Compilers: Course Notes

Oleg Kiselyov

May 1, 2025

Abstract

Compilers is a practical course. Its goal is to build a real compiler, which compiles a high-level language down to the actual x86-64 machine code and produces an executable that runs on student's laptops. The source language is Tiger': a procedural language in the spirit of Pascal – or C with arbitrarily nested functions. The compiler itself is to be developed in OCaml.

The other goal of the course is to give a taste of modern software development, specifically: test-driven development, version control, and the stress on reading, comprehending and extending code rather than writing from scratch.

The characteristic of the course is an iterative, incremental development: we start with the most trivial source language, develop the full compiler for it, and then keep extending the source language and the compiler in small steps, reusing the earlier work as much as possible. At each iteration, we build a *complete* end-to-end compiler producing runnable and testable executables, for a (progressively larger) subset of the source language.

Another characteristic is the extensive use of tagless-final style, taking the full advantage of extensibility afforded by it. The extensibility here means *reuse* – of type-checked and compiled artifacts from the previous increment – rather than copy-paste. The compiler is hence structured as a stack of domain-specific languages, with parsing at the bottom and assembly at the top. The languages are extended by adding new operations here and there (and only occasionally by redirection).

Yet another feature is the attention given to names, or 'variables', and associating attributes to them. Our approach, which readily permits adding attributes at will and analyzing variable usage, may remind some of algebraic effects.

We cover all standard material for the compiler course, from parsing and type-checking to analyses, optimizations, calling conventions and assembly generation – but in a quite non-traditional fashion.

Contents

1 Introduction

This is a practical course. Besides building a complete, realistic compiler, one of its goals is to give *a taste of modern software development*:

- test-driven development;
- pervasive use of version control; build pipelines;
- stress on reading, comprehending and extending code rather than writing from scratch;
- explicitly spelled-out requirements.

1.1 Prerequisites

+ Familiarity with OCaml or the closely related F#

+ Light familiarity with C: We make the compiled code compatible with C so we may write initialization and support code in C and reuse the C standard library

+ Basic data structures (tuples, variants, lists) and algorithms on them

– *No* requirement to know the x86-64 assembly language beyond the basics of computer organization

– *No* experience is assumed with parsing, type-checking, code-generation, etc.

1.2 Development environment

The first task is to set up and test the development environment.

1.2.1 Operating system and environment

Windows Install WSL2. After installing WSL2, you obtain the Unix/Linux environment. Therefore, when installing OCaml later, use that environment and follow the directions for 'Unix installation' (rather than for 'Windows installation'). Confirm that you have gcc (at least v11), git and GNU make installed. (If they are somehow missing, install them. You won't be able to install OCaml without gcc anyway.)

MacOS, Intel Install XCode, then Homebrew, and then make and git. Confirm the version of make (should be GNU make).

As an alternative to installing Homebrew, one can use a Virtual Machine or container running Linux (distribution does not matter).

MacOS, Mac M (Apple Silicon) There are two choices. One is to install Rosetta. Then install XCode, then Homebrew, and then make and git. Its better that all toolchain (especially the compiler, gcc or clang) be for *x86_64 architecture.* One way to ensure it is to run all install commands prefixing them with arch —x86_64. A better way is to open the terminal in the rosetta mode: arch —x86_64 alacritty and run all commands from there. You will use the same rosetta mode terminal to build the compiler, run it and run the compiled executable – basically do all the work in the class.[1] Our compiler (and development) will be under MacOS, using its tools, but for the x86_64 CPU architecture.

As an alternative, install UTM https://mac.getutm.app/, using, as a VM image, debian-12-nocloud-amd64.qcow2 (or newer) from https://cdimage.debian.org/cdimage/cloud/bookworm/latest/ (other distributions would also work). In that case, our compiler and development will be under Unix/Linux.

You may use any editor/IDE you like. If you have not used any programming editor yet, you may want to try VS Code. It is a modern editor with a good support for OCaml, among other languages.

1.2.2 OCaml

OCaml is the language we use to write our compiler. OCaml is truly very good for writing compilers: the first Rust compiler was written in OCaml; the reference Wasm implementation is in OCaml; Meta's Hack language is developed in OCaml. The quite well-known theorem prover Rocq (Coq) is written in OCaml (another well-known theorem prover Isabelle/HOL is written in Standard ML: OCaml's close relative).

