Reimplementing the Wheel: Teaching Compilers with a Small Self-Contained One

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We report on a one-semester compiler construction course based on the idea of implementing a small self-contained compiler for a small model language from scratch, not using other compiler construction frameworks. The course is built around an evolving family of languages with increasing expressiveness and complexity, which finally is crowned by a language with first-class functions, S-expressions, pattern matching, and garbage collection. The codegeneration technique is based on the idea of *symbolic interpreters*, which allows to implement a robust albeit not very efficient native code generator. We give the motivation for the course, describe its structure, and report some results of teaching based on students' post-course surveys.

1 Introduction

Compilers are probably the most important tools for software engineers; understanding how compilers work is one of the basic (if not the first) skills for them to master. Thus, to no surprise, compiler design and construction as a separate subject often is included in the curriculum in many colleges and universities all over the world.

Since the first compilers implemented in the middle of the 20th century the craft of compiler-making has advanced tremendously. Modern compilers implement a wide range of optimizations and perform a large number of transformations on the way to the executables, and their sources total millions of lines of code. This makes a balance between the completeness of covered topics and the completeness of reference compiler implementation a tough problem. Typically, a course on compiler construction collects a wide range of topics from lexical and syntax analysis to SSA form construction, register allocation, instruction scheduling, etc. As a rule, instead of a working hardware some simplified abstract machine (or even a high-level language like C or SCHEME) is taken; alternatively, an infrastructure like LLVM [21, 5], GCC [1], GraalVM [2] or WebAssembly [7] is used as a backend. This, in turn, sweeps a lot of work under the carpet. Even if some real processor is targeted the completeness of the implemented compiler remains questionable since it requires a lot of testing and debugging to generate a correct code for "serious" programs beyond simplistic ones used as smoke tests.

We advocate a different approach aimed at building a complete compiler for a simple, but not a toy language from scratch, not relying on any compiler construction framework. Moreover, instead of textbook codegeneration algorithms with advanced instruction selection, register allocation and scheduling [26, 25] we use a simplified one based on *symbolic interpreters*. This approach is much easier to understand, implement, debug and test, and it is not as fragile as the conventional ones at the price of less efficient code being generated. Yet it provides means to implement a full-fledged compiler from the source language to a real working machine code. We argue that after a simplistic but complete compiler

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```
import List;
import Fun;

public infixl ⇒ before $ (x, f) {
  fun (state) {
    case x (state) of
      [state, x] → [state, f (x)]
    esac
  }
}

public infix ⇛ at ⇒ (x, f) {
  fun (state) {
    case x (state) of
      [state, x] → f (x) (state)
    esac
  }
}

public fun returnST (x) {
  fun (state) {[state, x]}
}
```

(a) State monad implementation

```
var simpleStmt = memo $ eta syntax (
      kSkip                                    {Skip}
    | x=lident s[”:=”] e=exp                   {Assn (x, e)}
    | kRead   x=inbr[s(”(”), lident, s(”)”)] {Read (x)}
    | kWrite  e=inbr[s(”(”), exp   , s(”)”)] {Write (e)}
    | kWhile  e=exp b=inbr[kDo, stmt, kOd]   {While (e, b)}
    | kDo     b=stmt kWhile e=exp kOd        {DoWhile (b, e)}
    | −kIf ifPart −kFi
    ),
    elsePart = memo $ eta syntax (
      empty {Skip}
    | −kElse stmt
    | −kElif ifPart
    ),
    thenPart = memo $ eta syntax (−kThen stmt),
    ifPart   = memo $ eta syntax (
      cond=exp th=thenPart el=elsePart {If (cond, th, el)}
    ),
    stmt     = memo $ eta syntax (
      simpleStmt
    | s1=simpleStmt s[”;”] s2=stmt {Seq (s1, s2)}
    );
```

(b) An example of syntax description

Figure 1: $\lambda^a\mathcal{M}^a$ Samples

is implemented more advanced methods can be easily mastered later by those who actually strive to work in the real compiler industry.

For the course we have developed a language called “$\lambda^a\mathcal{M}^a$” (pronounced “*lamah*”) [4], which is an acronym for “λ-ALGOL” since the language inherited the shape of its syntactic constructs from ALGOL-68. In a nutshell, $\lambda^a\mathcal{M}^a$ is an ALGOL-like language with first-class functions and automatic memory management in the form of garbage collection; we describe it in more details in Section 2. The compiler for $\lambda^a\mathcal{M}^a$ was initially written in OCAML for X86-32/LINUX platform relying only on binutilities and internally using GCC as a driver. For several years the students were implementing their compilers in OCAML; however, during the recent three semesters, we switched the implementation language to $\lambda^a\mathcal{M}^a$ itself, which opens a way for bootstrapping. We consider using the same language both as the source and implementation one as an important advantage by a number of reasons. First, the ability to be used as implementation language is a strong argument for the maturity of the language and, more important, the maturity of the methods used in its compiler implementation. Thus, by using exactly the same language as they are implementing and the same compiler as they are writing the students acquire a justification that they are studying a working technology. Then, in order to implement a correct compiler the students need to internalize the knowledge of the source language semantics. Since the implementation language is the same as the source one, this makes the students better understand the semantics of the language they use. Finally, when the source language coincides with the implementation one some tasks can be solved in a simpler way due to the identity of their semantics.

2 The $\lambda^a\mathcal{M}^a$ Programming Language

$\lambda^a\mathcal{M}^a$ borrows the syntactic shape of operators from ALGOL-68 [30]; HASKELL [3] and OCAML [6] can be mentioned as other languages of inspiration. The general characteristics of the language are:

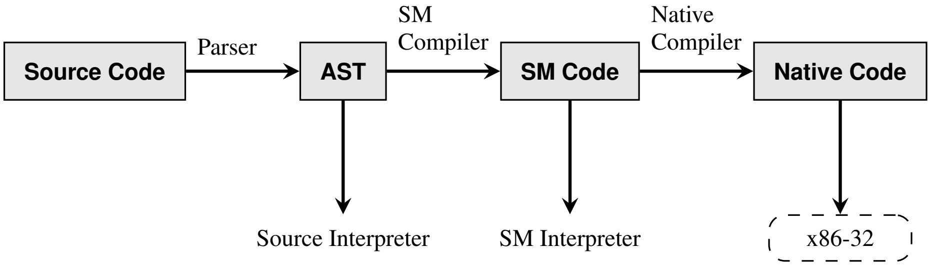

Figure 2: The structure of reference $\lambda^a\mathcal{M}^a$ compiler

- procedural with first-class functions — functions can be passed as arguments, placed in data structures, returned and “constructed” at runtime via closure mechanism;
- with lexical static scoping;
- strict — all arguments of function application are evaluated before function body;
- imperative — variables can be re-assigned, function calls can have side effects;
- untyped — no static type checking is performed;
- with S-expressions and pattern-matching;
- with user-defined infix operators, including those defined in local scopes;
- with automatic memory management (garbage collection).

The main purpose of $\lambda^a\mathcal{M}^a$ design is to present a repertoire of constructs with certain runtime behavior and relevant implementation techniques. The lack of a type system (a vital feature for a real-word language for software engineering) is an intentional decision that allows demonstrating an unchained diversity of runtime behaviors, including those which a typical type system is called to prevent. On the other hand, the language can be used in future as a raw substrate to apply various ways of software verification (including type systems).

In addition to a conventional set of constructs, $\lambda^a\mathcal{M}^a$ incorporates an extension to embed syntax definitions in the form of semantic-extended EBNF into the programs. These definitions are converted into the compositions of parser combinator applications from $\lambda^a\mathcal{M}^a$ standard library. In the Fig. 1 two $\lambda^a\mathcal{M}^a$ samples are given: a definition of state monad from the standard library (Fig. 1a) and an excerpt from $\lambda^a\mathcal{M}^a$ parser written in $\lambda^a\mathcal{M}^a$ itself (Fig. 1b).

3 The Structure of the Compiler

The current implementation of $\lambda^a\mathcal{M}^a$ contains a native code compiler for x86-32, written in OCaml ($\approx$ 3000 LOC), a runtime library with garbage-collection support, written in C ($\approx$ 1000 LOC), and a small standard library, written in $\lambda^a\mathcal{M}^a$ itself ($\approx$ 900 LOC). The native code compiler uses GCC as a driver.

The standard library implements a minimalistic set of features needed to fulfill all the assignments for the course: a set of collections, implemented as AVL trees, list- and array-processing functions, basic file operations, functional programming primitives for lazy evaluation, function application/composition/fix-pointing, etc., and the implementation of monadic CPS parser combinators with memoization [20, 19], which support left recursion and are capable of recognizing all context-free languages.

