

Computer Science Course Notes — 1st Semester

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Contents

Models of Computation	1
First Lesson	1
Contact Information	1
Course Contents	1
Set Definition	1
Bactus Normal Form	2
Beta Reduction	2
Types of Variables	3
Extra Rules	3
Second Lecture	4
Alpha Reduction	4
Arithmetic Expressions	4
Combinators	5
Third Lecture	5
Fourth Lecture	5

Models of Computation

First Lesson

Contact Information

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Actual lecture times:

- Wednesday 13:30 - 15:00
- Thursday 16:00 - 17:30, or 16:15 - 17:55

Course Contents

The course content will focus on **functional programming** and λ -calculus.

The main application of these languages is that of *function application*, these languages are devoid of *assignment* semantics, and are therefore called *pure*.

The main ingredients of our programs will be:

- Variables, which are usually denoted by lowercase letters
- Starting from these, you obtain the set of all programs, which are called λ -terms, this set is denoted as Λ .

Set Definition

We can provide an inductive definition of a set of λ -terms, Λ :

$$\frac{x \in V}{x \in \Lambda} \quad (\text{var})$$

$$\frac{M \in \Lambda \quad N \in \Lambda}{(MN) \in \Lambda} \quad (\text{app})$$

$$\frac{M \in \Lambda \quad x \in V}{\lambda x.M \in \Lambda} \quad (\text{abs})$$

Applying these inductive rules (variables, application, abstraction).

Bactus Normal Form

Another way of describing a set of lambda terms is by using Bactus Normal Form (BNF).

$$\Lambda :: Var | \Lambda \Lambda | \lambda Var. \Lambda$$

Which is essentially a grammar for the set of lambda terms.

Lambda calculus is left-associative:

$$((xy)z) = xyz \neq x(yz)$$

All functions are unary (we assume currying). For example, the function $f(x, y)$ is represented as:

$$\lambda x. \lambda y. fxy$$

.

Functions in lambda calculus can be applied to other functions or themselves, they can also return functions.

Beta Reduction

The main operation in lambda calculus is *beta reduction*, which is the application of a function to an argument.

$$\frac{(\lambda x. M)N}{redex} \rightarrow_{\beta} M[N/x]$$

Where $M[N/x]$ is the result of substituting all occurrences of x in M with N .

Some other examples:

$$(\lambda x. x)y \rightarrow_{\beta} y$$

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

$$(\lambda xy. yx)(\lambda u. u) \rightarrow_{\beta} \lambda y. y(\lambda u. u)$$

$$(\lambda xy. yx)(\lambda t. y) \rightarrow_{\beta} \lambda y. y(\lambda t. y)$$

This rule can be applied in any context in which it appears.

Formal Substitution Definition

We give a formal definition of substitution, $M[N/x]$:

$$x[N/x] = N$$

$$y[N/x] = y$$

$$(M_1 M_2)[N/x] = M_1[N/x] M_2[N/x]$$

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

As observed, substitution is always in place of *free* variables, therefore the abstraction is *not* replaced in the last rule.

If we had an abstraction of type $\lambda x. P$ where $x \in P$, it would be best to rename x in order to avoid name clashes.

Types of Variables

We distinguish two kinds of variables:

- Free variables: variables that are not bound by an abstraction
- Bound variables: variables that are bound by an abstraction

For example, in the term $\lambda x. xy$, y is a free variable, while x is a bound variable.

Bound variables can be renamed, whereas for free variables the naming is relevant.

$$\begin{cases} FV(x) = \{x\} \\ FV(MN) = FV(M) \cup FV(N) \\ FV(\lambda x. M) = FV(M) - \{x\} \end{cases}$$

A set of lambda terms where $LM(\Lambda) =$ is called *closed*.

Extra Rules

$$(\mu) \quad \frac{M \rightarrow_{\beta} M'}{NM \rightarrow_{\beta} NM'}$$

$$(\nu) \quad \frac{M \rightarrow_{\beta} M'}{MN \rightarrow_{\beta} M'N}$$

$$(\xi) \quad \frac{M \rightarrow M'}{\lambda x. M \rightarrow \lambda x. M'}$$

These rules allow us to select redexes in a context-free manner in the middle of our lambda term. We can then choose the order of evaluation of our redexes, while still taking care of the left-associative order of precedence. Our calculus is therefore not *determinate* but is still *deterministic*, meaning that there may be multiple reduction strategies but they all lead to the same result.