For this course we need OCaml version at least 4.14.1. We will only use the standard library; no extra packages are necessary. For build, we use Makefiles

[1] For configuring VS code, see https://stackoverflow.com/questions/70217885/configure-m1-vscode-arm-but-with-a-rosetta-terminal

at the very beginning, but then switch to a custom build pipeline. Therefore, dune will not be needed.

installation (Windows) https://tarides.com/blog/2024-05-08-how-to-setup-ocaml-on-windows-with-wsl/
To re-iterate, first install WSL2, open the WSL2 terminal and the install OCaml as for Unix/Linux, not Windows!

installation (Mac, Linux) https://ocaml.org/docs/install.html, or https://pl.cs.jhu.edu/fpse/coding.html
(You do not need to install any extra OPAM packages listed on that page, although ocaml-lsp-server, merlin and utop can be very useful.)

reference https://ocaml.org/manual/index.html

books See Clarkson [2022], Whitington [2013]

other resources https://batsov.com/articles/2022/08/29/ocaml-at-first-glance/

1.2.3 Git

Git is the de facto standard of software development. We will be using it extensively in this course.[2] First, install git and learn its basics. There are many, many git tutorial available on the internet; there are also several books. We will be using only the very basic git features (no branches, submodules, etc.). Specifically, you need to be familiar with git status, git pull, git add, git commit —a, git push. Also useful are git diff and git log —p —n. To make a repo, use git init or git clone.

Second,

- make an account for yourself at https://bitbucket.org/ To access it from your computer, you need either to create an APP password (click on Help and read the documentation[3]) or register SSH keys. If you set up the APP password, *be sure to save it somewhere*: you need to enter it every time you pull or push to the bibucket. (SSH keys are quite more convenient.)
- make a *private* repository for yourself, including your name or student ID in the repository name. This will be your development repository for your compiler.
- share that repository with me: e-mail address: oleg@okmij.org
Give me the *write* access to your repo.

[2] Adventurous may consider jujutsu, which is compatible with git: https://v5.chriskrycho.com/essays/jj-init/

[3] https://support.atlassian.com/bitbucket-cloud/docs/create-an-app-password/

Once I receive your invitation, I will share with you the class repo, which contains the code for the class and these notes. Both will be extended as the class progresses. Therefore, you may want to 'watch' that repository (that is, get notified on updates by e-mail): set-up via bitbucket.

When you receive the invitation to join the class repo, reply to it, clone the class repo and copy its directories (and also files `.gitignore` and `Makefile.common`) into your repo. To test the setup, go to the `scratch` directory and enter `make` there (on a Mac, enter `make mac`), which will try to build the code in §2. If the `make` finished successfully and the built program `sample` works, your set-up is done.

1.3 Exercises and Grading

This is a practical course. Each week there are 1-3 homework assignments: exercises. Usually, one exercise is to write tests for a new compiler feature, and the other is to extend the current compiler code to implement the feature and make the tests pass.

The purpose of the exercises is to deepen the understanding of the compiler code, to encourage thinking of implementation strategies – and to learn and practice modern software development. *There is no single right answer!*

Besides the mandatory exercises, there are also optional exercises, often a bit more challenging. Optional exercises do not have to be submitted. If submitted, they will be graded as regular ones. There is also a possibility of projects, for those looking for a challenge.

The exercises are graded on the scale 0–10, as a rule. Bonus points may be given for particularly clever or impressive solutions. The course grade is determined from the points you earn from these assignments. There is no final exam.

Submission deadline Homework assigned on week N must be submitted by the start of the $N+1$-week class.

Submission guideline Each assignment will ask you to develop some code or tests. All the development has to be done in your private bitbucket repository that you have shared with me. I also share with you the class repository, which contains the code covered in the class. Many assignments ask you to improve that code.

As the first step, copy that code in your repo and immediately commit it. Then start improving, as described in the assignment.

Overall, your answer to a homework should be in files or directories with the specified names, *committed* into your bitbucket repository.

At the deadline, I clone your repo, compile your code and run it on your, and perhaps also mine, tests. **If the code fails to compile or fails your own tests, you get 0 points.** Therefore, be sure to run it yourself before submitting.

The grade and the comments, if any, are reported in the file grade.txt that I commit to your private repository, in the same directory as the submitted homework.

Important *Read the assignment closely: at least two times* A submission that does not satisfy the assignment cannot be accepted. Please keep in mind this course is about programming. Programming is talking with a computer. A computer does not know what you mean: It only knows what you entered. Even a one letter mis-spell in a program is often fatal. (One-letter mistakes may create big problems also in real life: if you buy a plane ticket online and misspell your name, even by one latter, you will be denied boarding the plane.)

Test before submission Submit only tested code. If the submitted code fails to compile, you get 0 points. You also get 0 points if the submitted code fails tests: ends up in an exception or infinite loop although given valid input.

Submitting code that fails to compile or fails the tests is called 'breaking the build' and is regarded as one of the cardinal sins in software development. You might want to search the net or YouTube for 'breaking the build' to see how companies, or colleagues, treat those who break the build. Getting 0 points is a comparatively minor punishment.

There is no single right answer On the other hand, if a submitted answer satisfies all the conditions of the assignment, it will get the full 10 points (or maybe more, if particularly clever or otherwise impressive).

