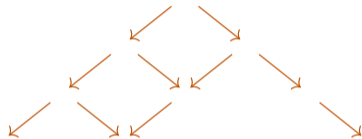
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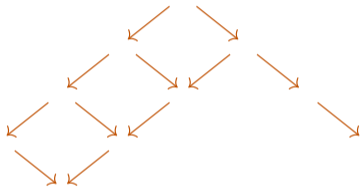
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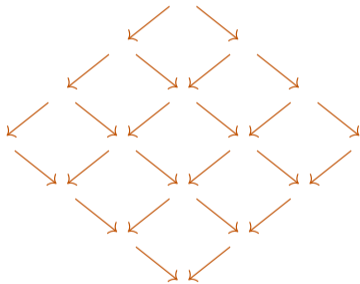
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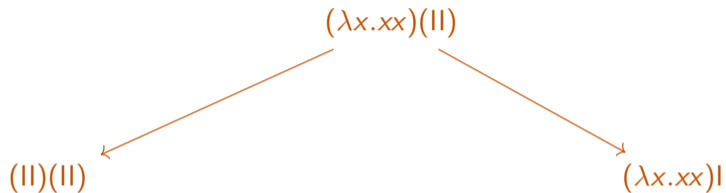
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Showing confluence: the diamond property

Excepting that λ -calculus does not satisfy the diamond property:

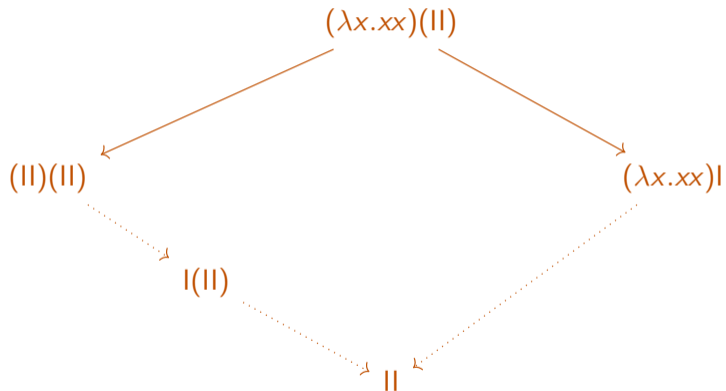
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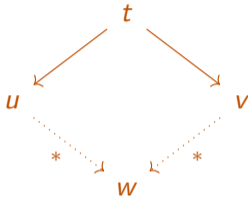
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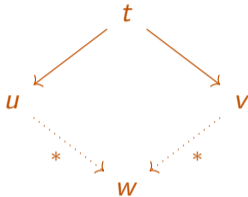
Showing confluence: local confluence

By case analysis, we can show **local confluence**:

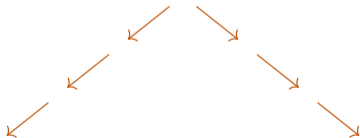


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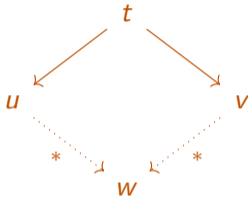


from which we should be able to deduce confluence:

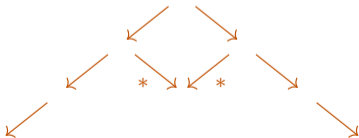


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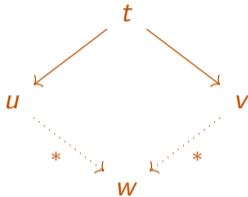


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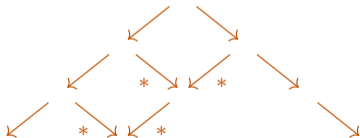


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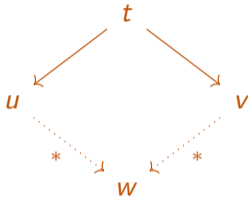


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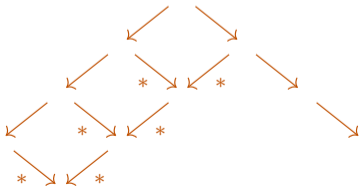


Showing confluence: local confluence

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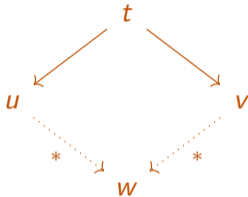


from which we should be able to deduce confluence:

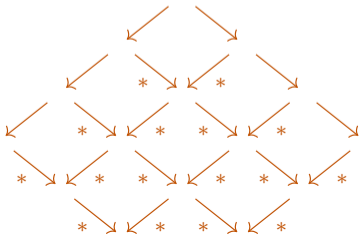


Showing confluence: local confluence

By case analysis, we can show **local confluence**:

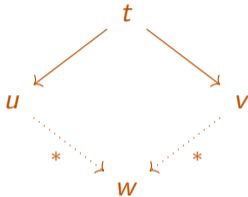


from which we should be able to deduce confluence:



Showing confluence: local confluence

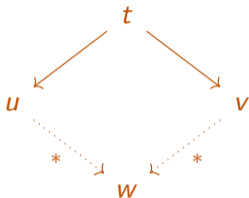
By case analysis, we can show **local confluence**:



from which we cannot deduce confluence. Why?

Showing confluence: local confluence

By case analysis, we can show **local confluence**:



but this does not imply confluence.