```
printf (”Hello, world!\n”)
```

(a) Source code

```
LABEL (”main”)
BEGIN (”main”, 2, 0, [], [], [])
STRING (”Hello, world!\\n”)
CALL (”Lprintf”, 1, false)
END
```

(b) Stack machine code

```
        .globl  main
        .data
string_0:.string ”Hello, world!\n”
main:
# BEGIN (”main”, 2, 0, [], [], []) /
# STRING (”Hello, world!\\n”) /
        movl    $string_0,      %ebx
        pushl   %ebx
        call    Bstring
        addl    $4,     %esp
        movl    %eax,   %ebx
# CALL (”Lprintf”, 1, false) /
        pushl   %ebx
        call    Lprintf
        addl    $4,     %esp
        movl    %eax,   %ebx
# END /
        movl    %ebx,   %eax
Lmain_epilogue:
        movl    %ebp,   %esp
        popl    %ebp
        xorl    %eax,   %eax
        ret
```

(c) Native code

Figure 3: An example of a program, stack machine code and native code

The structure of the compiler is shown in Fig. 2. Overall, it maintains the generic scheme of compiler implementation as a sequence of passes each of which performs a transformation of some intermediate representation of a program being compiled. In our case there are two such representations: an abstract syntax tree (AST) and a code for an abstract stack machine (SM). The compilation from AST to stack machine requires two passes taking into account closure conversion; the transformation from SM code into the native one requires one pass. In Fig. 3 an example of “Hello, world!” program compilation is presented; besides the source program itself its SM representation is shown as well as the native code for X86-32, compiled directly from that representation.

Besides conventional components, the compiler contains two extra ones: a source-level reference interpreter, which literally encodes the operational semantics, and an interpreter for the stack machine. Thus, a $\lambda^a\mathcal{M}^a$ program can be run is three modes: being interpreted in a direct correspondence with operational semantics, compiled to the stack machine code and compiled to native code. It is expected that the results of execution in all three modes should coincide for any program.

The decision to include two interpreters into the compiler serves the didactic purposes. As student assignments repeat the implementation of the reference compiler, they would involve implementing these interpreters as well, which serves the purpose of better understanding of how operational semantics works. In addition a capability of running a program in different representations would make it possible to discover and fix errors at earlier stages.

Language	**№**	**Assignments**
Straight-line Code with Assignments	1	INT, SM
	2	X86
	3	PARSER
Structural Control Flow	4	PARSER, INT
	5	SM, X86
Control Flow Expressions	6	PARSER, INT, SM, X86
Functions and Declaration Scopes	7	PARSER, INT
	8	SM, X86
Arrays and Strings	9	PARSER, INT, SM, X86
Fixnum Arithmetic	10	X86
S-expressions	11	PARSER, INT, SM, X86
Pattern-matching	12	PARSER, INT
	13	SM, X86
Closure Conversion and First-Class Functions	14	PARSER, INT
	15	SM, X86
Memory Management	16	RUNTIME

PARSER: parser
INT: reference interpreter
SM: stack machine interpreter and stack machine compiler
X86: native-code compiler
RUNTIME: runtime support library

Figure 4: The structure of the course

4 The Structure of the Course

The course revolves around a set of 12-16 assignments (depending on the actual schedule; it is assumed that an assignment has to be completed within a week). The assignments are *vertically*-oriented: a certain language feature has to be implemented in all components of the compiler from the parser to the code generator. Thus, instead of implementing, say, a parser for the whole language first, then a reference interpreter for the whole langauge, then stack machine compiler, etc., we ask students to implement in a top-down manner a set of compilers for an evolving family of languages. We argue that this structure of the course helps the students to internalize relevant compiler implementation techniques by completing the similar sets of tasks with increasing complexity level over and over again.

As we said earlier, the compiler consists of a reference source-level interpreter, a stack machine compiler and the stack machine interpreter, and a native code compiler. As a rule, each language in the family is implemented in two steps: first, a parser and a reference interpreter are implemented, and then the stack machine compiler and interpreter and native code compiler are added. For each language, its operational semantics is given as well as operational semantics for the current version of the stack machine (the stack machine evolves as well), which makes it possible to assess the correctness of the compiler formally (although we do not require this to be done).

We supply the students with the set of regression tests, some of which are hand-written and some —-autogenerated. The set of tests evolves together with the language to reflect its relevant properties. It is required that the student impementation passes all the tests, and it is forbidden for students to make