2 What is a compiler?

First of all, what is a computer? I hope I don't need to elaborate: everybody knows. Everybody also knows that a computer has the CPU to execute programs, memory to store programs and data, and some sort of IO devices. Programs are sequences of instructions for the CPU. What are they?

Here is an example.

```
                        48 83ec28e8
00000000 48894424 0848c744 24180000
000048c7 44241001 000000eb 18e80000
00004889 0424488b 04244801 44241848
83442410 01488b44 2410483b 4424087e
dc488b44 24184889 c7e80000 00004883
c428c3
```

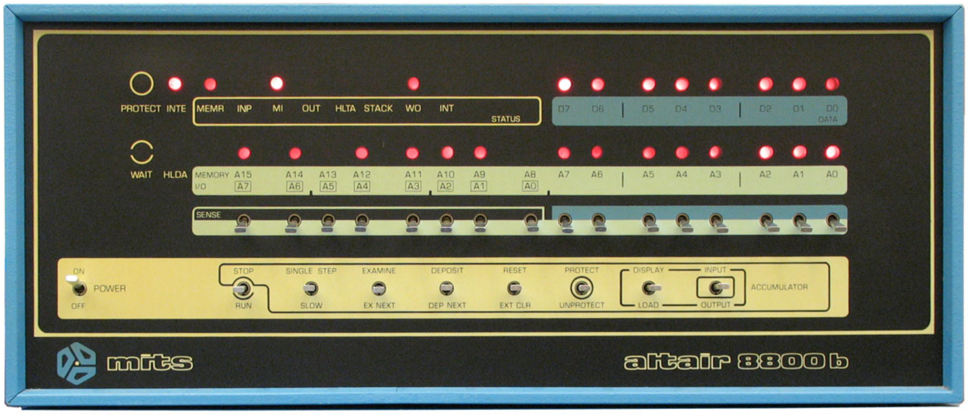
The numbers you see are the instructions, for the modern Intel/AMD CPU, called x86-64 architecture. (See CS107 [2021a,b] for introduction and Cloutier [Ed.] for complete reference.) It is currently the most widely used architecture for desktop and laptop computers.[4]

[4] If you own a recent Mac, you are using a different, ARM architecture. Still, it has the x86-64 emulation mode.

The numbers are hexadecimal numbers (do you know what are they?) and represent instructions. Can anyone tell what the instructions are and what does this program do?

For example, the number 4889C7 here instructs the CPU take data from the register rax and put into the register rdi. The next instruction, staring with e8, is the function call. We will talk about these instructions in more detail in §4.1.

In old times, people indeed programmed computers by manually entering these numbers into memory, using switches – as was the case for Altair, the first commercial Personal Computer in the world (Altair 8800 debuted in 1974).



The original Altair had no display or keyboard. What you see is the entire user interface. One enters a program using switches, and reads the results by displaying memory bytes (bits) on the indicator lamps.

I vouch for that: I myself programmed that way, for a different computer, when I was a student. I could look at such list of hexadecimal numbers and see the program and understand what it does. It is not as difficult when you learn and get used to it. Still, there are lots of bothersome things, like offsets in jump instructions and figuring out the target of a jump. (see EB18 at the 3d line near the end; there 18 is the offset).

To help with such tedious tasks, and also to make the program more readable, assembly language was invented. Here is the same program in assembly.[5]

```
        .globl  ti_main
        .type   ti_main, @function
ti_main:
        subq    $40, %rsp
        call    read_int
        movq    %rax, 8(%rsp)
```

[5] The listing uses the so-called AT&T notation (also called GAS notation) common on Unix (including MacOS) and Linux. There is another, nearly opposite, x86-64 assembly notation called Intel or MASM. It is typically used on Windows and in Intel documentation. In this class we stick to the GAS notation.

```
        movq    $0, 24(%rsp)
        movq    $1, 16(%rsp)
        jmp     .L5
.L6:
        call    read_int
        movq    %rax, (%rsp)
        movq    (%rsp), %rax
        addq    %rax, 24(%rsp)
        addq    $1, 16(%rsp)
.L5:
        movq    16(%rsp), %rax
        cmpq    8(%rsp), %rax
        jle     .L6
        movq    24(%rsp), %rax
        movq    %rax, %rdi
        call    print_int
        addq    $40, %rsp
        ret
```

This is a good place to recall how a CPU executes the instructions: the main CPU loop:

1. fetch the instruction pointed out by the instruction pointer (rip);
2. decode the instruction and increment rip;
3. execute the instruction, modifying registers, memory or CPU flags; repeat. A branch instructions changes rip, by loading a new address or adding/subtracting an offset.
4. repeat.

For more details, see the simple Intel x86-64 emulator in `scratch/emulator.ml` of the class repository.

