Υλοποίηση ενός διερμηνέα για Λάμβδα Λογισμό

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13 Νοεμβρίου 2013

The Syntax

$$
\begin{aligned}
e := \; & e_1 \;\; e_2 \\
& \mid \text{``}\boldsymbol{\lambda}\text{''} \; id \; \text{``.''} \; e \\
& \mid \text{``}\textbf{\textit{let}}\text{''} \; [\text{``}\textbf{\textit{rec}}\text{''}] \; id \; \text{``} = \text{''} \; e_1 \; \text{``}\textbf{\textit{in}}\text{''} \; e_2 \\
& \mid \text{``[''} e1 \text{``, ''} \; e2 \text{``]''} \\
& \mid id \\
& \mid \text{``}\textbf{\textit{true}}\text{''} \mid \text{``}\textbf{\textit{false}}\text{''} \\
& \mid \text{``}\textbf{\textit{if}}\text{''} \;\; e_1 \; \text{``}\textbf{\textit{then}}\text{''} \; e_2 \; \text{``}\textbf{\textit{else}}\text{''} \; e_3 \\
& \mid e_1 \;\; op \; e_2 \\
& \mid e_1 \;\; rop \; e_2 \\
& \mid e_1 \;\; bop \; e_2
\end{aligned}
$$

$$
\begin{aligned}
op := \; & \text{`` } + \text{ ''} \mid \text{`` } - \text{ ''} \\
& \mid \text{`` } * \text{ ''} \\
& \mid \text{`` } * * \text{''} \\
rop := \; & \text{`` } = \text{ ''} \mid \text{`` } < \text{ ''} \\
& \mid \text{`` } <= \text{ ''} \mid \text{`` } > \text{ ''} \\
& \mid \text{`` } >= \text{ ''} \\
bop := \; & \text{``\&\&''} \\
& \mid \text{``||''}
\end{aligned}
$$

Type System

The language is strongly typed featuring the **Hindley-Milner** type system. The types are implicit in the source (à la Curry) and they are automatically reconstructed using the **algorithm W** for type inference.

Hindley-Milner typing

Hindley-Milner type system is a restriction of system F, featuring let polymorphism. Unlike system F, in which type reconstruction is undecidable, the types can be inferred using the algorithm W.

Significant Limitation: Let-polymorphism is rank-1 polymorphism, that means that functions cannot take as arguments polymorphic functions.

Hindley-Milner typing

Examples

```
> ./jebus annot
let const = \x. \y. x in
[const 1 true, const false 42]
———————————————
let const : a1 -> a2 -> a1 =
  \x. : a1. \y. : a6 . x
in
  [const 1 true, const false 42]
```

Figure 1 : Here *const* has type $\forall a.\forall b.(a \rightarrow b \rightarrow a)$

```
> ./jebus annot
let id = \x. x in
let f = \g. [g 1, g true] in
  f id
Could not match type Nat with
type Bool
```

Figure 2 : g's type cannot be a polymorphic function!

Hindley-Milner typing

Types

We will use τ for simple types, σ for type schemes and α for type variables.

$$
\begin{aligned}
\tau :=\ & \tau_1 \to \tau_2 \\
& |\tau_1 \times \tau_2 \\
& |Nat \\
& |Bool \\
& |\alpha
\end{aligned}
\qquad\qquad
\begin{aligned}
\sigma :=\ & \forall\alpha.\sigma_1 \\
& \mid \tau \\
\\
\alpha :=\ & \alpha_1|\alpha_2|....
\end{aligned}
$$

Hindley-Milner typing

Typing Rules

$$\frac{}{\Gamma, x : \sigma \vdash x : \sigma}\,var$$

$$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2}{\Gamma \vdash \lambda x.e : \tau_1 \to \tau_2}\,\lambda$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \to \tau_2 \quad \Gamma \vdash e_2 : \tau_1}{\Gamma \vdash e_1\ e_2 : \tau_2}\,@$$

$$\frac{\Gamma \vdash e_1 : \sigma \quad \Gamma, x : \sigma \vdash e_2 : \tau}{\Gamma \vdash let\,[rec]\ x\ =\ e_1\ in\ e_2 : \tau}\,let$$

$$\frac{\Gamma \vdash e : \sigma \quad \alpha \notin FV(\Gamma)}{\Gamma \vdash e : \forall a.\sigma}\,gen$$

$$\frac{\Gamma \vdash e : \forall a.\sigma}{\Gamma \vdash e : \sigma[\alpha \to \tau]}\,inst$$

$$\frac{\Gamma \vdash e : Bool \quad \Gamma \vdash e_1 : \tau \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash if\ e\ then\ e_2\ else\ e_3 : \tau}\,ite$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash [e_1,\ e_2] : \tau_1 \times \tau_2}\,pair$$

