

Introduction to functional programming and lambda calculus

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# Introduction to functional programming and lambda calculus

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Hogeschool Rotterdam Rotterdam, Netherlands



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## Introduction



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### Course introduction

- Course topic: what is this course about?
- Examination: how will you be tested?
- Start with course



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## Course topic: functional programming

- Lambda calculus
- From lambda calculus to functional programming
- Functional programming using F<sup>#</sup> and Haskell



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## Advantages of functional programming

- Strong mathematical foundations
- Easier to reason about programs
- Parallelism for "free"
- Correctness guarantees through strong typing (optional)



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#### Examination

- Theory exam: test understanding of theory
- Practical exam: test ability to apply theory in practice



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## Theory exam: reduction and typing

- One question on reduction in lambda calculus
- One question on typing in lambda calculus, F<sup>‡</sup>, or Haskell
- Passing grade if both questions answered correctly



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## Practical exam: interpreter for a virtual machine

- In a group, build an interpreter for a virtual machine
- According to a specification that will be provided
- Groups may consist of up to 4 students
- Understanding of code tested individually



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### Lecture topics

- Semantics(meaning) of imperative languages
- Lambda calculus, the foundation for functional languages



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## Semantics of imperative languages



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### Imperative program: sequence of statements

- Statements directly depend on and alter memory
- Meaning of statements may depend on contents of memory
- Any statement may depend on (read) any memory location
- Any statement may alter any memory location



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#### Example: meaning of statement sequence

- ullet Statement  $s_1$  changes the machine state from  $S_0$  to  $S_1$
- ullet Statement  $s_2$  changes the machine state from  $S_1$  to  $S_2$
- ullet Run statement  $s_1$ , then run statement  $s_2$ :  $s_1s_2$
- ullet Statement  $s_1s_2$  changes the machine state from  $S_0$  to  $S_2$

$$(S_0 \xrightarrow{s_1} S_1) \land (S_1 \xrightarrow{s_2} S_2) \implies S_0 \xrightarrow{s_1 s_2} S_2$$



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### Example: meaning of statement sequence

- ullet Statement  $s_1$  changes the machine state from  $S_0$  to  $S_1$
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- ullet Run statement  $s_1$ , then run statement  $s_2$ :  $s_1s_2$
- ullet Statement  $s_1s_2$  changes the machine state from  $S_0$  to  $S_2$

$$(S_0 \xrightarrow{s_1} S_1) \land (S_1 \xrightarrow{s_2} S_2) \implies S_0 \xrightarrow{s_1 s_2} S_2$$

What about  $s_2s_1$ ?



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### Swap order of $s_1s_2$ : $s_2s_1$

- ullet Sometimes  $s_2s_1$  has the same meaning as  $s_1s_2\ldots$
- Sometimes  $s_2s_1$  is completely different from  $s_1s_2!$
- ullet It depends on  $s_1$ ,  $s_2$ , and the relevant machine state  $S_0$
- ullet It depends on implementation details of  $s_1$  and  $s_2$
- Implementation details matter \impless leaky abstraction!



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### Swap order of $s_1s_2$ : $s_2s_1$

- ullet Sometimes  $s_2s_1$  has the same meaning as  $s_1s_2\ldots$
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- ullet It depends on implementation details of  $s_1$  and  $s_2$
- Implementation details matter ⇒ leaky abstraction!

Can we do better?



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## Idea for better abstraction: remove implicit dependencies

- ullet No implicit dependencies  $\Longrightarrow$  all dependencies explicit
- No access to arbitrary machine state
- Only explicitly-mentioned state may be accessed



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## Idea for better abstraction: remove implicit dependencies

- No access to arbitrary machine state
- Only explicitly-mentioned state may be accessed

What if  $s_1$  and  $s_2$  access the same state?



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What if  $s_1\{x\}$  and  $s_2\{x\}$  only read the same state x?

ullet  $s_1\{x\}$  calculates x+x, and  $s_2\{x\}$  calculates the square  $x^2$ 

Can we reorder  $s_1\{x\}$  and  $s_2\{x\}$ ?



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What if  $s_1\{x\}$  and  $s_2\{x\}$  only read the same state x?

ullet  $s_1\{x\}$  calculates x+x, and  $s_2\{x\}$  calculates the square  $x^2$ 

Can we reorder  $s_1\{x\}$  and  $s_2\{x\}$ ?

What if  $s_1\{x\}$  and  $s_2\{x\}$  alter the same state x?

•  $s_1\{x\}$  sets x to 1, and  $s_2\{x\}$  sets x to 2

Can we reorder  $s_1\{x\}$  and  $s_2\{x\}$ ?



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What if  $s_1\{x\}$  and  $s_2\{x\}$  only read the same state x?

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Can we do better?



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## Idea for better abstraction: remove implicit dependencies

- ullet No implicit dependencies  $\Longrightarrow$  all dependencies explicit
- No reading of arbitrary machine state
- No mutating of arbitrary machine state
- Only explicitly-mentioned machine state may be read



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### Idea for better abstraction: remove implicit dependencies

- ullet No implicit dependencies  $\Longrightarrow$  all dependencies explicit
- No reading of arbitrary machine state
- No mutating of arbitrary machine state
- Only explicitly-mentioned machine state may be read

NB: No provision at all is made for mutating machine state



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### Wait a minute, this is just like functions

- Not statements, but (mathematical) functions
- Functions depend only on arguments
- Functions do not mutate machine state
- Can calculate function value when all arguments are known
- Can always replace a function call by its value



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### Wait a minute, this is just like functions

- Not statements, but (mathematical) functions
- Functions depend only on arguments
- Functions do not mutate machine state
- Can calculate function value when all arguments are known
- Can always replace a function call by its value

## NB: Imperative "functions" need not be functions!

Non-function "functions" are more properly called procedures



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### Referential transparency:

It is always valid to replace a function call by its value



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### Referential transparency:

It is always valid to replace a function call by its value

#### Advanced topic:

Allow mutation of state without losing referential transparency



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## Lambda calculus



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#### What is lambda calculus?