The assembly code is more readable, isn't it? An *assembler* is a program that translates code in this notation to the numbers we have seen earlier. The translation is straightforward: using the dictionary that relates a string such as `movq %rax, %rdi` to the corresponding number, `4889C7` in this case. Jumps like `jmp` and `jle` interrupt the sequential, instruction-after-instruction execution and transfer control to some other place in the instruction sequence. In assembly, the target of a jump in assembly is denoted by a label. The corresponding instruction needs a distance (offset), which the assembler also computes. This is very welcome, since it is very tedious to do by hand (I did it, and I still remember the tediousness).

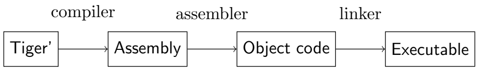
Still, this assembly code, although quite more readable than numbers, is rather difficult to comprehend. Anyone can tell what the program does? It is also difficult to write such assembly code, because it is so low-level. One have to think of so many details: which registers to use and when to reuse, what register or stack location like 24(%rsp) means what, figure out how much space for temporary data the program needs and reserve it at the beginning and free at the end (see subq and addq instructions, etc.)

And so were invented higher-level languages, to make programs easier to comprehend and to write. The first higher-level language was FORTRAN, which means FORmula Translator. (FORTRAN was the first programming language I learned, in high school in late 1970s). The idea was to write formulas in a conventional math notation. Many, many more programming languages were developed since FORTRAN. In this class, we will be dealing with a language called Tiger': a dialect of Tiger developed in Appel [1998]. It is a high-level procedural language in the spirit of Pascal or C. You can think of it as C with nested functions, and with keywords instead of curly braces. Our running example looks in Tiger' as

```
let
  val n := read_int()
  var sum := 0
in
  for i:=1 to n do
    let val v := read_int()
    in sum := sum + v end
  done;
  print_int(sum)
end
```

Has it become easier to understand? Anyone can tell what the program does?

We also need a program to translate such easier to understand code to the assembly. This program is the *compiler*. The overall flow is hence as follows.



The linker, not mentioned earlier, is needed to find and pull in the code for library functions (like read_int) and put their address into the corresponding call instructions. The complete executable also needs start-up code, which the linker also arranges for.

Creating a compiler from Tiger' to x86-64 is the goal of this class. We shall indeed compile the above Tiger' code and obtain the assembly, very similar to the one shown before, with identical functionality.

2.1 Incremental approach

The characteristic of this course is *incremental* development, in many small steps. As pointed out by Ghuloum in Ghuloum [2006], traditional compiler courses teach a compiler one pass at a time; “many of the issues that a compiler writer has to be aware of are solved beforehand and only the final solution is presented. The reader is not engaged in the process of developing the compiler.”

There is too much focus on individual passes and not enough focus on the "big picture".

Like Ghuloum [2006], this course is different. Our development is by extending the complete, working compiler one small step at a time. At each step we end up with the working compiler, for a subset of the source language. Specifically, the methodology ([Ghuloum, 2006, §2.6]):

1. choose a small subset of the source language that is easy to directly compile to assembly;

2. Write the extensive test cases;

3. Write a compiler for the chosen subset to the assembly language;

4. Run all the tests;

5. Base on the experience, refactor or optimize. Make sure the tests still pass;

6. Enlarge the subset of the source language and extend the compiler correspondingly, refactoring as needed;

7. Repeat from 2.

In contrast to Ghuloum [2006], we rely on the tagless-final approach Kiselyov [2024], which makes extensibility easy. We hence use the motivation of Ghuloum, but apply it diametrically differently. (Our source language is also different, Tiger' rather than Scheme.)

3 Introduction to tagless-final style and OCaml reminder

OCaml is the language used in this course to write the compiler and keep extending it. OCaml is similar to F# with which you should be familiar from earlier classes.[6] This section is a brief reminder, stressing the module system (quite more powerful, compared to F#), which we will be using extensively.

The characteristic of the course is treating a compiler as a stack of DSLs. DSL – Domain-Specific Language – is a relatively small language designed for a specific task and hence has the vocabulary, syntax, idioms, semantics tailored for that task Hudak [1996]. Broadly speaking, DSLs are *conlangs* – at least that is how we would look at them. DSLs can be either standalone or embedded. The latter are DSLs incorporated into a larger, general-purpose language – called host language or metalanguage – and piggy-back on its its syntax and some vocabulary, but still possessing their own semantics and specialized vocabulary. One may say that an embedded DSL is a *jargon* of its host language.

[6] Actually, F# started as a dialect of OCaml, but later diverged.

This section also introduces the so-called tagless-final style Kiselyov [2024] of embedding domain-specific languages (DSL) and writing their interpreters and transformers. The characteristic of the tagless-final style is extensibility: the ability to add features to a DSL one-by-one, reusing the already written code. As we shall later see, we treat Tiger' as a DSL, and the Tiger' compiler as one of its interpreters. The assembly and the intermediate languages are also treated as (embedded) DSLs. The extensibility of interpreters is particularly valuable in the incremental approach.