```
— Redefinition of standard infix operators
infix +  at +  (l, r) {Binop (”+”,  opnd (l), opnd (r))}
infix −  at −  (l, r) {Binop (”−”,  opnd (l), opnd (r))}
infix ∗  at ∗  (l, r) {Binop (”∗”,  opnd (l), opnd (r))}
infix /  at /  (l, r) {Binop (”/”,  opnd (l), opnd (r))}
infix %  at %  (l, r) {Binop (”%”,  opnd (l), opnd (r))}
infix == at == (l, r) {Binop (”==”, opnd (l), opnd (r))}
infix != at != (l, r) {Binop (”!=”, opnd (l), opnd (r))}
infix <  at <  (l, r) {Binop (”<”,  opnd (l), opnd (r))}
infix <= at <= (l, r) {Binop (”<=”, opnd (l), opnd (r))}
infix >  at >  (l, r) {Binop (”>”,  opnd (l), opnd (r))}
infix >= at >= (l, r) {Binop (”>=”, opnd (l), opnd (r))}
infix && at && (l, r) {Binop (”&&”, opnd (l), opnd (r))}
infix !! at !! (l, r) {Binop (”!!”, opnd (l), opnd (r))}
```

(a) A fragment of deep embedding implementation

```
read (”x”) >>
read (”y”) >>
”z” ::= ”y” ∗ ”y” >>
write (”x”+”z”)
```

(b) A sample test in the form of deep embedding

Figure 5: Deep embedding of straight-line programming language in $\lambda^a\mathcal{M}^a$

changes in the infrastructural parts of the project (e.g. in the Makefiles).

In addition to the tests we provide the students with the ready-to-use implementation of the infrastructure parts of the compiler. Such components as driver (which controls the order of transformations, reads and writes files, parses command-line options, etc.), implementations of symbol tables/environments, the interfaces between passes, etc., are all important parts of the compiler which define its architecture and are easy to mess with. At the same time the implementation of these components have only a distant relevance to the essence of compilation. By pre-supplying these compponents to the students we, first, free them from the burden of implementing and debugging the most “boring” parts of the compiler; at the same time we facilitate the use of the best practices in compiler writing since we provide students with an architecturally solid environment. Finally, using the same infrastructural parts of the compiler makes it easier for students’ implementations to pass the same set of tests since there is no difference in their interfaces.

The majority of assignments are incremental, meaning, that they amount to adding some functionality to previously completed assignments. There are some cases, however, when the architecture of the whole compiler changes drastically. We specifically point out these cases and help the students to go through the refactoring.

Some tasks might require more that one week to implement, debug and test in full. In this case we decompose the assignments in such a way that the hard one comes first, being followed by relatively simpler. We incrementally add more complex tests for the first one in each following assignment and warn the students, that they will most likely encounter more errors in already implemented parts of the compiler. Thus, we help the students to amortize their debugging and testing efforts by gradually increasing the complexity and coverage of the tests.

The summary of the course is shown in Fig. 4. In the next subsections we address specifically the concrete languges in the family and describe the assignments in more details.

4.1 Straight-line Programs with Assignments

The first language in the family contains a set of expressions and simple statements in the form of assignments, sequential composition, empty operator (“**skip**”) and reading/writing primitives. Expressions can contain variables, integer constants and thirteen basic arithmetic and logic operators; logic operators work on integer values *a la* C. Note, on this level the language is already equipped with a full set of arithmetic and logic operators of $\lambda^a\mathcal{M}^a$. No declarative constructs exist in the language at this stage; all variables are treated as global ones, defined implicitly.

The first assignment involves implementing a reference interpreter for the language, based on its big-step operational semantics, a stack machine interpreter and a compiler from the source language into the stack machine code. It does not, however, contain such task as implementing parser. Instead of the parser we use a deep embedding of the language into the $\lambda^a\mathcal{M}^a$. This embedding is implemented by redefining the standard binary operators of $\lambda^a\mathcal{M}^a$ to work with abstract syntax trees instead of integer values; additionally C preprocessor is used in a minimalistic manner (see Fig. 5a for a implementation snippet and Fig. 5b for a sample regression test in the form of deep embedding). This approach allows students to concentrate immediately on essential tasks — implementation of interpreter and stack machine compiler — without distracting them with so far not very important problem of implementing a parser.

The second assignment concerns implementing a native code generator. As we've said earlier, we utilize the concept of symbolic interpreter to generate machine code. We address this approach in more details in Section 5. Since in the first assignment the students have already implemented an interpreter for stack machine, the problem should not be very challenging. There are, however, a number of subtleties — for example, unlike stack machine and source-level interpreter in machine code a number of declarations for global variables has to be generated. Another issue concerns the implementation of binary operators — while in source-level interpreter and stack machine the correspondence between operators in target and source languages is one-to-one, in the machine code a more elaborated projections have to be used. Finally, in X86 registers are not fully symmetric — there are some dedicated registers which should be used to perform certain operations, and these requirements have to be taken into account. For the second assignment we provide the students with a minimalistic set of tests which only verify the basic cases. We add more tests in the next assignments thus providing the students more time for debugging.

Finally, the third assignment consists of implementing a parser for already implemented compiler. Thus, after three assignments (and three weeks) the students cover all essential tasks in order to implement a native code compiler for a simple imperative language.

4.2 Structural Control Flow

The next language in the family introduces control flow constructs: branching and looping. Two assignments are scheduled for this language: for the first, a parser and reference interpreter have to be implemented, for the second — the compiler and interpreter for the stack machine and native code compiler.

With this language we introduce the students to the notion of a *syntax extension*, or "desugaring". On abstract syntax level, we only introduce a simplistic branching construct

$$\textbf{if}\ c\ \textbf{then}\ s_1\ \textbf{else}\ s_2\ \textbf{fi}$$

However, in concrete syntax we add two derived forms: a reduced one with no "**else**" part and multiple-branching form

$$\begin{array}{l}\textbf{if}\ c_1\ \textbf{then}\ s_1\\ \textbf{elif}\ c_2\ \textbf{then}\ s_2\\ \dots\\ \textbf{elif}\ c_k\ \textbf{then}\ s_k\\ \textbf{else}\ s_{k+1}\end{array}$$