Namely, the following situation



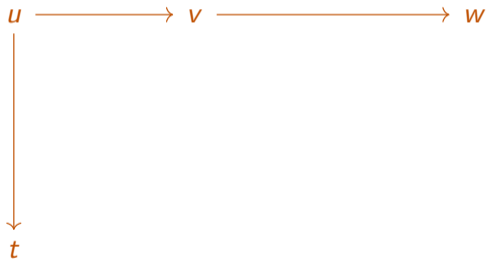
is locally confluent but not confluent.

Showing confluence: local confluence

With



we have

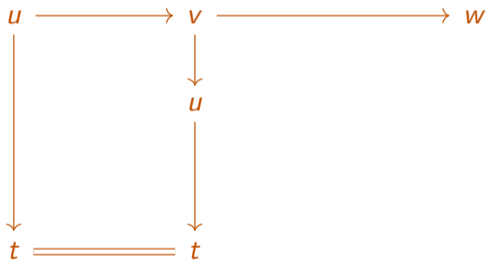


Showing confluence: local confluence

With



we have



Showing confluence: local confluence

With

$$t \longleftarrow u \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} v \longrightarrow w$$

we have

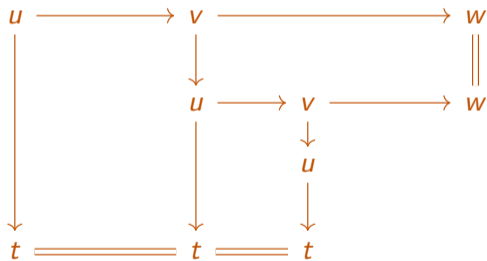
$$\begin{array}{ccccc} u & \longrightarrow & v & \longrightarrow & w \\ \downarrow & & \downarrow & & \parallel \\ & & u & \longrightarrow & v \longrightarrow w \\ \downarrow & & \downarrow & & \\ t & \equiv & t & & \end{array}$$

Showing confluence: local confluence

With



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Showing confluence: local confluence

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$$t \longleftarrow u \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} v \longrightarrow w$$

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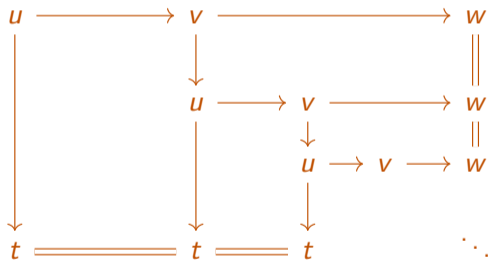
$$\begin{array}{ccccc} u & \longrightarrow & v & \longrightarrow & w \\ \downarrow & & \downarrow & & \parallel \\ & & u & \longrightarrow & v \longrightarrow w \\ & & \downarrow & & \parallel \\ & & u & \longrightarrow & v \longrightarrow w \\ \downarrow & & \downarrow & & \downarrow \\ t & \longleftarrow & t & \longleftarrow & t \end{array}$$

Showing confluence: local confluence

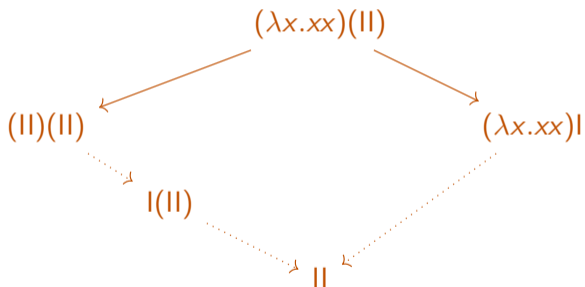
With

$$t \longleftarrow u \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} v \longrightarrow w$$

we have



The idea is to use an auxiliary reduction, which does have the diamond property and whose confluence implies the one of β -reduction.



The β -reduction

The β -reduction consists in replacing a subterm

$$(\lambda x.t) u \longrightarrow_{\beta} t[u/x]$$

The β -reduction

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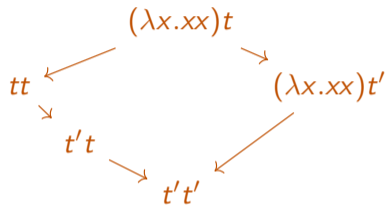
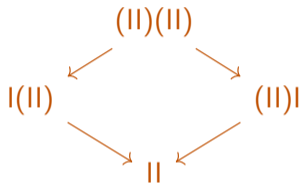
$$(\lambda x.t) u \longrightarrow_{\beta} t[u/x]$$

This thus is the smallest relation such that

$$\frac{}{(\lambda x.t)u \longrightarrow_{\beta} t[u/x]} \quad \frac{t \longrightarrow_{\beta} t'}{\lambda x.t \longrightarrow_{\beta} \lambda x.t'} \quad \frac{t \longrightarrow_{\beta} t'}{tu \longrightarrow_{\beta} t'u} \quad \frac{u \longrightarrow_{\beta} u'}{tu \longrightarrow_{\beta} tu'}$$

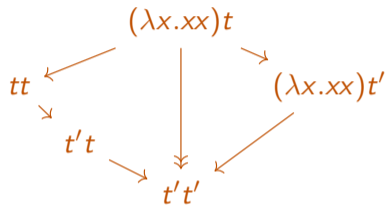
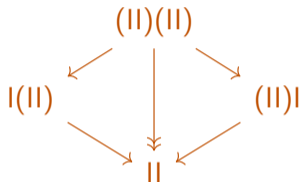
The parallel β -reduction

We would like to allow multiple reductions in parallel, e.g.