3.1 A simple embedded DSL and its interpreters and transformers

We start with the simplest DSL (whose extension will be the homework assignment). Let's call it Lang. It has only integer literals and the addition operation. Here are a few sentences, or expressions, of Lang: each on a separate line in a column.

1
-1
((4 + 0) + -1)
((4 + 0) + (-1 + -1))

0
(4 + 0)
(-1 + -1)
(((4 + 0) + -1) + -1)

In other words: (i) an integer is an expression; (ii) connecting two existing expression with the plus sign (and putting parentheses around) makes a new expression. With fewer words, Lang's language definition can be stated in the form of a context-free grammar:

$$\mathsf{S} \to \mathsf{integer}$$
$$\mathsf{S} \to (\mathsf{S} + \mathsf{S})$$

Let's embed Lang in OCaml: that is, represent its sentences in the form of OCaml expressions. OCaml is a functional language, so the fundamental operation is application. It seems appropriate then to represent Lang's sentences as OCaml applications. Assume a function int. Then the application int 1 can be used to represent the sentence 1 of Lang. Assume a two-argument function add. Then the application

```
add (add (int 4) (int 0)) (add (int (−1)) (int (−1)))
```

could represent the sentence $((4 + 0) + (-1 + -1))$, which is our running example.

If we just enter the above expression into OCaml's top level, we immediately get an error that add is not defined. Saying to ourselves 'assume add exists' is not enough: we have to say it to OCaml. As the first step, we have to consider the types of int and add. Lang's sentences are represented as OCaml's applicative expressions. All expressions in OCaml (that is, the ones accepted by OCaml (compiler)) have a type. OCaml expressions representing Lang must also have some type. At this point, of describing the language, we do not care what exactly it is. Therefore, we leave it abstract, call repr. The functions int and add then have the types

```
int: int → repr
add: repr → repr → repr
```

To formally declare to OCaml that int and add are assumptions, we make them function arguments. After all, a function is an implication: given the value of its arguments it produces the value of its body. Hence in full, the sample Lang sentence is represented by the following OCaml expression:[7]

```
fun (type repr) (int:int→repr) (add:repr→repr→repr) →
  add (add (int 4) (int 0)) (add (int (−1)) (int (−1)))
```

This is a tagless-final embedding of Lang – in a preliminary form at least.

The obvious drawback is the need to enumerate the constructor functions int and add all the time (more realistic languages have quite more constructors) and remember their argument order, which is not really important. It would also be useful to group int and add with their types, and to finally be able to attach the name Lang. OCaml's module signatures is the facility to do exactly such grouping.

Here is Lang's definition in the form of the module signature, which lists the language operations (sentence constructors) and their types (i.e., arity).

```
module type Lang = sig
  type repr
  val int: int → repr
  val add: repr → repr → repr
end
```

The abstract type repr stands for *some* representation of language expressions. The type of int says that we can make DSL expressions from OCaml integers, like int 4. The type of add says that given two DSL expressions (remember, they are represented as values of the type repr), we can make a new DSL expression: their sum. Note how closely Lang matches the context-free grammar of the language shown earlier. One may say therefore that Lang defines the *syntax* of our DSL.

Using the signature, the sample Lang expression is written as

```
module Ex1(L:Lang) = struct
  open L
  let res = add (add (int 4) (int 0))
                (add (int (−1)) (int (−1)))
end
```

Here, L is the name of some implementation of the signature Lang: that is, some Lang interpreter. The expression **open** L brings the operations it defines – int and add – into scope, so that we may use them (without needing to attach L. prefix all the time).

[7] It may be surprising that a very similar expression appears in the paper that introduced ML, the predecessor of OCaml, back in 1978 Gordon et al. [1978]. Perhaps one should not be too surprised: after all, ML was designed for representing languages. That is what ML stood for: Meta Language.

To evaluate that expression we need an implementation of the Lang signature. Here is one:

```
module Eval = struct
  type repr = int
  let int x = x
  let add = (+)
end
```

It is an interpreter of our DSL, interpreting its expressions as familiar addition expressions over integers. Hence the representation type is int: the value of DSL expressions in *this* interpretation. The Eval interpreter maps DSL operations directly to the corresponding OCaml operations: Eval is a so-called *meta-circular* interpreter for the tiny subset of OCaml. To evaluate the sample Ex1 we interpret it with the Eval interpreter. That is, we apply Ex1 to Eval, effectively evaluating Ex1 with Eval being the implementation L of Lang:

```
module M = Ex1(Eval)
```

and see what res has evaluated to

```
M.res
```

which is 2: the meaning of Ex1 in Eval as an OCaml integer. More compactly – as a single line and single expression – the interpretation of Ex1 can be written as

```
let module M = Ex1(Eval) in M.res
```

Lang hence may also be viewed as the signature of the DSL interpreters, which give a particular meaning to DSL expressions.[8] Eval is not the only possible interpreter of Lang. We way also interpret DSL expressions as strings, so to display them. The meaning for an expression is hence its printed representation:

```
module Pp = struct
  type repr = string
  let int = string_of_int
  let add x y = "(" ^ x ^ "␣+␣" ^ y ^ ")"
end
```

Interpreting the same Ex1 using Pp, as

```
let module M = Ex1(Pp) in M.res
```

now gives the string "((4␣+␣0)␣+␣(−1␣+␣−1))".