Hindley-Milner typing

Typing Rules (cont.)

$$\frac{\Gamma \vdash e_1 : \mathit{Nat} \quad \Gamma \vdash e_2 : \mathit{Nat}}{\Gamma \vdash e_1 \diamond e_2 : \mathit{Nat} \quad \diamond \in \{+, -, *, /, **\}}\,op$$

$$\frac{\Gamma \vdash e_1 : \mathit{Nat} \quad \Gamma \vdash e_2 : \mathit{Nat}}{\Gamma \vdash e_1 \diamond e_2 : \mathit{Bool} \quad \diamond \in \{<, <=, ==, >, >=\}}\,rop$$

$$\frac{\Gamma \vdash e_1 : \mathit{Bool} \quad \Gamma \vdash e_2 : \mathit{Bool}}{\Gamma \vdash e_1 \diamond e_2 : \mathit{Bool} \quad \diamond \in \{\&\&, ||\}}\,bop$$

$$\frac{\Gamma \vdash e : \mathit{Bool}}{\Gamma \vdash \mathit{not}\ e : \mathit{Bool}}\,not$$

The Core Language

The internal representation is actually a pretty small language. Most of the language's expressions are defined as syntactic sugar

$$
\begin{aligned}
e :=\ & e_1 \ \ e_2 \\
\mid\ & \boldsymbol{\lambda}\ id\ \boldsymbol{.}\ e \\
\mid\ & \boldsymbol{Fix}\ e_1
\end{aligned}
$$

The Core Language

Syntactic Sugar

- **Integers** The integers are represented internally with church encoding

$$n \equiv \lambda\ s.\ \lambda\ z.\ \underbrace{s(s \ldots (s}_{\text{n times}}\, z) ..)$$

- **Arithmetical Operations**
  $e_1 + e_2 \equiv (\lambda\ x.\ \lambda\ y.\ x\ succ\ y) e_1\ \ e_2$
  $e_1 - e_2 \equiv (\lambda\ x.\ \lambda\ y.\ y\ pred\ x) e_1\ \ e_2$
  $e_1 * e_2 \equiv (\lambda\ x.\ \lambda\ y.\ \lambda\ z.\ x\ y\ z) e_1\ \ e_2$
  $e_1 * * e_2 \equiv (\lambda\ x.\ \lambda\ y.\ y\ x) e_1\ \ e_2$

The Core Language

Syntactic Sugar

- **Boolean Constants**
  $\mathit{true} \equiv \lambda\ x.\ \lambda\ y.\ x \qquad \mathit{false} \equiv \lambda\ x.\ \lambda\ y.\ y$
- **Pairs** $[e_1,\ e_2] \equiv \lambda\ x.\ x\ e_1\ \ e_2$
- **Provided functions for pairs**
  $\mathit{fst} \equiv \lambda\ x.\ x\ \mathit{true}$ with type $\forall\ a.\forall b.\ a \times b \to a$
  $\mathit{snd} \equiv \lambda\ x.\ x\ \mathit{false}$ with type $\forall\ a.\forall b.\ a \times b \to b$
- **Provided functions for Integers**
  $\mathit{succ} \equiv \lambda\ x.\ \lambda\ s.\ \lambda\ z.\ s\ (n\ s)\ z$ with type $Nat \to Nat$
  $\mathit{iszero} \equiv \lambda\ x.\ x\ (\mathit{true}\ \mathit{false})\ \mathit{true}$ with type $Nat \to Bool$
  $\mathit{pred} \equiv \lambda\ x.\ \mathit{snd}\ (x\ \mathit{next}\ [0, 0])$ with type $Nat \to Nat$
  where $\mathit{next} \equiv \lambda\ x.\ [\mathit{succ}\ (\mathit{fst}\ x),\ (\mathit{fst}\ x)]$