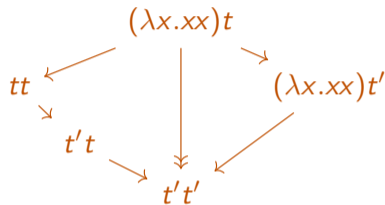
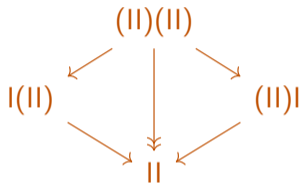
The parallel β -reduction

We would like to allow multiple reductions in parallel, e.g.



The parallel β -reduction

We would like to allow multiple reductions in parallel, e.g.



We define the **parallel β -reduction** as

$$\frac{}{x \twoheadrightarrow x}$$

$$\frac{t \twoheadrightarrow t' \quad u \twoheadrightarrow u'}{(\lambda x.t)u \twoheadrightarrow t'[u'/x]}$$

$$\frac{t \twoheadrightarrow t' \quad u \twoheadrightarrow u'}{tu \twoheadrightarrow t'u'}$$

$$\frac{t \twoheadrightarrow t'}{\lambda x.t \twoheadrightarrow \lambda x.t'}$$

The parallel β -reduction

The parallel β -reduction thus allows to perform multiple reductions in parallel:

Lemma

If $t \twoheadrightarrow u$ then $t \xrightarrow{}_{\beta} u$.*

The parallel β -reduction

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Lemma

If $t \twoheadrightarrow u$ then $t \twoheadrightarrow_{\beta}^ u$.*

Note that this does not mean that we can always go to a normal form in one step, because some reductions are created by other:

$$(\lambda x.xx)(\lambda y.y) \twoheadrightarrow (\lambda y.y)(\lambda y.y)$$

The parallel β -reduction

The parallel β -reduction thus allows to perform multiple reductions in parallel:

Lemma

If $t \longrightarrow^ u$ then $t \longrightarrow_{\beta}^* u$.*

Conversely, any β -reduction step is in particular, one β -reduction step in “parallel”:

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If $t \longrightarrow_{\beta} u$ then $t \longrightarrow^ u$.*

The parallel β -reduction

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If $t \longrightarrow u$ then $t \xrightarrow{} \rightarrow_{\beta} u$.*

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If $t \xrightarrow{} \rightarrow_{\beta} u$ then $t \longrightarrow u$.*

Therefore,

Lemma

We have $t \xrightarrow{} \rightarrow_{\beta} u$ iff $t \xrightarrow{*} u$.*

The parallel β -reduction

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If $t \rightarrow_{\beta} u$ then $t \twoheadrightarrow u$.

Therefore,

Lemma

We have $t \xrightarrow{} \rightarrow_{\beta} u$ iff $t \twoheadrightarrow u$.*

Proof.

$$\begin{aligned} t \xrightarrow{*} \rightarrow_{\beta} u &= t \rightarrow_{\beta} t_1 \rightarrow_{\beta} t_2 \rightarrow_{\beta} \dots \rightarrow_{\beta} u \\ &= t \twoheadrightarrow t_1 \twoheadrightarrow t_2 \twoheadrightarrow \dots \twoheadrightarrow u \end{aligned}$$

The parallel β -reduction

The parallel β -reduction thus allows to perform multiple reductions in parallel:

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Conversely, any β -reduction step is in particular, one β -reduction step in “parallel”:

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If $t \xrightarrow{\beta} u$ then $t \longrightarrow^ u$.*

Therefore,

Lemma

We have $t \xrightarrow{}_\beta u$ iff $t \longrightarrow^* u$.*

Proof.

$$\begin{aligned} t \xrightarrow{*} u &= t \longrightarrow t_1 \longrightarrow t_2 \longrightarrow \dots \longrightarrow u \\ &= t \xrightarrow{\beta} t_1 \xrightarrow{\beta} t_2 \xrightarrow{\beta} \dots \xrightarrow{\beta} u \end{aligned}$$

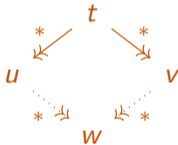


Parallel β -reduction: confluence

Our goal is to show:

Theorem

The parallel β -reduction is confluent: if $t \xrightarrow{} u$ and $t \xrightarrow{*} v$ then there exists w such that $u \xrightarrow{*} w$ and $v \xrightarrow{*} w$.*

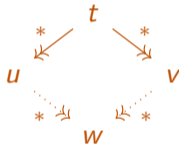


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Corollary

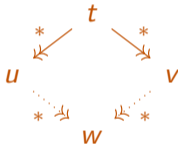
The β -reduction is confluent.

Parallel β -reduction: confluence

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Corollary

The β -reduction is confluent.

We first need some lemmas.

Parallel β -reduction: reflexivity

Lemma

For every term t , we have $t \longrightarrow t$.

Proof.