Besides evaluating DSL expressions we may also want to transform them. The transformation in the tagless-final style can be viewed from two different viewpoints. As a lead-up, let's consider yet another interpreter. Like Eval it interprets an expression in Lang as an integer: the same integer as Eval but with the opposite sign:

[8] In the graduate school you may learn that a Lang implementation specifies a denotational semantics for our language: repr defines the domain, and int and add give the meaning to DSL integer literals and the addition in this domain. The denotation for complex expressions is determined compositionally, from the denotations of their sub-expressions.

```
module NegEval = struct
  type repr = int
  let int x = -x
  let add   = (+)
end
```

An integer literal is interpreted as that number with the opposite sign. For add, we used the fact that $-(x+y) = (-x) + (-y)$: that is, if we merely add the negated expressions we get the negated sum. The running example

```
let module M = Ex1(NegEval) in M.res
```

is interpreted as −2: indeed, the opposite of the EvaL interpretation.

The interpreter NegEval was written from scratch. Let's try to write it in terms of Eval, reusing (however little) its functionality:

```
module NegEval = struct
  type repr = Eval.repr
  let int x = Eval.int (-x)
  let add   = Eval.add
end
```

We could have also written **let** int x = − (Eval.int x). But in this case we have to know that Eval.int returns an integer – but in the former case we did not have to. Therefore, it is more general and can be generalized, by abstracting out Eval:

```
module Neg(F:Lang) = struct
  type repr = F.repr
  let int x = F.int (-x)
  let add   = F.add
end
```

Neg is a parameterized interpreter: it interprets Lang expressions in terms of another interpreter, F (from 'From'). On the surface of it, Neg is an interpreter transformer: it takes one implementation of Lang and produced another implementation. We may hence transform the earlier Eval and Pp implementations and use the result to interpret the same Ex1, for example,

```
let module M = Ex1(Neg(Eval)) in M.res
let module M = Ex1(Neg(Pp)) in M.res
```

The result is easy to imagine. Although 'negating' Eval gives us back the NegEval that we started with, Neg(Pp) does shows something new. We can 'negate' any Lang interpreter.

We also confirm that

```
let module M = Ex1(Neg(Eval)) in M.res
let module M = Ex1(Eval) in M.res
```

indeed give the opposite results.

Dually, Neg may also be regarded as an *expression* transformer. Here is the Neg-transformed Ex1:

```
module Ex1Neg(F:Lang) = Ex1(Neg(F))
```

Ex1Neg has the same type as the original Ex1: given an interpreter Lang it computes the meaning of res in that interpreter. That is, Ex1Neg is a tagless-final representation of a Lang expression – namely, the expression in which all integer literals have the opposite sign. We could have written that expression by hand

```
module Ex1Neg'(L:Lang) = struct
  open L
  let res = add (add (int (-4)) (int 0))
                (add (int 1) (int 1))
end
```

Neg hence accomplishes an expression transformation: of flipping the signs on integer literals. The very form of Neg makes it clear:

```
module Neg(F:Lang) = struct
  type repr = F.repr
  let int x = F.int (-x)
  let add   = F.add
end
```

Neg flips the signs of int literals and leaves add as is.

The transformed expression can be interpreted with the existing Eval and Pp interpreters, or even the Neg-transformed interpreters:

```
let module M = Ex1Neg(Eval) in M.res
     -2
let module M = Ex1Neg(Pp) in M.res
     "((-4␣+␣0)␣+␣(1␣+␣1))"
let module M = Ex1Neg(Neg(Eval)) in M.res
      2
```

(The evaluation result is shown, indented, underneath each expression.) The pretty-printing of Ex1Neg confirms that it is the Ex1 expression with flipped signs on the literals.

3.2 Separate compilation: making a project

We further ‘modularize’ our DSL development, arranging the DSL definition, interpreters, transformers, and the testing script each in a separate file. Look in the directory tfintro of the class repo. It has the typical organization for our projects. It always has the file OREADME.dr, which describes the project and explains the other files there. There is also Makefile, which tells how to make the project.