The Core Language

Syntactic Sugar

- **Boolean Operators**

  $not \equiv \lambda\ x.\ x\ false\ true$

  $e_1 \&\& e_2 \equiv (\lambda\ x.\ \lambda\ y.\ x\ y\ false)\ e_1\ \ e_2$

  $e_1 || e_2 \equiv (\lambda\ x.\ \lambda\ y.\ x\ true\ y)\ e_1\ \ e_2$

- **Relative Operators**

  $e_1 \leq e_2 \equiv (\lambda\ x.\ \lambda\ y.\ iszero\ (n\ pred\ m))\ e_1\ \ e_2$

  $e_1 < e_2 \equiv (\lambda\ x.\ \lambda\ y.\ not\ (y\ leq\ x))\ e_1\ \ e_2$

  $e_1 == e_2 \equiv (\lambda\ x.\ \lambda\ y.\ (y\ leq\ x) \&\& (x\ leq\ y))\ e_1\ \ e_2$

  $e_1 \geq e_2 == e_2 \leq e_1$

  $e_1 > e_2 == e_2 < e_1$

The Core Language

Syntactic Sugar

- **Let Definitions**
  $let\ x\ =\ e_1\ in\ e_2 \equiv (\lambda\ x.\ e_2)\ e_1$
- **Let rec is more tricky**
  $let\ rec\ x\ =\ e_1\ in\ e_2 \equiv (\lambda\ x.\ e_2)\ (\boldsymbol{Y}\ (\lambda\ x.\ e_1))$
  remember that $Y \equiv \lambda\ f.\ (\lambda\ x.\ f\ (x\ x))\ (\lambda\ x.\ f\ (x\ x))$
  Alternatively, we can add a new construct to simulate Y's behavior: $let\ rec\ x\ =\ e_1\ in\ e_2 \equiv (\lambda\ x.\ e_2)\ (\boldsymbol{Fix}\ (\lambda\ x.\ e_1))$
  In both cases e_1 is allowed to refer to x. The difference is that, unlike Y, $\boldsymbol{Fix}$ can be typed with the following rule:

$$\frac{\Gamma \vdash e : \tau \rightarrow \tau}{\Gamma \vdash Fix\ e : \tau}fix$$

The Core Language

Evaluation Strategies

Currently Jebus supports two different evaluation strategies: normal order and applicative order, with the former being a non-strict evaluation strategy and the later a strict one.

In general:

- **Normal Order** The leftmost outermost redex is always reduced first
- **Applicative Order** The leftmost innermost redex is always reduced first

Both strategies evaluate the body of an unapplied function.

Evaluation Strategies

Normal Order

The normal order reduction will always produce a normal form, if one exists!

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

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

$$\frac{e\ \rightarrow\ e'}{v\ e \rightarrow v\ e'}$$

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

Evaluation Strategies

Applicative Order

Applicative order reduction is not normalizing!

$$\frac{}{(\lambda\ x.\ v_1)\ v_2 \rightarrow v_1[v_2/x]}$$

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

$$\frac{e \ \rightarrow\ e'}{v\ e \rightarrow v\ e'}$$

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

Evaluation Strategies

Semantics for fix

We can think fix as function that takes a function and computes its fixed point.

$$\frac{}{(\mathit{fix}\ \lambda\ x.\ e) \rightarrow e[\mathit{fix}\ \lambda\ x.e/x]}$$

$$\frac{e \ \rightarrow \ e'}{\mathit{fix}\ e \rightarrow \mathit{fix}\ e'}$$

Note that $e[\mathit{fix}\ \lambda\ x.e/x] \equiv_{\beta} (\lambda\ x.e)\ (\mathit{fix}\ \lambda\ x.e) \equiv \mathit{fix}\ \lambda\ x.e$, just like $f\ (\ Y\ f) \equiv\ Y\ f$.