- Model of computation based on functions
- Completely different from Turing machines, but equivalent
- Foundation of all functional programming languages
- Truly tiny when compared with its power
- Consists of only (function) abstraction and application



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### A lambda calculus term is one of three things:

- a variable (from some arbitrary infinite set of variables)
- an abstraction (a "function of one variable")
- an application (a "function call")



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## Variables (arbitrary infinite set):

 $a, b, c, \ldots$ 

 $a_0, a_1, \ldots$ 

 $b_0, b_1, \dots$ 

#### Abstractions:

For any variable x and lambda term T:  $(\lambda x.T)$ 

### Applications:

For any lambda terms F and T: (FT)



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A simple example: the identity function (just returns its input)

 $(\lambda x.x)$ 



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A simple example: call the identity function on a variable

 $((\lambda x.x) v)$ 



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#### $\beta$ -reduction

- Redex: application of an abstraction to an argument
- Result: in abstraction body replace parameter by argument

$$((\lambda x.B)A) \to_{\beta} B[x \mapsto A]$$



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Multiple parameters via nested abstractions:

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

The parameters are then given one at a time:

 $(((\lambda x y.(x y)) A) B)$ 



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 $(((\lambda x y.(x y)) A) B)$ 



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$$(((\lambda x y.(x y)) A) B)$$

$$(((\lambda x y.(x y)) A) B)$$



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 $(((\lambda x y.(x y)) A) B)$ 



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$$(((\lambda x y.(x y)) A) B)$$

$$((\lambda y.(Ay))B)$$



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 $((\lambda y.(A y)) B)$ 



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$$((\lambda y.(A y)) B)$$



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 $((\lambda y.(A y)) B)$ 



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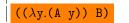
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(A B)



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#### Example executions of (apparently) nonsensical programs

- Manual execution of various lambda programs.
- Try to work out the result of these programs.



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What is the result of this program?

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



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



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```
(((\lambda x y.(x y)) (\lambda z.(z z))) A)
```

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



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```
(((\lambda x y.(x y)) (\lambda z.(z z))) A)
```



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```
((\lambda x y.(x y)) (\lambda z.(z z))) A)
```

```
((\lambda y.(\lambda z.(z z)) y)) A)
```



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



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

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



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



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



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 $((\lambda z.(z z)) A)$ 



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$$((\lambda z.(z z)) A)$$



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 $((\lambda z.(z z)) A)$ 



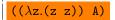
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What is this program's result? Hint: scope!

$$(((\lambda x x.(x x)) A) B)$$



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 $(((\lambda x x.(x x)) A) B)$ 



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$$(((\lambda x x.(x x)) A) B)$$

$$(((\lambda x x.(x x)) A) B)$$



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 $(((\lambda x x.(x x)) A) B)$ 



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(((\lambda x x.(x x)) A) B)
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$$((\lambda x.(x x)) B)$$



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 $((\lambda x.(x x)) B)$ 



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$$((\lambda x.(x x)) B)$$

$$((\lambda x.(x x)) B)$$



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 $((\lambda x.(x x)) B)$ 



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 $((\lambda x.(x x)) B)$ 

(BB)



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Outer x is shadowed by inner x!

$$(((\lambda x x.(x x)) A) B)$$



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To disambiguate, turn:

 $(((\lambda x x.(x x)) A) B)$ 

into:

 $(((\lambda y x.(x x)) A) B)$ 



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 $(((\lambda y x.(x x)) A) B)$ 



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$$(((\lambda y x.(x x)) A) B)$$

$$(((\lambda y x.(x x)) A) B)$$



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 $(((\lambda y x.(x x)) A) B)$ 



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$$((\lambda y x.(x x)) A) B)$$

$$((\lambda x.(x x)) B)$$



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$$((\lambda x.(x x)) B)$$

$$((\lambda x.(x x)) B)$$



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 $((\lambda x.(x x)) B)$ 



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 $((\lambda x.(x x)) B)$ 

(BB)



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What is this program's result? Is there even one?

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



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```
((\lambda x.(x x)) (\lambda x.(x x)))
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((\lambda x.(x x)) (\lambda x.(x x)))
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$$((\lambda x.(x x)) (\lambda x.(x x)))$$



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



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



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((\lambda x.(x x)) (\lambda x.(x x)))
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```
((\lambda x.(x x)) (\lambda x.(x x)))
```



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```
((\lambda x.(x x)) (\lambda x.(x x)))
```

```
It never ends! Like a while true: ...
```



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### What you are all thinking:

This is no real programming language!

### Is this a joke?

- We have some sort of functions and function calls
- We do not have booleans and if's
- We do not have integers and arithmetic operators
- We do not have a lot of things!



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#### Surprise!

All these things are in there awaiting discovery!



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### What you are all thinking:

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### Surprise!

All these things are in there awaiting discovery!

### Stay tuned

This will be a marvelous voyage!



### This is it!

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The best of luck, and thanks for the attention!