Compilation II: In Practice

CAS CS 320: Principles of Programming Languages

December 5, 2024 (Lecture 25)

Practice Problem

$$\cdot \vdash \lambda x.\lambda y.\lambda z.xz(yz) : \tau \dashv \mathcal{C}$$

Determine τ and $\mathcal{C}$ so that the above judgment is derivable in Hindley-Milner Light (HM^{-}). Solve the constraints $\mathcal{C}$ and determine the principle type of this expression

Answer

$$\cdot \vdash \lambda x.\lambda y.\lambda z.xz(yz) : \tau \dashv \mathcal{C}$$

Today

- Discuss stack-based languages
- Look a bit more deeply at the inner-workings of OCaml's compiler
- Talk briefly about what you can do if you're still interested in PL
- Fill out course evals(!)

Outline

Recap: Stack-Based Languages

Compilation/Bytecode Interpretation

Variables

OCaml Backend

What's next?

Recall: High-Level

A stack-oriented language is a programming language which directly manipulates a stack of values (or multiple stacks)

There are roughly two categories of stack-oriented languages:

- "usable" stack-oriented languages, e.g. Forth
- instruction sets for virtual machines, e.g., JVM, CPython interpreter, Lua (not any more), OCaml bytecode interpreter

A virtual (stack) machine is a computational abstraction, like a Turing machine (but usually **easier to implement**).

Virtual machines are typically implemented as bytecode interpreters, where "programs" are streams of bytes and a command in the language are represented as a byte

Arithmetic (Syntax)

$$
\begin{aligned}
\texttt{<prog>} &::= \{\texttt{<com>}\} \\
\texttt{<com>} &::= \texttt{ADD} \mid \texttt{SUB} \mid \texttt{MUL} \mid \texttt{DIV} \mid \texttt{PUSH}\ \texttt{<num>} \\
\texttt{<num>} &::= \mathbb{Z}
\end{aligned}
$$

Arithmetic (Values and Configurations)

$$\langle\ \mathcal{S}\ ,\ \mathcal{P}\ \rangle$$

We take a value to be an integer ($\mathbb{Z}$)

A **configuration** is made up of a stack ($\mathcal{S}$) of values and a program ($\mathcal{P}$) given by `<prog>`

Arithmetic (Small-step Semantics)

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\, m :: n :: \mathcal{S} \;,\; \texttt{ADD}\ \mathcal{P} \,\rangle \longrightarrow \langle\, (m+n) :: \mathcal{S} \;,\; \mathcal{P} \,\rangle}\ \textsf{(add)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\, m :: n :: \mathcal{S} \;,\; \texttt{SUB}\ \mathcal{P} \,\rangle \longrightarrow \langle\, (m-n) :: \mathcal{S} \;,\; \mathcal{P} \,\rangle}\ \textsf{(sub)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\, m :: n :: \mathcal{S} \;,\; \texttt{MUL}\ \mathcal{P} \,\rangle \longrightarrow \langle\, (m \times n) :: \mathcal{S} \;,\; \mathcal{P} \,\rangle}\ \textsf{(mul)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z} \qquad n \neq 0}{\langle\, m :: n :: \mathcal{S} \;,\; \texttt{DIV}\ \mathcal{P} \,\rangle \longrightarrow \langle\, (m/n) :: \mathcal{S} \;,\; \mathcal{P} \,\rangle}\ \textsf{(div)}$$

$$\frac{}{\langle\, \mathcal{S} \;,\; \texttt{PUSH}\ n\ \mathcal{P} \,\rangle \longrightarrow \langle\, n :: \mathcal{S} \;,\; \mathcal{P} \,\rangle}\ \textsf{(push)}$$

Example (Evaluation)

```
PUSH 2 PUSH 3 ADD PUSH 4 MUL
```

Outline

Compilation

Compilation is the process of *translating* a program in one language to another, maintaining semantic behavior.

Compilation can be a part of interpretation as well, like with bytecode interpretation (this is what OCaml does).

Simple case: *every arithmetic expression can be represented as an equivalent expression in reverse polish notation.*

Bytecode Interpreters

A bytecode interpreter is an implementation of a virtual machine with a simple-command based language where each operation is mapped to a *byte*. This is called the code of the operation, or the opcode

The primary benefits are simplicity and portability. There's no parser, there's no fussing with string

Let's take a quick look at some code

Example (Compilation, by Intuition)

```
4 * (2 + 3)
```

Demo: Compiling Arithmetic Expressions

We'll walk though a small bit of code for compiling arithmetic expressions, both into a program and into a stream of bytes which piped to a bytecode interpreter.