By induction on the term t :

$$\frac{}{x \longrightarrow x} \quad \frac{t \longrightarrow t' \quad u \longrightarrow u'}{(\lambda x.t)u \longrightarrow t'[u'/x]} \quad \frac{t \longrightarrow t' \quad u \longrightarrow u'}{tu \longrightarrow t'u'} \quad \frac{t \longrightarrow t'}{\lambda x.t \longrightarrow \lambda x.t'}$$

□

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

We recall that the rules defining parallel β -reduction are

$$\frac{}{x \longrightarrow x} \quad \frac{t_1 \longrightarrow t'_1 \quad t_2 \longrightarrow t'_2}{(\lambda x. t_1) t_2 \longrightarrow t'_1[t'_2/x]} \quad \frac{t_1 \longrightarrow t'_1 \quad t_2 \longrightarrow t'_2}{t_1 t_2 \longrightarrow t'_1 t'_2} \quad \frac{t_1 \longrightarrow t'_1}{\lambda x. t_1 \longrightarrow \lambda x. t'_1}$$

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

If $t = x$ and we used

$$\frac{}{x \longrightarrow x}$$

we have

$$t[u/x] = u \longrightarrow u' = t'[u'/x]$$

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

If $t = y \neq x$ and we used

$$\frac{}{y \longrightarrow y}$$

we have

$$t[u/x] = y \longrightarrow y = t'[u'/x]$$

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

If $t = (\lambda y.t_1)t_2$ with $y \neq x$ and we used

$$\frac{t_1 \longrightarrow t'_1 \quad t_2 \longrightarrow t'_2}{(\lambda y.t_1)t_2 \longrightarrow t'_1[t'_2/y]}$$

we have $t[u/x] = (\lambda y.t_1[u/x])t_2[u/x] \longrightarrow t'_1[u'/x][t'_2[u'/x]/y] = t'[u'/x]$

since, using induction hypothesis,

$$\frac{t_1[u/x] \longrightarrow t'_1[u'/x] \quad t_2[u/x] \longrightarrow t'_2[u'/x]}{(\lambda y.t_1[u/x])t_2[u/x] \longrightarrow t'_1[u'/x][t'_2[u'/x]/y}}$$

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

If $t = t_1 t_2$ and we used

$$\frac{t_1 \longrightarrow t'_1 \quad t_2 \longrightarrow t'_2}{t_1 t_2 \longrightarrow t'_1 t'_2}$$

we have $t[u/x] = (t_1[u/x])(t_2[u/x]) \longrightarrow (t'_1[u'/x])(t'_2[u'/x]) = t'[u'/x]$

since, using the induction hypothesis,

$$\frac{t_1[u/x] \longrightarrow t'_1[u'/x] \quad t_2[u/x] \longrightarrow t'_2[u'/x]}{(t_1[u/x])(t_2[u/x]) \longrightarrow (t'_1[u'/x])(t'_2[u'/x])}$$

Parallel β -reduction and substitution

Lemma

If $t \longrightarrow t'$ and $u \longrightarrow u'$ then $t[u/x] \longrightarrow t'[u'/x]$.

Proof.

By induction on the derivation of $t \longrightarrow t'$.

If $t = \lambda y.t_1$ with $y \neq x$ and we used

$$\frac{t_1 \longrightarrow t'_1}{\lambda y.t_1 \longrightarrow \lambda y.t'_1}$$

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since, using the induction hypothesis,

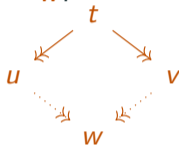
$$\frac{t_1[u/x] \longrightarrow t'_1[u'/x]}{\lambda y.t_1[u/x] \longrightarrow \lambda y.t'_1[u'/x]}$$

□

Parallel β -reduction: diamond property

Theorem

The parallel β -reduction has the **diamond property**: if $t \twoheadrightarrow u$ and $t \twoheadrightarrow v$ then there exists w such that $u \twoheadrightarrow w$ and $v \twoheadrightarrow w$.



Proof.

By induction on the derivation of $t \twoheadrightarrow u$.

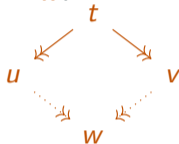
We recall that the rules defining parallel β -reduction are

$$\frac{}{x \twoheadrightarrow x} \quad \frac{t_1 \twoheadrightarrow t'_1 \quad t_2 \twoheadrightarrow t'_2}{(\lambda x. t_1) t_2 \twoheadrightarrow t'_1[t'_2/x]} \quad \frac{t_1 \twoheadrightarrow t'_1 \quad t_2 \twoheadrightarrow t'_2}{t_1 t_2 \twoheadrightarrow t'_1 t'_2} \quad \frac{t_1 \twoheadrightarrow t'_1}{\lambda x. t_1 \twoheadrightarrow \lambda x. t'_1}$$

Parallel β -reduction: diamond property

Theorem

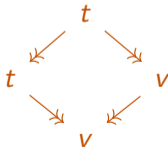
The parallel β -reduction has the **diamond property**: if $t \twoheadrightarrow u$ and $t \twoheadrightarrow v$ then there exists w such that $u \twoheadrightarrow w$ and $v \twoheadrightarrow w$.



Proof.