This corollary is called the *Church Rosser Theorem*, discovered in 1936.

In general, a call-by-value-like semantic is preferable when choosing evaluation paths, as it clears the most amount of terms as early as possible.

- Call By Value is *efficient*
- Call By Name is *complete*, **if** the lambda term is normalizable

Second Lecture

Alpha Reduction

Alpha reduction is the renaming of bound variables in a lambda term.

$$\lambda x.M \rightarrow_{\alpha} \lambda y.M[y/x]$$

This rule is used to avoid name clashes between bound variables.

Arithmetic Expressions

The set of all valid arithmetic expressions has a very precise syntax. In general, a syntax can be viewed either as a tool for checking validity or as a generator of valid expressions (a grammar).

We proceed to give a definition for arithmetic expressions

$$\frac{x \in \mathbb{N}}{x \in \text{Expr}} \quad (\text{num})$$

$$\frac{X \in \text{Expr} \quad Y \in \text{Expr}}{X + Y \in \text{Expr}} \quad (\text{add})$$

$$\frac{X \in \text{Expr} \quad Y \in \text{Expr}}{X \times Y \in \text{Expr}} \quad (\text{mul})$$

Etc, etc... for all the other binary operations.

From this, we can successfully decompose any arithmetic expression into a syntactic tree. With this set of rules, we have a slight problem: we can't represent negative numbers. We could solve this either by adding a rule for unary minus, or by specifying the num rule over \mathbb{Z} instead of \mathbb{N} .

Combinators

We define three combinators:

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

$$K = \lambda xy.x$$

$$I = \lambda u.u$$

We have that $SKy \rightarrow_{\beta} I$

Exercise 1.1: β -reduce $S(KS)S$

This reduces to $\lambda zbc.z(bc)$, which is the B combinator (composition).

Exercise 1.2: β -reduce $S(BBS)(KK)$.

This reduces to $\lambda zcd.zdc$, which is the C combinator (permutation).

For exercise this, we show a step-by-step reduction:

$$\begin{aligned} & S(BBS)(KK) \\ \rightsquigarrow & \lambda z.(BBS)z((KK)z) \\ \rightsquigarrow & \lambda z.(\lambda c.B(Sc))z((KK)z) \\ \rightsquigarrow & \lambda z.(\lambda c.B(Sc))zK \\ \rightsquigarrow & \lambda z.B(Sz)K \\ \rightsquigarrow & \lambda z.(\lambda c.(Sz)(Kc)) \\ \rightsquigarrow & \lambda zc.Sz(Kc) \\ \rightsquigarrow & \lambda zcd.zd(Kcd) \\ \rightsquigarrow & \lambda zcd.zdc \quad \square. \end{aligned}$$

Third Lecture

Recupera!!!

Fourth Lecture

First we do a simple exercise, β -reduce $\lambda uv.(\lambda z.zz)(\lambda t.tuv)$.

$$\begin{aligned}
& \lambda uv.(\lambda z.zz)(\lambda t.tuv) \\
& \rightarrow_{\beta} \lambda uv.(\lambda t.tuv)(\lambda t.tuv) \\
& \rightarrow_{\beta} (\lambda t.tuv)(\lambda t.tuv) \\
& \rightarrow_{\beta} \lambda uv.(\lambda t.tuv)uv \\
& \rightarrow_{\beta} \lambda uv.uuvv \quad \square.
\end{aligned}$$

Find a term X s.t $Xx = \lambda t.t(Xx)$

$$\begin{aligned}
Xx &= \lambda t.t(Xx) \\
X &= (\lambda fxy.t(fx))X \\
X &= Y(\lambda fxy.t(fx))
\end{aligned}$$

Find a term H s.t $H(\lambda x_1x_2x_3.P) = \lambda x_3x_2x_1.P$

This corresponds to performing a function call with the arguments in reverse order:

$$H := \lambda f x_3 x_2 x_1. f x_1 x_2 x_3$$

You can see by beta reduction that this is the correct term:

$$\begin{aligned}
& H(\lambda x_1x_2x_3.P) \\
& \rightarrow_{\beta} (\lambda f x_3 x_2 x_1. f x_1 x_2 x_3)(\lambda x_1x_2x_3.P) \\
& \rightarrow_{\beta} (\lambda x_3x_2x_1. (\lambda x_1x_2x_3.P)x_1x_2x_3) \\
& \rightarrow_{\beta} \lambda x_3x_2x_1.P \quad \square.
\end{aligned}$$