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(Immutable) Variables (Syntax)

<prog> ::= {<com>}

<com> ::= ADD | SUB | MUL | DIV | PUSH <num>

| ASSIGN <var> | LOOKUP <var>

<num> ::= $\mathbb{Z}$

<var> ::= $\mathbb{I}$

(Immutable) Variables (Values and Configurations)

$$\langle\ \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle$$

We take a value to be an integer ($\mathbb{Z}$)

A **configuration** is made up of a stack ($\mathcal{S}$) of values, *an environment* ($\mathcal{E}$) *mapping identifiers* ($\mathbb{I}$) *to values*, and a program ($\mathcal{P}$) given by <prog>

(Immutable) Variables (Small-step Semantics)

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\ m :: n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{ADD}\ \mathcal{P}\ \rangle \longrightarrow \langle\ (m + n) :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle}\ \textsf{(add)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\ m :: n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{SUB}\ \mathcal{P}\ \rangle \longrightarrow \langle\ (m - n) :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle}\ \textsf{(sub)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z}}{\langle\ m :: n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{MUL}\ \mathcal{P}\ \rangle \longrightarrow \langle\ (m \times n) :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle}\ \textsf{(mul)}$$

$$\frac{m \in \mathbb{Z} \qquad n \in \mathbb{Z} \qquad n \neq 0}{\langle\ m :: n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{DIV}\ \mathcal{P}\ \rangle \longrightarrow \langle\ (m / n) :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle}\ \textsf{(div)}$$

$$\frac{}{\langle\ \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{PUSH}\ n\ \mathcal{P}\ \rangle \longrightarrow \langle\ n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\ \rangle}\ \textsf{(push)}$$

(Immutable) Variables (Small-step Semantics)

$$\frac{}{\langle\, n :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{ASSIGN}\ x\ \mathcal{P}\,\rangle \longrightarrow \langle\, \mathcal{S}\ ,\ \mathcal{E}[x \mapsto n]\ ,\ \mathcal{P}\,\rangle}\ \textsf{(assign)}$$

$$\frac{\mathcal{E}(x) \neq \bot}{\langle\, \mathcal{S}\ ,\ \mathcal{E}\ ,\ \texttt{LOOKUP}\ x\ \mathcal{P}\,\rangle \longrightarrow \langle\, \mathcal{E}(x) :: \mathcal{S}\ ,\ \mathcal{E}\ ,\ \mathcal{P}\,\rangle}\ \textsf{(assign)}$$

Example

```
PUSH 2 ASSIGN x PUSH 3 ASSIGN y
LOOKUP x LOOKUP y ADD
```

Scoping

The language we've just described is only good for compiling from languages with dynamic scoping.

How would we compile the following program?

```
let y = 1 in
let x =
  let y = 2 in
  y + y
in x + y
```

Answer: *closures.* This is also how we deal with functions. (feel free to chat with me after if you're interested)

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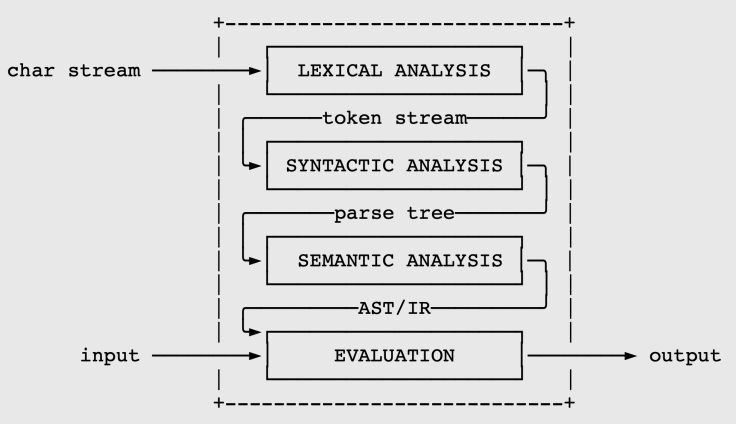
The Pipeline



OCaml's interpretation/compilation pipeline is *roughly* what we've implemented (with a couple more steps). Let's take a look

The OCaml Bytecode Compiler

OCaml has an underlying bytecode interpreter for a specially designed Caml virtual machine (designed by Xavier Leroy in 1990 in his master's thesis).

It's like the one we just looked at but *much* more complicated. Let's take a look

OCaml code is tranformed into bytecode and the run with `ocamlrun`

Let's do a quick demo

An Aside: The OCaml Native Compiler

If you want *fast* OCaml code, OCaml has a native compiler. This means it will generate assembly language

It works *completely differently* from the bytecode compiler

But it means it's possible to generate some pretty competitive code

If you're interested I recommend taking a look at the chapter in Real-World OCaml on the compiler backend

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Directions for Exploration

- More OCaml
  - More advanced module usage
  - Functional Data Structures
  - Real-World OCaml
  - Jane Street LINK
- More PL
  - Come learn Rust (and linear types) with me next semester!
  - Learn Haskell, Elm, Scala?
- More Math/Type Theory
  - Go learn more about grammars with Professor Stoughton next semester!
  - Go learn about session types with Professor Das next semester!
  - Category theory (functors, monads, comonads)
  - Logic
  - Type theory
- More Computers
  - Compilers (e.g., LLVM)
  - Formal methods

Fill out a Course Eval(!)