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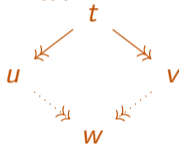
If the reduction is $t = x \twoheadrightarrow x = u$ then we conclude immediately with



Parallel β -reduction: diamond property

Theorem

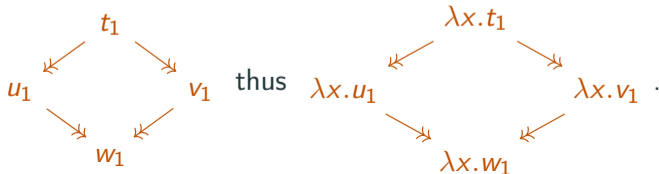
The parallel β -reduction has the **diamond property**: if $t \twoheadrightarrow u$ and $t \twoheadrightarrow v$ then there exists w such that $u \twoheadrightarrow w$ and $v \twoheadrightarrow w$.



Proof.

By induction on the derivation of $t \twoheadrightarrow u$.

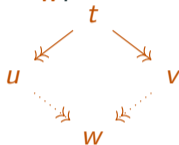
If the reduction is $\frac{t_1 \twoheadrightarrow u_1}{\lambda x. t_1 \twoheadrightarrow \lambda x. u_1}$ then the other one is $\frac{t_1 \twoheadrightarrow v_1}{\lambda x. t_1 \twoheadrightarrow \lambda x. v_1}$ and we have



Parallel β -reduction: diamond property

Theorem

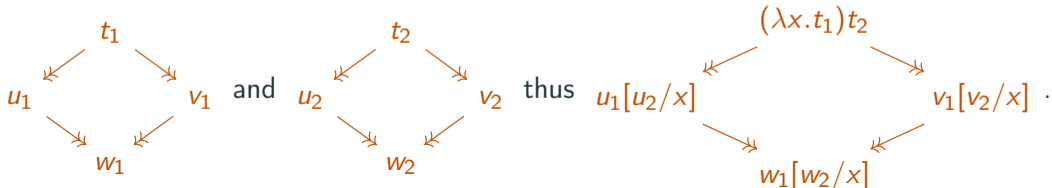
The parallel β -reduction has the **diamond property**: if $t \twoheadrightarrow u$ and $t \twoheadrightarrow v$ then there exists w such that $u \twoheadrightarrow w$ and $v \twoheadrightarrow w$.



Proof.

By induction on the derivation of $t \twoheadrightarrow u$.

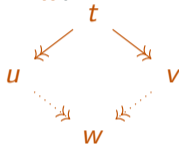
If the reduction is $\frac{t_1 \twoheadrightarrow u_1 \quad t_2 \twoheadrightarrow u_2}{(\lambda x. t_1)t_2 \twoheadrightarrow u_1[u_2/x]}$ and the other is $\frac{t_1 \twoheadrightarrow v_1 \quad t_2 \twoheadrightarrow v_2}{(\lambda x. t_1)t_2 \twoheadrightarrow v_1[v_2/x]}$ then



Parallel β -reduction: diamond property

Theorem

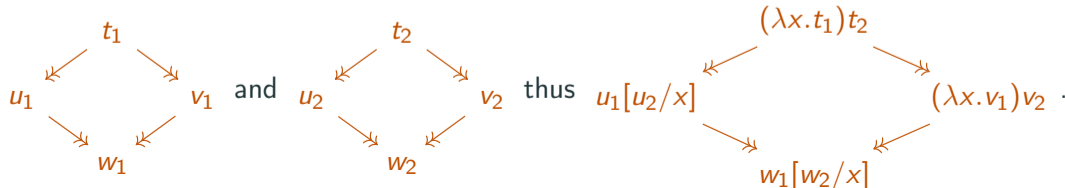
The parallel β -reduction has the **diamond property**: if $t \twoheadrightarrow u$ and $t \twoheadrightarrow v$ then there exists w such that $u \twoheadrightarrow w$ and $v \twoheadrightarrow w$.



Proof.

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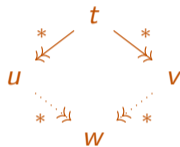
If $\frac{t_1 \twoheadrightarrow u_1 \quad t_2 \twoheadrightarrow u_2}{(\lambda x. t_1) t_2 \twoheadrightarrow u_1[u_2/x]}$ and $\frac{\lambda x. t_1 \twoheadrightarrow \lambda x. v_1 \quad t_2 \twoheadrightarrow v_2}{(\lambda x. t_1) t_2 \twoheadrightarrow (\lambda x. v_1) v_2}$ then



Parallel β -reduction: confluence

Theorem

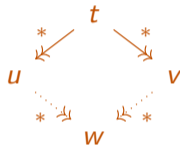
The parallel β -reduction is confluent: if $t \xrightarrow{*} u$ and $t \xrightarrow{*} v$ then there exists w such that $u \xrightarrow{*} w$ and $v \xrightarrow{*} w$.



Parallel β -reduction: confluence

Theorem

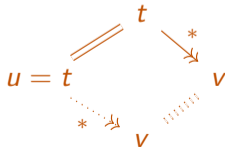
The parallel β -reduction is confluent: if $t \xrightarrow{*} u$ and $t \xrightarrow{*} v$ then there exists w such that $u \xrightarrow{*} w$ and $v \xrightarrow{*} w$.



Proof.

By induction on the length of the reduction $t \xrightarrow{*} u$.