```
start :
        ⟦c⟧
        JZ  exit     (⋆)
        ⟦s⟧
        JMP start
exit :
```

(a) Naïve

```
        JMP cond
loop :
        ⟦s⟧
cond :
        ⟦c⟧
        JNZ loop
```

(b) Advanced

Figure 6: A naïve and advanced implementations for **while** c **do** s **od**

fi

and require to convert these derived forms during the parsing stage into the basic AST using the obvious rules. Similarly, at abstract syntax level we introduce a basic looping construct

while c **do** s **od**

while in concrete syntax we add a derived form

for s_1 , c , s_2 **do** s_3 **od**

which should be converted into

s_1 ; **while** c **do** s_3 ; s_2 **od**

Thus, we show how using a simple method a language can be "pumped" with a variety of constructs. And here comes a counterexample: we demonstrate, that this method can not be used to implement a post-condition looping construct. Indeed, an obvious conversion rule

do s **while** c **od** $\rightsquigarrow$ s; **while** c **do** s **od** $(\star)$

would lead to an *exponential* growth of AST in the case of nested loops. Thus, instead, we ask the students to devise a direct big-step operational semantics for post-condition loops in such a way the relation $(\star)$ holds, and implement the construct in a direct style.

In stack machine all control flow constructs are represented using labels and conditional/unconditional jumps. The correspondence between stack machine code and native code is almost one-to-one, so the main job has to be done at stack machine compilation stage. Here we address two subtleties:

- A naïve conversion of control constructs into the composition of labels and jumps can lead to a situation when an exit from a nested branching/looping construct is performed by a chain of jump-to-jump instructions of the length proportional to the nesting level;
- There is a well-known technique of compiling precondition loops when an additional jump to the condition test is introduced first which allows to reduce the number of jumps in the body. In Fig. 6a a naïve loop implementation is shown with extra jump instruction marked by $(\star)$; a better version is given in Fig. 6b. Here $[\![\bullet]\!]$ denotes the result of codegeneration for a given construct.

For modern processors with branch prediction neither of these subtleties are essential from the performance standpoint. We, however, still consider discussing these issues an essential component of the course.

$$
\begin{array}{cccc}
\mathbf{ref}\ x : \mathbf{Ref} & x : \mathbf{Val} & \mathbf{ignore}\ x : \mathbf{Void} & x \in \mathscr{X} \\[1em]
 & z : \mathbf{Val} & \mathbf{ignore}\ z : \mathbf{Void} & z \in \mathbb{N} \\[1em]
 & \dfrac{l : \mathbf{Val}\,, \quad r : \mathbf{Val}}{l \oplus r : \mathbf{Val}} & \dfrac{l : \mathbf{Val}\,, \quad r : \mathbf{Val}}{\mathbf{ignore}\ l \oplus r : \mathbf{Void}} & \\[1em]
 & & \mathbf{skip}\ : \mathbf{Void} & \\[1em]
 & \dfrac{l : \mathbf{Ref}\,, \quad r : \mathbf{Val}}{l := r : \mathbf{Val}} & \dfrac{l : \mathbf{Ref}\,, \quad r : \mathbf{Val}}{\mathbf{ignore}\ \ (l := r) : \mathbf{Void}} & \\[1em]
 & & \mathbf{read}\ \ (x) : \mathbf{Void} & \\[1em]
 & & \dfrac{e : \mathbf{Val}}{\mathbf{write}\ \ (e) : \mathbf{Void}} & \\[1em]
\dfrac{s_1 : \mathbf{Void}\,, \quad s_2 : a}{s_1 ; s_2 : a} & \dfrac{e : \mathbf{Val}\,, \quad s_1 : a, \quad s_2 : a}{\mathbf{if}\ e\ \mathbf{then}\ s_1\ \ \mathbf{else}\ s_2\ \ \mathbf{fi}\ \ : a} & \dfrac{e : \mathbf{Val}\,, \quad s : \mathbf{Void}}{\mathbf{while}\ e\ \mathbf{do}\ s\ \mathbf{od} : \mathbf{Void}} & \\[1em]
 & \dfrac{e : \mathbf{Val}\,, \quad s : \mathbf{Void}}{\mathbf{do}\ s\ \mathbf{while}\ e\ \mathbf{od} : \mathbf{Void}} & &
\end{array}
$$

Figure 7: Inference system for expression well-formedness

4.3 Control-Flow Expressions

In the previous language there were two main syntactic categories: expressions and statements. Thus, one could not write

```
if x then y else 3 fi + z
```

or

```
if x then y else z fi := 3
```

etc. As we eventually plan to end up with a language with first-class functions, which is expected to be essentially expression-type, we need to refactor the language by converting statements into expressions.

The only assignment at this point is the first non-incremental one. Although no new constructs are introduced in the languages, the syntactic roles of some of them change, which amounts to an essential refactoring of the compiler. Fortunately, this refactoring primarily concerns parser. All other components of the compiler have to undergo only cosmetic changes.

The main problem which has to be addressed now is the problem of AST well-formedness. Indeed, in the previous language the well-formedness could easily be enforced syntactically. Now, however, we need a more elaborated way to prevent one from writing a “meaningless” code like

```
while x do skip od := y
```

or

```
skip + 3
```

```
var simpleStmt = memo $ eta syntax (
      kSkip                              {Skip}
    | x=lident s[”:=”] e=exp             {Assn (x, e)}
    | kRead    x=inbr[s(”(”), lident, s(”)”)] {Read (x)}
    | kWrite   e=inbr[s(”(”), exp   , s(”)”)] {Write (e)}
    | kWhile   e=exp b=inbr[kDo, stmt, kOd]   {While (e, b)}
    | kDo      s=stmt kWhile e=exp kOd        {DoWhile (s, e)}
    | ...);
```

(a) Simple semantic actions