Let’s look at OREADME.dr and examine the files mentioned therein. The file lang.mli contains:

```
type repr                        (* representation type (abstract) *)

(* Two operations of the language *)
```

```
val int: int → repr
val add: repr → repr → repr
```

which is the content of **module type** Lang introduced earlier. In OCaml, a file with the .mli extension such as `lang.mli` is treated as a module type (signature) declaration: as if **module type** Lang = **sig** . . . **end** were wrapped around it. That is, an .mli file is a signature declaration that can be separately compiled (the compiled file has the .cmi suffix). The signature name is derived from the file name by capitalizing its first letter. After compiling `lang.mli`, the signature it contains can then be referred to as **module type of** Lang.

Likewise, the file `eval.ml` contains:

```
type repr = int

let int x = x
let add  = (+)
```

which is the content of the earlier **module** Eval. In OCaml, a file with the .ml extension such as `eval.ml` is treated as a module declaration: as if **module** Eval = **struct** . . . **end** were wrapped around it. The module name is the file name with the first letter capitalized. After compiling `eval.ml` (which gives the `eval.cmo` file), we can refer to its content as Eval.int, Eval.add, etc. (The compiled `eval.cmo` have to be linked in into the executable – or, if using the top-level interpreter, loaded by the #load directive.)

Alas, no straightforward wrapping exists for functors. The contents of `neg.ml` is:

```
module Neg(F:module type of Lang) = struct
  type repr = F.repr
  let int x      = F.int (−x)
  let add e1 e2 = F.add e1 e2
end
```

which is the module Neg containing the functor also named Neg. To refer to the functor, we have to say Neg.Neg.

Please pay particular attention to `ex1.ml`:

```
module type Lang = module type of Lang

module Ex1(L:Lang) = struct
  open L
  let res = add (add (int 4) (int 0))
                (add (int (−1)) (int (−1)))
end

let x = let module M = Ex1(Eval) in M.res
let _ = assert (x=2)

let x = let module M = Ex1(Pp) in M.res
let _ = assert (x = "((4␣+␣0)␣+␣(−1␣+␣−1))")
```

```
module Ex1Neg(F:Lang) = Ex1(Neg.Neg(F))

let x = let module M = Ex1Neg(Eval) in M.res
let _ = assert (x= −2)

...
let () = print_endline "All␣Done"
```

(The first line introduces the abbreviation Lang for **module type of** Lang.) The file is not just an example of using the DSL. It also contains assert statements, that check the results match expectations. In case of mismatch, assert will crash the program. Therefore, `ex1.ml` is also a regression test: if running it finishes normally, printing "All Done", there is some confidence things work as expected. If it fails with an error, we have to investigate.

Exercise 1. Extend the language with some other operation, and correspondingly extend the interpreters Eval, Pp and Neg. Write an example that uses the old and the added operations, and try interpreting it in the extended interpreters.

In more detail:

- Copy the `tfintro` directory into your repo.
- Add new files: `lang2.mli` (language extended by you), `eval2.ml` (extended Eval interpreter), `pp2.ml` (extended Pp interpreter), `neg2.ml` (extended Neg transformer), `ex2.ml` (with the tests that cover your added feature, and also the tests checking that the earlier features are not broken by your additions).
- Make sure that the regression test `ex2.ml` passes.
- Confirm on a sample example(s) that in the extended language as well, evaluating using Neg2(Eval2) gives the result opposite to that of the Eval2 evaluation.
- Add the ex2 target to `Makefile` and update `0README.dr` correspondingly.

By the submission deadline, the `tfintro` directory in your repository must contain the above mentioned files (in addition to the files copied from the class repo's `tfintro`) and the updated `Makefile`, `0README.dr`.

4 Making the compiler

We now build the compiler for Tiger’, in many small steps.

4.1 The simplest source language

All the code for this section is in the directory step1 in the class repo. Furthermore, the directory util contains commonly used utility code. Copy both directories into your private repository. Compile the utility code by typing make while in util directory.

As in §3, we start with the simplest language: in fact, even simpler. Our first language to compile has only integer literals. To be precise, see Spec. 1.

Specification 1. Our compiler is to read a source file that contains a single signed 64-bit integer. If the source file does not contain only a single integer, or contains a signed integer that does not fit within 64-bits, the compiler must report an error. Otherwise, it is to produce an assembly code and, eventually, an executable that, when run, prints the integer that was in the source file.

Although the source language cannot be any simpler, its compilation, albeit trivial, has lots of minute, bothersome details. Building a running executable does take a bit of work.