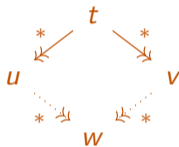
- If the length is zero then this is immediate:



Parallel β -reduction: confluence

Theorem

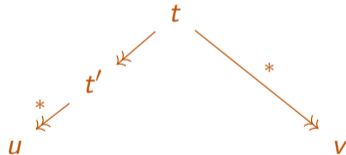
The parallel β -reduction is confluent: if $t \xrightarrow{*} u$ and $t \xrightarrow{*} v$ then there exists w such that $u \xrightarrow{*} w$ and $v \xrightarrow{*} w$.



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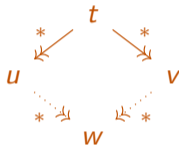
- Otherwise,



Parallel β -reduction: confluence

Theorem

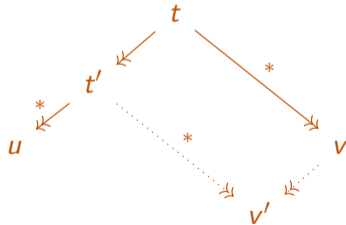
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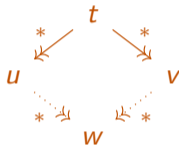
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Parallel β -reduction: confluence

Theorem

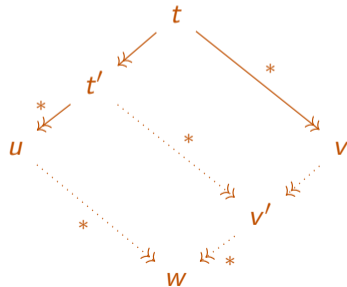
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- Otherwise,



Part V

De Bruijn indices

Again, α -conversion (renaming of bound variables) is one of the greatest source of bugs and problems.

An idea to eliminate the need for renaming is consists in having a convention for naming variables.

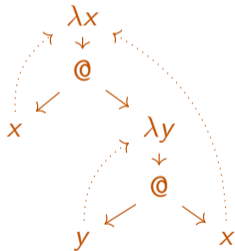
De Bruijn indices



In a closed term, such as

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

every variable is bound by some λ -abstract above:



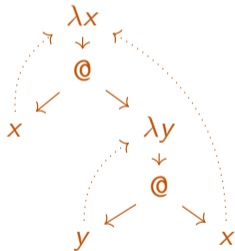
De Bruijn indices



In a closed term, such as

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

every variable is bound by some λ -abstract above:



The **de Bruijn convention**: replace every variable by the number of λ s to jump over

$$\lambda.0(\lambda.01)$$

De Bruijn indices

We now consider λ -terms generated by the grammar

$$t, u ::= i \mid tu \mid \lambda.t$$

where $i \in \mathbb{N}$ is a **de Bruijn index**.

Again, an index i means the variable declared by the i -th λ above.

De Bruijn indices

We now consider λ -terms generated by the grammar

$$t, u ::= i \mid t u \mid \lambda. t$$

where $i \in \mathbb{N}$ is a **de Bruijn index**.

Again, an index i means the variable declared by the i -th λ above.

If there are not enough λ s, then it is a free variable:

$$\lambda x. x x_0 x_2 \quad \text{becomes} \quad \lambda. 0 1 3$$

(we can assume that the free variables are $\{x_0, \dots, x_{k-1}\}$)

The rule for β -reduction is the usual one:

$$(\lambda.t)u \longrightarrow_{\beta} t[u/0]$$

excepting that the substitution now has to take care of properly handling indices.

Reduction

The reduction

$$\lambda x.(\lambda y.\lambda z.y) (\lambda t.t) \longrightarrow_{\beta} \lambda x.(\lambda z.y)[\lambda t.t/y] = \lambda x.\lambda z.y[\lambda t.t/y] = \lambda x.\lambda z.\lambda t.t$$

corresponds to

$$\lambda.(\lambda.\lambda.1) \lambda.0 \longrightarrow_{\beta} \lambda.(\lambda.1)[\lambda.0/0] = \lambda.\lambda.1[\lambda.0/1] = \lambda.\lambda.\lambda.0$$

and we are tempted to define substitution by

$$i[u/i] = u$$

$$j[u/i] = j$$

for $j \neq i$

$$(t t')[u/i] = (t[u/i]) (t'[u/i])$$

$$(\lambda.t)[u/i] = \lambda.t[u/i+1]$$

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$$(\lambda.t)[u/i] = \lambda.t[u/i+1]$$

Incorrect: in the last case, t might contain free variables.

Reduction

The reduction

$$\lambda x.(\lambda y.\lambda z.y) x \longrightarrow_{\beta} \lambda x.(\lambda z.y)[x/y] = \lambda x.\lambda z.y[x/y] = \lambda x.\lambda z.x$$

corresponds to

$$\lambda.(\lambda.\lambda.1) 0 \longrightarrow_{\beta} \lambda.(\lambda.1)[0/0] = \lambda.\lambda.1[1/1] = \lambda.\lambda.1$$

and the last case of substitution should actually be

$$(\lambda.t)[u/i] = \lambda.t[\uparrow_0 u/i+1]$$

where $\uparrow_0 u$ is u with all free variables increased by 1 (and other unchanged).

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and the last case of substitution should actually be

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where $\uparrow_0 u$ is u with all free variables increased by 1 (and other unchanged).

Still incorrect: β -reduction removes abstractions!