```
var primary  = memo $ eta syntax (
      ...
      loc=pos kSkip                                  {fun (a) {assertVoid (a, Skip, loc)}}
    | loc=pos kRead  x=inbr[s (”(”), lident, s (”)”)] {fun (a) {assertVoid (a, Read (x), loc)}}
    | loc=pos kWrite e=inbr[s (”(”), exp   , s (”)”)] {fun (a) {assertVoid (a, Write (e (Val)))}}
    | loc=pos kWhile e=exp b=inbr[kDo, exp, kOd]     {fun (a) {assertVoid (a, While (e (Val), b (Void)), loc)}}
    | loc=pos kDo s=exp kWhile e=exp kOd             {fun (a) {assertVoid (a, DoWhile (s (Void), e (Val)), loc)}}
    | ...);
```

(b) Semantics actions in the form of inference system

Figure 8: Parser implementation with simple semantic actions vs. semantic actions in the form of inference system

For this purpose we equip the language with a simple effect system, which assigns a certain *kind* to each expression. The kinds are propagated in a top-down manner, and are used both to *check* and *infer* well-formed AST.

There are three kinds: **Ref** , **Val** , and **Void** , which correspond, respectively, to a reference (an expression in assignment position), integer value, or an empty value. Additionally, there are two specific nodes in the AST — “**ignore**” and “**ref**” — which do not have a direct representation in the concrete syntax. These nodes are *inferred* in order to make the AST well-formed. The topmost kind is always **Void** .

The inference system for kinds is shown in Fig. 7; we demonstrate how it works by example. Let us have the following expression:

if x **then** y **else** z **fi** := 2

The topmost kind is **Void** , and the topmost construct is assignment. Thus, the only possible well-formed AST which can be inferred is

ignore (**if** x **then** y **else** z **fi** := 2) : **Void**

under the assumptions

if x **then** y **else** z **fi** : **Ref**

and

2 : **Val**

The second ones checks immediately; the first one is reduced to

x : **Val**
y : **Ref**
z : **Ref**

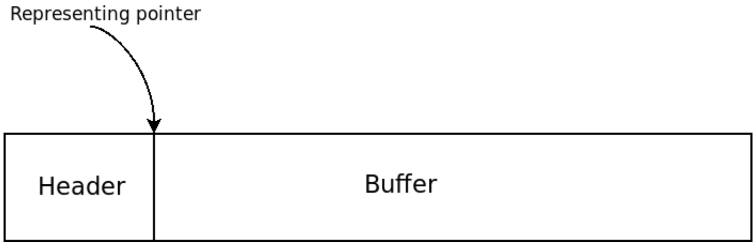

Figure 9: The representation of boxed data

which finally gives us the following well-formed AST:

ignore (**if** x **then** (**ref** y) **else** (**ref** z) **fi** := 2)

The inference system is implemented directly in the parser. As we noticed earlier, the kinds are propagated in a top-down manner, and the only inference steps are those inserting extra **ref**/**ignore** AST nodes. This can be easily implemented by lifting parser semantic actions into kind-accepting functions. Thus, a function which takes a top-level kind is returned from the parser. By applying this function to **Void** we either get a well-formed AST, or fail with an error. An example of parser implementation with simple/lifted semantic actions is shown in Fig. 8. For the assignment we give students a partially-refactored parser and ask them to complete it.

4.4 Scopes of Definitions and Functions

The next language in the family adds scopes of definitions and functions. Although functions in this language can be syntactically nested, at this stage they can not use the declarations from the enclosing functions yet; later we implement closure conversion, a general technique for first-class functions.

The declarations come in two flavors — for variables (mutable) and values (immutable). Of course these constructs are introduced at the expression level in the form of *scope expressions*. Additionally, the existing parser is modified by allowing scope expressions in a number of contexts (for example, in the branches of conditional expressions, etc.) Two assignments are scheduled for this language. In the first, scope expressions and functions have to be implemented in the parser and reference interpreter. In the interpreter the scopes are represented in a direct way as lists of declarations and their values. In the second assignment a compiler for stack machine and native-code compiler have to be implemented; the main work has to be done at stack machine level since the correspondence between stack machine and native code is almost one-to-one. Unlike reference interpreter, in stack machine all local definitions in a function have to be accumulated and properly addressed; in addition, in machine code calling conventions have to be respected and activation records of functions have to be properly organized.

4.5 Arrays, Strings and Builtins

All previous languages in the family operated only with scalar integer values. The next one introduces the constructs to deal with arrays and strings; in particular, it puts to work the notion of *builtin* functions — predefined functions which the compiler is aware of.

Arrays and strings are introduced by adding new kinds of expressions:

- string, character and array constants;
- indexing expressions.

It is assumed that indexing expressions can be used both to extract an element form array/string as well as to assign to an element; the kind inference system described in Section 4.3 is modified to handle the new kinds of expressions.

As arrays and strings are represented by references, in operational semantics an abstraction of memory is introduced in a conventional way. It is interesting, however, that in reference interpreter no explicit representation for memory abstractions is needed. Indeed, as the implementation language coincides with the source one, it is already natively equipped with exactly the same abstractions. In other words, in reference interpreter we can represent arrays by arrays and strings by strings, which delivers us the expected behavior.

At this stage for the first time we need a non-trivial support from the runtime library. In all previous languages the runtime support library only included two primitives for reading/writing integer values from standard input and output. For arrays and string we need, first, to define their representation in memory and, second, provide a number of builtin functions.

The generic layout for arrays/strings is shown in Fig. 9. Both are represented as a contiguous region of memory (buffer) preceded by a header. The header contains some supplementary information (in particular, a tag to distinguish strings from arrays, and the length of the buffer; later a few bits are allocated in the header for garbage collection support). The difference between string and arrays is that for strings the length of the buffer is calculated in bytes, while for generic arrays — in words. In addition an extra ending zero is kept at the end of a string. The interesting part is that both strings and arrays are represented in $\lambda^a\mathcal{M}^a$ programs by a pointer to the beginning of the buffer, not to the header. This trick makes it possible to mimic data representation compatible with GLIBC (in particular, it makes it possible to pass $\lambda^a\mathcal{M}^a$ strings as arguments to GLIBC functions).

The same layout will be later used for the rest of data structures in $\lambda^a\mathcal{M}^a$ — S-expressions and closures.

The set of builtin functions for array/string support includes those for creating arrays and strings, assigning to an element and taking an element by an index. All of them are implemented in C, some of them take a variable number of parameters. We provide the students with these functions implementation. The assignment at this stage includes studying the runtime and implementing arrays/strings at all levels of the compiler — the reference interpreter, extended stack machine, and native code.

4.6 Fixnum Arithmetic

In $\lambda^a\mathcal{M}^a$ numbers are represented in a fixnum form with the least significant bit of a value always set to 1. This representation makes it possible to tell pointers apart from scalar values, which is essential for a number of language features support (in particular, pattern matching and garbage collection).

An assignment to introduce fixnum representation is the second non-incremental one since it requires reimplementation of arithmetic binary operators support in the native code compiler. No changes to the language itself are made at this stage.

4.7 S-expressions

In this assignment S-expressions are introduced into the language. Similarly to arrays/strings, this requires a number of runtime functions to be implemented. In memory S-expressions are represented similarly to arrays and strings (see Fig. 9); however, an additional word is required to store the symbol itself. In current implementation the first five characters of the symbol are packed into a 32-bit word; thus, the symbols are distinguished only by their first five characters.