Evaluation Strategies

Fix: Example

$$
\begin{aligned}
& \quad \mathit{let\ rec\ fact} \ = \ \lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)\ \mathit{in\ fact}\ 3 \\
&\rightarrow (\lambda\ \mathit{fact}.\ \mathit{fact}\ 3)\ (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1))) \\
&\rightarrow (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ 3 \\
&\rightarrow (\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (x-1))\ 3 \\
&\rightarrow \mathit{if\ iszero}\ 3\ \mathit{then}\ 1\ \mathit{else}\ 3 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (3-1) \\
&\rightarrow 3 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ 2 \\
&\rightarrow 3 * (\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (x-1))\ 2 \\
&\rightarrow 3 * \mathit{if\ iszero}\ 2\ \mathit{then}\ 1\ \mathit{else}\ 2 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (2-3) \\
&\rightarrow 3 * 2 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ 1 \\
&\rightarrow 3 * 2 * (\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (x-1))\ 1 \\
&\rightarrow 3 * 2 * \mathit{if\ iszero}\ 1\ \mathit{then}\ 1\ \mathit{else}\ 1 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (1-1) \\
&\rightarrow 3 * 2 * 1 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ 0 \\
&\rightarrow 3 * 2 * 1 * (\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (x-1))\ 0 \\
&\rightarrow 3 * 2 * 1 * \mathit{if\ iszero}\ 0\ \mathit{then}\ 1\ \mathit{else}\ 0 * (\boldsymbol{\mathit{fix}}\ (\lambda\ \mathit{fact}.\lambda\ x.\ \mathit{if\ iszero}\ x\ \mathit{then}\ 1\ \mathit{else}\ x * \mathit{fact}\ (x-1)))\ (0-1) \\
&\rightarrow 3 * 2 * 1 * 1
\end{aligned}
$$

Evaluation Strategies

Normal Order vs. Applicative Order

Consider the following programs:

```
> cat ite.lam
let f = \x.
    if (iszero x) then x + 3
    else x * 3
in
    f 0
```

Figure 3 : ite.lam

```
> cat fact.lam
let rec fact = \x.
    if (iszero x) then 1
    else x * fact (x-1)
in
    fact 4
```

Figure 4 : fact.lam

Evaluation Strategies

Normal Order vs. Applicative Order

Applicative order needs 4 more beta reductions. Applicative order is a strict reduction strategy so both the then and the else parts will be evaluated.

```
> ./jebus eval -e=normal -t < ite.lam
(\f . f (\f . \x . x)) ...... =>
... =>
...
... =>
\f . \x . f (f (f x))
Performed 11 beta reductions.
```

Figure 5 : Evaluate ite.lam with normal order strategy. Only 11 beta reductions needed.

```
> ./jebus eval -e=applicative -t < ite.lam
(\f . f (\f . \x . x)) ...... =>
... =>
...
... =>
\f . \x . f (f (f x))
Performed 14 beta reductions.
```

Figure 6 : Evaluate ite.lam with applicative order strategy. 15 beta reductions needed.

Evaluation Strategies

Normal Order vs. Applicative Order

```
> ./jebus eval -e=normal -t < fact.lam
((\. fac (\f . \x . f (f (f (f x))))) . . . . . . =>
. . . =>
. . .
. . . =>
\z . \x . z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z (z x)...)
Performed 9236 beta reductions.
```

Figure 7 : Evaluate fact.lam with normal order strategy. The program terminates after 9236 reductions.

Evaluation Strategies

Normal Order vs. Applicative Order

```
> ./jebus eval -e=applicative -t < fact.lam
((\. fac (\f . \x . f (f (f (f x))))) ...... =>
... =>
...
...
```

Figure 8 : Evaluate fact.lam with applicative order strategy. The program does not terminate.

How to use Jebus

Jebus reads a program from the standard input and can print the type annotated version of the program after the type inference or evaluate the program with the selected strategy. You can also trace the evaluation and count the number of reduction steps.

```
jebus [COMMAND] ... [OPTIONS]

Common flags:
  -h –help              Display help message
  -V –version           Print version information

jebus annot
  Print an explicitly typed version of the program

jebus eval [OPTIONS]
  Interpret the program

  -t –trace             show each beta reduction
  -e –eval=EVALMODE     specify evaluation strategy: normal
                        (default) or applicative
```

Useful links

- Notes form NTUA's Applications of Logic in Computer Science course
- Chapter 5 from the book Formal Syntax and Semantics of Programming Languages, Kenneth Slonneger, Barry L. Kurtz
- Hindley-Milner Typing and Algorithm W from Compiler Construction course notes, Utrech University
- lambda library from NYU Lambda Seminar
- Simply typed lambda calculus extensions from Programming Languages course notes, University of Washington

The end!

Demo

Fork here!