Reduction

The reduction

$$\lambda x.(\lambda y.x) (\lambda t.t) \longrightarrow_{\beta} \lambda x.x[\lambda t.t/y] = \lambda x.x$$

corresponds to

$$\lambda.(\lambda.1) (\lambda.0) \longrightarrow_{\beta} \lambda.1[\lambda.0/0] = 0$$

Reduction

The reduction

$$\lambda x.(\lambda y.x)(\lambda t.t) \longrightarrow_{\beta} \lambda x.x[\lambda t.t/y] = \lambda x.x$$

corresponds to

$$\lambda.(\lambda.1)(\lambda.0) \longrightarrow_{\beta} \lambda.1[\lambda.0/0] = 0$$

and the first case of substitution should actually be, for $j \neq i$,

$$j[u/i] = \downarrow_i j$$

with

$$\downarrow_l i = \begin{cases} i - 1 & \text{if } i > l \\ i & \text{if } i < l \end{cases}$$

Reduction

In summary, the β -reduction can be defined as

$$(\lambda.t)u \longrightarrow_{\beta} t[u/0]$$

with

$$i[u/i] = u$$

$$j[u/i] = \downarrow_j j$$

for $j \neq i$

$$(t t')[u/i] = (t[u/i]) (t'[u/i])$$

$$(\lambda.t)[u/i] = \lambda.t[\uparrow_0 u/i+1]$$

We are only left to define $\uparrow_0 u$ which is u with all free variables increased by **1**.

For instance,

$$\uparrow_0(0(\lambda.01)) =$$

Note that, under the λ , we should only increase free variables of index ≥ 1 .

We are only left to define $\uparrow_0 u$ which is u with all free variables increased by **1**.

For instance,

$$\uparrow_0(0(\lambda.01)) = 1(\lambda.02)$$

Note that, under the λ , we should only increase free variables of index ≥ 1 .

Given a “cutoff level” l , we define

$$\uparrow_l u$$

which is u with all free variables of index $\geq l$ increased by 1:

$$\uparrow_l i = \begin{cases} i & \text{if } i < l \\ i + 1 & \text{if } i \geq l \end{cases}$$

$$\uparrow_l (t u) = (\uparrow_l t) (\uparrow_l u)$$

$$\uparrow_l (\lambda.t) = \lambda.(\uparrow_{l+1} t)$$

We can define a translation from λ -terms to de Bruijn and back.

Theorem

The β -reduction is compatible with translations.

Part VI

Combinatory logic

Combinatory logic

Combinatory logic was introduced by Schönfinkel and Curry, in order to provide a syntax which does not need to use variable binding or α -conversion.

It begins with the observation that all the λ -terms can be generated by composing a finite number of those:

$$S = \lambda xyz.(xz)(yz)$$

$$K = \lambda xy.x$$

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For instance, $I = \lambda x.x$ can be implemented as

$$\begin{aligned} SKK &= (\lambda xyz.(xz)(yz))(\lambda xy.x)(\lambda xy.x) \longrightarrow_{\beta} \lambda z.((\lambda xy.x)z)((\lambda xy.x)z) \\ &\longrightarrow_{\beta} \lambda z.(\lambda y.z)(\lambda y.z) \\ &\longrightarrow_{\beta} \lambda z.z \end{aligned}$$

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Note that

- **S** allows the duplication of a variable which is given to two terms in an application,
- **K** allows the erasure of a variable given as argument.

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$$S = \lambda xyz.(xz)(yz)$$

$$K = \lambda xy.x$$

Note that these terms satisfy:

$$S t u v \longrightarrow_{\beta} (t v) (u v)$$

$$K t u \longrightarrow_{\beta} t$$

Combinatory logic

The terms are defined as

$$T, U ::= x \mid T U \mid S \mid K$$

where x is a variable.

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The reduction rules are

$$\overline{S T U V} \longrightarrow (T V)(U V)$$

$$\overline{K T U} \longrightarrow T$$

$$\frac{T \longrightarrow T'}{T U \longrightarrow T' U}$$

$$\frac{U \longrightarrow U'}{T U \longrightarrow T U'}$$

Combinatory logic

The terms are defined as

$$T, U ::= x \mid T U \mid S \mid K$$

where x is a variable.

The reduction rules are

$$\overline{STUV} \longrightarrow (TV)(UV)$$

$$\overline{KTU} \longrightarrow T$$

$$\frac{T \longrightarrow T'}{TU \longrightarrow T'U}$$

$$\frac{U \longrightarrow U'}{TU \longrightarrow TU'}$$

For instance,

$$SKKT \longrightarrow (KT)(KT) \longrightarrow T$$

Translation to λ -calculus

We define a translation from combinatory terms to λ -terms by

$$\llbracket x \rrbracket_\lambda = x \quad \llbracket T U \rrbracket_\lambda = \llbracket T \rrbracket_\lambda \llbracket U \rrbracket_\lambda \quad \llbracket K \rrbracket_\lambda = \lambda xy. x \quad \llbracket S \rrbracket_\lambda = \lambda xyz. (xz)(yz)$$

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Proposition

Given combinatory terms T and T' , we have

$$T \longrightarrow T' \quad \text{implies} \quad \llbracket T \rrbracket_\lambda \xrightarrow{*}_\beta \llbracket T' \rrbracket_\lambda$$

Translation from λ -calculus

Given a combinatory term T and a variable x , we define the term $\Lambda x.T$ by

$$\Lambda x.x = I = S K K$$

$$\Lambda x.T = K T$$

$$\Lambda x.(T U) = S (\Lambda x.T) (\Lambda x.U)$$

if $x \notin FV(T)$,

otherwise.