```
var primary  = memo $ eta syntax (
   ...
     loc=pos kSkip {fun (a) {assertVoid (a, returnST $ Skip, loc)}}
   | loc=pos kWhile e=exp b=inbr[kDo, scopeExpr, kOd] {
       fun (a) {
         assertVoid (a, e (Val)  ⇛ fun (e) {
                       b (Void)  ⇒  fun (b) {
                         While (e, b)
                       }},
                     loc)
       }
     }
   | loc=pos kDo s=scopeExpr kWhile e=exp kOd {
       fun (a) {
         assertVoid (a, s (Void) ⇛ fun (s) {
                       e (Val)   ⇒  fun (e) {
                         distributeScope (s, fun (s) {DoWhile (s, e)})
                       }},
                     loc)
       }
     }
   | ...);
```

Figure 10: Lifting semantic actions into a state monad

Since S-expressions are represented similarly to arrays, they can be operated in a similar way. In particular, they can be indexed and their subvalues can be assigned. For example, the following equalities hold

```
A (1, 2) [1]          == 2
A (B (3)) [0][0]      == 3
length (C (1, 2, 3)) == 3
```

et cetera.

4.8 Pattern Matching

In the support of pattern matching we again use desugaring in order to simplify the implementation. Namely, we desugar bindings in patterns into a number of value declarations. For example, the following source-level expression

```
case f (x + y) of
   A (_, n)      → n
|  B (C (k, l))  → k + l
esac
```

is desugared into

```
val s = f (x + y);
case s of
   A (_, _)      → val n = s[1]; n
|  B (C (_, _))  → val k = s[0][0], l = s[0][1]; k + l
esac
```

This approach greatly simplifies the support for pattern bindings by reducing it to already implemented support of nested declaration scopes. On the other hand, the desugaring has to be implemented properly. As, generally speaking, we need fresh names to bind scrutinees to, we need to reimplement the parser again, this time lifting the semantic actions into a state monad. The snippet from parser implementation is shown in Fig. 10.

Two assignments are scheduled for this language. First, the support for pattern matching has to be implemented in the parser and reference interpreter; this assignment, again, is not incremental since it involves the refactoring of the whole parser. Second, the support for pattern matching in stack machine and native-code compiler has to be implemented. As a rule, students use a simple top-down branching in their implementations, although we discuss in the class more elaborated methods for implementation of pattern matching [23, 24].

4.9 Closure Conversion and First-class Functions

Implementing first-class functions constitutes the final step in the language family evolution. Two assignments are scheduled for the task. In the first one first-class functions have to be implemented in parser and reference interpreter. In parser besides the implementation of lambda-expressions call expressions have also to be generalized to allow arbitrary expressions in the callee position. Surprisingly, the support for first-class functions in the interpreter is not a hard task at all since we already have the environments collected at right places.

The second assignment involves implementing closure conversion. This step is performed during the compilation to the stack machine code. First, a “draft” stack machine code is generated with a placeholders at closure initialization and call sites. During this first pass the following supplementary data structures are built:

- function declarations nesting tree;
- immediate closure elements (i.e. immediately referenced declarations from enclosing scopes);
- function reference graph (which function references which).

The construction of these data structures is performed within a compilation environment which implementation is provided as a part of the assignment; the students only need to call certain methods at certain places. After these data structures are built, the closure conversion can be implemented by propagating immediate closure elements using function reference graph and function nesting tree. Then the stack machine code generated during the first pass is traversed yet again and the placeholders for closure initializations and calls are replaced with the correct instructions.

Once stack machine code in generated, the implementation of native-code compiler becomes straightforward. The closures are represented in a similar way as other data structures, so a certain support from the runtime library has to be provided.

4.10 Memory Management

In this assignment the students are offered to implement a memory manager equipped with one of the basic garbage collection algorithms — mark-and-copy. The assignment consists of two parts. The first one is to implement a two-space heap with a simple sequential allocator which initializes garbage collection in case the active space is full. The second is a garbage collector implementation consisting of two classical subtasks: root identification and mark-and-copy phase. In order to identify all roots it

```
case i of
  READ        →  case readWorld (w) of
                   [n, w] → [n : st, s, w]
                 esac
| WRITE       →  case st of
                   n : st → [st, s, writeWorld (n, w)]
                 esac
| CONST (n)   →  [n : st, s, w]
| LD    (x)   →  [s (x) : st, s, w]
| ST    (x)   →  case st of
                   n : st → [st, s <- [x, n], w]
                 esac
| ...
esac
```

(a) Regular