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otherwise.

We can finally translate a λ -term t by

$$\llbracket x \rrbracket_{\text{cl}} = x$$

$$\llbracket t u \rrbracket_{\text{cl}} = \llbracket t \rrbracket_{\text{cl}} \llbracket u \rrbracket_{\text{cl}}$$

$$\llbracket \lambda x.t \rrbracket_{\text{cl}} = \Lambda x.\llbracket t \rrbracket_{\text{cl}}$$

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$$\llbracket \lambda x.\lambda y.x \rrbracket_{cl}$$

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$$\Lambda x.T = K T \quad \text{if } x \notin FV(T),$$

$$\Lambda x.(T U) = S (\Lambda x.T) (\Lambda x.U) \quad \text{otherwise.}$$

For instance,

$$\llbracket \lambda x.\lambda y.x \rrbracket_{cl} = \Lambda x.\llbracket \lambda y.x \rrbracket_{cl}$$

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For instance,

$$\begin{aligned} \llbracket \lambda x.\lambda y.x \rrbracket_{cl} &= \Lambda x.\llbracket \lambda y.x \rrbracket_{cl} \\ &= \Lambda x.\Lambda y.\llbracket x \rrbracket_{cl} \end{aligned}$$

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Given a combinatory term T and a variable x , we define the term $\Lambda x.T$ by

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Given a combinatory term T and a variable x , we define the term $\Lambda x.T$ by

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For instance,

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Lemma

For any λ -term t , $\llbracket \llbracket t \rrbracket_{\text{cl}} \rrbracket_{\lambda} \xrightarrow{*}_{\beta} t$.

For instance,

$$\llbracket \llbracket \lambda x.x \rrbracket_{\text{cl}} \rrbracket_{\lambda} = \llbracket \text{S K K} \rrbracket_{\lambda} = (\lambda xyz.(xz)(yz))(\lambda xy.x)(\lambda xy.x) \xrightarrow{*}_{\beta} \lambda x.x$$

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Corollary

Every closed λ -term can be obtained by composing the λ -terms **S** and **K**.

Limitations of the translations

It is not true that $t \xrightarrow{*}_\beta u$ implies $\llbracket t \rrbracket_{\text{cl}} \xrightarrow{*} \llbracket u \rrbracket_{\text{cl}}$.

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For instance,

$$\llbracket \lambda x. (\lambda y. y) x \rrbracket_{\text{cl}} = S(KI)I$$

$$\llbracket \lambda x. x \rrbracket_{\text{cl}} = I$$

(both are normal forms!)

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It is not true that $t \xrightarrow{*}_{\beta} u$ implies $\llbracket t \rrbracket_{\text{cl}} \xrightarrow{*} \llbracket u \rrbracket_{\text{cl}}$.

For instance,

$$\llbracket \lambda x. (\lambda y. y) x \rrbracket_{\text{cl}} = S(KI)I \qquad \llbracket \lambda x. x \rrbracket_{\text{cl}} = I$$

(both are normal forms!)

However, it gets true if we apply them to enough arguments:

$$S(KI)IT \longrightarrow KIT(IT) \longrightarrow I(IT) \longrightarrow IT \longrightarrow T \qquad \text{and} \qquad IT \longrightarrow T$$

The translation of a combinatory term in normal form is not necessarily a normal form:

$$\llbracket K x \rrbracket_{cl} = (\lambda xy.x) x \longrightarrow_{\beta} \lambda y.x$$

Limitations of the translation

A combinatory term T is not convertible with $\llbracket T \rrbracket_{\lambda}$ in general

$$\llbracket K \rrbracket_{\lambda} = \llbracket \lambda xy. x \rrbracket_{\lambda} = S(KK)I \neq K$$

(they are both normal forms and combinatory logic can be shown to be confluent)

Limitations of the translation

All those defects are due to the fact that combinatory terms might be stuck (compared to λ -terms) if they don't have enough arguments.

The translation is still quite useful.

The system

$$T, U ::= x \mid T U \mid S \mid K$$

with rules

$$\overline{S T U V \rightarrow (T V)(U V)}$$

$$\overline{K T U \rightarrow T}$$

$$\frac{T \rightarrow T'}{T U \rightarrow T' U}$$

$$\frac{U \rightarrow U'}{T U \rightarrow T U'}$$

simulates λ -calculus and is thus undecidable!

We have reduced λ -calculus to 2 combinators, can we do 1?

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Yes,

$$\iota = \lambda x.x SK$$

Namely,

$$I = \iota \iota$$

$$K = \iota (\iota (\iota \iota))$$

$$S = \iota (\iota (\iota (\iota \iota)))$$

The reduction is

$$\iota T \longrightarrow T (\iota (\iota (\iota (\iota \iota)))) (\iota (\iota (\iota \iota)))$$

The terms are generated by the grammar

$$t, u ::= \iota \mid t u$$

A term t can be encoded as a binary word $[t]$ defined by

$$[\iota] = 1 \qquad [t u] = 0[t][u]$$

so that $\iota(\iota(\iota\iota))$ is encoded as **0101011**.

We thus get an interesting binary encoding of λ -terms.