```
case i of
  READ →
    case env.allocate of
      [s, env] → [env, code <+
                       Call ("Lread") <+
                       Mov (eax, s)]
    esac
| WRITE →
    case env.pop of
      [s, env] → [env, code <+
                       Push (s) <+
                       Call ("Lwrite") <+
                       Pop (eax)]
    esac
| CONST (n) →
    case env.allocate of
      [s, env] → [env, code <+ Mov (L (n), s)]
    esac
| LD (x) →
    case env.addGlobal (x).allocate of
      [s, env] → [env, code <+> move (env.loc (x), s)]
    esac
| ST (x) →
    case env.addGlobal (x).pop of
      [s, env] → [env, code <+> move (s, env.loc (x))]
    esac
| ...
esac
```

(b) Symbolic

Figure 11: Regular vs. symbolic interpreters for stack machine

is necessary to traverse the call stack and the static area word-by-word and identify all pointers into the heap. Due to the fixnum arithmetics the last bit of each word is used to precisely distinguish pointers from integers. Next, the marking phase is implemented by a recursive procedure which copies all the live object into the second space eliminating external fragmentation, lefts a forwarding pointer in the object old location, traverses the object for heap pointers and recursively calls the marking procedure. Finally, the second space has to be traversed in order to change the pointers to new objects locations. An additional optional challenge is to implement the marking procedure in an iterative manner with support for recovery after the stack overflow.

5 Code Generation with Symbolic Interpreters

In this section we describe the codegeneration approach which we use throughout the course. As we could see from the previous sections, the course involves implementing a variety of constructs in a tight schedule. This means that a robust method for codegeneration has to be used, since otherwise the amount of required debugging and testing efforts would exceed the students' capacity.

Conventionally, codegeneration can be logically split into the following subtasks:

- Instruction selection: a decomposition of source program constructs into a sequence of concrete machine instructions.
- Register allocation: an assignment of concrete registers as operands to selected instructions.

- Instruction scheduling: reordering instructions to make use of intrinsic parallelism of a concrete processor.

As a rule, these tasks can not be solved independently: for example, some instructions can not be chosen due to the lack of available registers at the moment; the way machine code can be scheduled depends on which concrete instructions were selected, etc. Thus, in real-world compilers multiple passes are performed in order to eventually solve all the tasks. Finally, generating production-quality code involves some combinatorial problems (for example, graph coloring) to be solved, which, in turn, require a specific supplementary data structures to be constructed. All this makes the process of codegenerator implementation a very fragile and error-prone task which require a lot of efforts to debug and test properly. However, in our course the task of implementing a codegenerator has to be solved multiple times, and applying conventional approaches would require unreasonable amount of efforts.

There is, however, a simple method which makes it possible to perform instruction selection and register allocation in one pass. The approach in question in fact is a part of compiler-writing folklore which is used to be known under the name "abstract interpretation" before the term was taken by a framework in the area of static analysis. The key idea is to use a symbolic interpreter for a language being compiled which operates on *locations* of data instead of the data itself. Thus, the task of implementing codegenerator reduces to the task of implementing yet another interpreter, making the whole approach a scalable and robust at the price of poorer code quality.

We demonstrate the codegeneration with the symbolic interpreter at work by the following simple example. Assume we have a stack machine with the following instructions:

- `LD` x — loads a value of a global variable x onto the stack;
- `ST` x — stores a value from the top of the stack into a global variable x;
- `CONST` n — puts a constant n onto the stack;
- `BINOP`$\otimes$ — performs a binary operation "$\otimes$" on the top two positions of the stack and puts the result back.

This stack machine is actually an essential subset of that for the first assignment. Let us have the following stack machine code:

```
CONST 1
LD  x
BINOP +
ST  y
```

A conventional stack machine interpreter would operate on a stack of numbers; the symbolic one, however, operates on a stack of locations w.r.t. hardware architecture (in our case, X86-32). We can assume that each location is either a hardware register (`%eax`, `%ebx`, ...) or a position on the hardware stack (`S` (0), `S` (1), `S` (2) etc., later converted into −4(`%ebp`), −8(`%ebp`), etc.) The evaluation steps of the symbolic interpreter update the content of the symbolic stack and emit corresponding machine code, which can be summarized with the following table:

Stack before	Stack machine instruction	Stack after	Machine instruction emitted
{}	`CONST` 1	{`%eax`}	`movl $1, %eax`
{`%eax`}	`LD` x	{`%eax`, `%ebx`}	`movl $x, %ebx`
{`%eax`, `%ebx`}	`BINOP +`	{`%eax`}	`addl %ebx, %eax`
{`%eax`}	`ST` y	{}	`movl %eax, $y`

The rightmost column accumulates generated code. As one may notice we in fact generated extra instructions in this very short example (in `X86-32` the effect can be expressed with a single instruction). However, it's rather clear that with this simplistic method the number of generated machine instructions can not be less then the number of stack machine instructions. In Fig. 11 the snippets from two interpreters of the second assignment — regular and symbolic — are shown. In the symbolic one all the operations on the symbolic stack are implemented by mean of an immutable environment (`env`); otherwise the structure of the interpreters is very similar.

There is a number of considerations which have to be taken into account in order for this method to work properly. First, an essential invariant which has to be preserved is the order of allocations on the symbolic stack, which has to be fixed. A reasonable solution is to allocate the registers first (and in a *fixed* order) and only when the depth of the stack exceeds the number of available registers we allocate hardware stack slots. The motivation for this is very clear: we use registers first since they provide a better performance. An interesting question is the efficiency of register allocator, implemented this way. In our case, taking into account the way the stack machine compiler generates code, registers are assigned in a bottom-up left-to-right traversal of expression tree. It is known [8, 29] that for n registers this method allows to generate a machine code with no spilling for a balanced trees with $2^n - 1$ nodes, which is not bad at all.

With the fixed order of symbolic stack allocation we can always recover the contents of the stack from its depth.

Another issue with the symbolic interpreter is that in fact it sometimes performs steps which are never taken by a conventional one. Indeed, the conventional one interprets the program in a normal way, making use of available actual data. In particular, it performs conditional and unconditional jumps as prescribed by their semantics. In contrast, the symbolic interpreter traverses the program once in a top-down manner, thus taking some branches which in fact are never taken by the regular interpreter — for example, while the regular one jumps to an appropriate label when it encounters an unconditional jump, the symbolic one goes to the next instruction. This observations raise a question if the symbolic interpreter approach can work at all.

Fortunately, it can be shown that stack machine programs generated by the stack machine compiler in fact posses the following important invariants:

A: no unreachable code is introduced;

B: all instructions are always performed with the same stack depth;

C: for each label there is at least one preceding instruction which jumps (conditionally or unconditionally) to this label.

These properties obviously do not hold for stack programs of general shape; thus, a symbolic interpreter approach works properly only being coupled with a specific stack machine compiler. The invariants we mentioned above can be put at work as follows:

- By invariant A for each label the depth of the stack is the same since labels are instructions.
- When we encounter a jump (conditional or unconditional) we associate the current stack level with corresponding label; by the invariant C every label will be associated with a certain depth during the top-down traversal prior to visiting.
- When we encounter an unconditional jump, the next instruction has to be a label (otherwise the next instruction is unreachable, which contradicts the invariant A), and this label has already a stack depths associated with. Thus, we can reconstruct the stack contents and continue.

- When we encounter a conditional jump, nothing has to be done additionally since the next instruction corresponds to a fallthrought branch.

Another issue which has to be addressed is if this method of codegeneration worth studying from a didactic standpoint. As we've shown before, by choosing symbolic interpreter we traded code quality for the simplicity of codegeneration approach; in addition we completely omitted from consideration the methods which are actually used in production compilers implementation. The question is if we sacrificed too much. We argue that we actually did not.

From a didactic point of view while we, indeed, do not consider advanced codegeneration methods like bottom-up rewriting systems [28, 18, 17] or register allocation by coloring [22, 14, 14], we still present the students with the tasks of instruction selection and register allocation, albeit in a very simple form. They still need to study the instruction set of a concrete real-world processor, the assembly language, calling conventions, etc., and they have a certain freedom in controlling the quality of the code they generate. Thus, for the first-time encounter with the essence of native code generation they already have enough on their plates. At the same time, while, indeed, the generated code comes 2-3 times slower then when using more advanced techniques, it actually much faster then could be produced by other methods with comparable simplicity (for example, threaded code).

Finally, we have to note, that actually the stack machine compiler is organized in the same way as a symbolic interpreter of the source language. Thus, we put the same idea to work twice.

6 The Course Trivia, Results, and Students' Feedback

In this section we present some technical details concerning the organization of the course; we also summarize the results of the post-course anonymous surveys which were collected during the last three semesters.

The course is being taught for a number of universities in Saint Petersburg, Russia. Initially, those included the Saint-Petersburg University[1], the Saint-Petersburg Department of the Higher School of Economics[2], and the ITMO University[3]. However, the unfolding of the coronavirus pandemy forced the course to go online, which made it possible for the students from other cities of Russia to join. For now, those include Nizhni Novgorod, Novosibirsk, and Moscow.

There are 50-80 attendees each semester. As students come from different universities with different programs and different specializations, we offer them a choice of a "lightning" division: a test of 100+ questions for the grade C (3 of 5, "satisfactory" in Russian grading system), instead of the regular assignments. Around 1/3 of student usually take this route.

For the rest, we announce a GITHUB repository[4], in which all the assignments are being published as the course proceeds. Each assignment is put in a separate branch and contains the implementation of the compiler for relevant language with some parts replaced by placeholders. The students fill in these parts and use provided tests to debug and fix the errors. When they have all the tests passed locally, they make pull requests to the parent repository. Each pull request is built and test on the CI server via the GITHIB to TRAVIS CI integration. The results of CI build are analyzed and accounted for automatically. Additionally, we selectively review pull requests in order to identify the plagiarism or

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[1] `https://english.spbu.ru`

[2] `https://spb.hse.ru/en`

[3] `https://en.itmo.ru`

[4] The current one: `https://github.com/danyaberezun/compilers-2021-spring`

make recommendations. The deadline for each assignment is set for one week with yet another week added as a grace period.

In addition to regular weekly lectures we also provide the students with a live support via Telegram chat, where they can ask general and concrete technical questions, complain on assignment incompleteness, etc.

Our experience shows that among those students who have chosen the "hard way" around 25% form a motivated core, whose members complete the assignments on time, ask questions in the chat, suggest various improvements and even implement some optimizations in the compiler besides those required by the assignments.

By the end of the course we ask students to provide us some feedback in the form of a survey. The average results over the last three semesters are as follows:

- The vast majority qualified the course material as *new* for them (42% — completely new, 58% — mostly new);
- 42% qualified the material as potentially *irrelevant* to their future professional activity; 25% as relevant, and the rest as partially relevant;
- An essential fraction complained about the lack of a type system in $\lambda^a\mathcal{M}^a$ (prior to the spring of 2020 — about the type system in OCaml).

We would like to complete this section by citing two drastically different students' summaries:

> *Writing a compiler for* $\lambda^a\mathcal{M}^a$ *in* $\lambda^a\mathcal{M}^a$ *was a terrible thing when you had no experience with neither* $\lambda^a\mathcal{M}^a$ *nor its relative language* OCaml.
>
> *A very pleasant thing was that* $\lambda^a\mathcal{M}^a$ *was developed specifically for the course and was truly convenient for compiler implementation, especially if one had no prior experience with* OCaml.

7 Related Works

In this section we survey some works which we consider related to our course. The amount of exisiting literature on compiler construction is enormous, and there are hundreds of compiler construction courses around. Thus, it would be vitrually impossible to cite and compare with every one. Instead, we mention here some of those which we found the most relevant to the objectives and the structure of our course, or which were served as the source of our inspiration.

No paper on compiler construction can manage without mentioning the classical "behemots" in the area [26, 25, 9], including probably the most earlier one [10], which, from the standpoint of modern compiler implementation, now can be only of historical interest. These works were never designed as a short (one-semester) introductions to the subject. Instead, they present a comprehensive and close to complete survey of relevant methods for a productive-level compiler construction. An attempt to implement a compiler using all the covered techniques would end up by another infrastructure like GCC or LLVM. At the same time, these books can be used to compile a short course by carefully choosing the topics considered relevant. We can categorize our course as a prerequisite for a fearless reading of these books.

A classical book by Wirth [31] and a more recent series of books by Appel [11, 13, 12] take a similar to our approach. In [31] an implementation of a compiler for Oberon-0 language (a simplified Oberon) is considered in details. The compiler itself is written in Oberon and generates an idealized

RISC code, so the approach is very close to ours. In [11, 13, 12], a compiler from a model language TIGER to MIPS processor is chosen for the reference. In both approaches, the source languages belong to procedural/object-oriented family (in particular, they do not provide the support for first-class functions, S-expressions and pattern matching). In addition, in contrast to our approach, the compilers are constructed in a horizontal manner, from complete frontends to complete codegenerators.

We have also to mention an interesting works [16, 15] on *retargerable* compiler for ANSI C. Being written in ASNI C itself, it can be bootstrapped and represents an interesting attempt to implement a self-contained retargetable compiler. As a codegeneration engine bottom-up-rewriting system [28] is used, and bin-packing is utilized for register allocation.

Finally, we can mention a work on CHOCOPY [27] — a compiler for a subset of PYTHON to RISC-V, written in PYTHON. The compiler is implemented in a horizontal manner; in contrast to regular PYTHON, in CHOCOPY first-class functions are not supported.

In conclusion, we can state that, to our knowledge, currently there is no course on compiler construction which would incorporate all the following features at the same time:

- The source language coincides with the implementation one.
- The compiler is gradually implemented for an evolving family of languages.
- For each language its operational semantics is provided, as well as forfor abstract machine used as imtermediate representation.
- As a result a self-contained codegenerator for a real hardware processor is implemented with no heavy compiler construction infrastructure used.

8 Conclusion and Future Work

We shared here our experience on teaching compiler construction with a simple native code compiler implemented from scratch. Several further improvements to our work can be done. First, we consider extending the native code part to a few new targets, for example, X86-64. Then, we plan to address the performance issues with the generated code. We consider generating efficient native code with symbolic interpreters an interesting research problem. We can also consider extending the language with more advanced features — objects, continuations, or some means for concurrent/parallel programming.

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