4.1.1 Printing an integer, in Assembly

How to write an assembly code that prints an integer? Especially if one does not know any assembly? Let’s ask something that does know: for example, the C compiler. Here is a simple C program that prints a 64-bit integer, -42.

```
#include <stdio.h>
#include <stdint.h>

int main(void) {
  int64_t x = −42LL;   // A sample integer
  printf("%lld", (long long int)x);
  printf("\nDone\n");
  return 0;
}
```

Our compiler has to create a similar code, but in Assembly. Looking at the code closely, we clearly see the finalization part (the last three lines). The first printf, for printing a 64-bit integer, probably could be separated in its own function; we only need to generate the call to it. All in all, we can partition the code into the part that deals with setting up and clean up, and contains the useful utilities like print_int.

```
#include <stdio.h>
#include <stdint.h>

// Main Tiger function
```

```
extern void ti_main(void);

void print_int(int64_t x) {
 printf("%lld", (long long int)x);
}

int main(void) {
  ti_main();
  printf("\nDone\n");
  return 0;
}
```

One can expect this code to be roughly the same no matter what Tiger' program we are to compile. This part may remain in C: see `init.c` in the repo.

The part that our compiler is really responsible for can be represented by the following C function. Let's call it ti_main. It is invoked by the set-up/clean-up code init.c.

```
#include <stdint.h>

extern void print_int(int64_t);

void ti_main(void)
{ print_int(−42LL); }
```

Our compiler has to produce something like that, but in Assembly. To learn what assembly code to generate, let's make a C compiler generate it for us (by passing the flag −S) and look at the result. The cleaned and commented assembly code is as follows (see the file clean_int.s):[9]

```
# Beginning of the code
        .text
# The name (label) defined below is global (visible outside this file)
        .globl  ti_main
# This name is a function name (that is, it points to code)
        .type   ti_main, @function
# The declaration of the name itself
ti_main:
# x86-64 ABI, stack alignment: see the text
        subq    $8, %rsp
# move -42 to the argument register
        movq    $-42, %rdi
# call the external function
        call    print_int
# restore the stack
        addq    $8, %rsp
```

[9] The listing looks a bit different on a Mac, since MacOS uses a different executable file format and hence different conventions for naming sections and global identifiers *sigh*. We will have to adapt to it later.

```
# return
        ret
```

Most of the code is self-explanatory: see CS107 [2021a,b] for a brief but sufficient reference, and Cloutier [Ed.] for the complete reference. It is essentially the invocation of print_int, passing it the number to print. According to the x86-64 Application Binary Interface (ABI), the first argument to a function is passed in the register rdi (see Fog [2022]). Therefore, our ti_main loads the number into the register and invokes print_int. We also see the mysterious subq and addq instructions, adding and subtracting 8 from rsp, seemingly for no reason. We shall see the reason later, when we talk about the stack in more detail. For now, let's just accept that it is a part of function entry/exit code, again dictated by the ABI conventions.

With the above assembly code as a template, we write our first compiler: file compiler0.ml, which takes an input stream and produces the assembly code file.

> I insist on writing type signatures of all top-level functions (perhaps except those extremely small), in one of the two styles (see the code).

The code takes the 'template-base code generation' to the heart. It is really just the template substitution, using printf. It is very similar to the familiar C printf. In particular, characters '%' in the format string that are meant to be printed literally have to be doubled. Unlike C however, if you forget it, you get a type error.

```
let compile (ich:in_channel) (och:out_channel) : unit =
  Scanf.fscanf ich "%d" @@ fun n →
  Printf.fprintf och {q|
        .text
        .globl  ti_main
        .type   ti_main, @function
 ti_main:
        subq    $8, %%rsp
        movq    $%d, %%rdi
        call    print_int
        addq    $8, %%rsp
        ret
 |q} n
```

Here, {q|...|q} is the alternative OCaml syntax for string literals, suitable for multi-line strings. This code is not only simple but also can be tested right away, at the top level: compile stdin stdout. Its drawback is that it is too simple: too specific and hard to generalize. And generalize we must, already, to account for MacOS, whose executable format is a bit different.

4.1.2 Assembly as a DSL and writing a simple but real compiler

Let's look at the assembly as a DSL: as a simple language (see §3, DSL as a jargon). What words and phrases do we need to be able to write the simple ti_main assembly code in the previous section? We need to build instructions (function calls, moving a number into %rdi); compose them into a sequence; and to turn an instruction sequence to the code for the ti_main function, wrapping into the suitable prologue and epilogue. And we need to write the complete code into a file. Hence we come to the following interface (see asm.mli).

```
type instr                                  (* abstract *)
val (@) : instr → instr → instr             (* concatenate instructions *)

val call : name → instr

type register                               (* abstract *)
val rdi : register

type operand                                (* abstract *)
val imm : int → operand                     (* immediate value *)
val reg : register → operand

val movq : operand → operand → instr

val make_function : name → instr → instr

val write_file : out_channel → instr → unit
```

Using this interface, the compiler code becomes

```
let compile (ich:in_channel) (och:out_channel) : unit =
  let n = Scanf.bscanf (Scanf.Scanning.from_channel ich) "%d" Fun.id in
  let open Asm in
  (movq (imm n) (reg rdi) @ call "print_int") |> make_function "ti_main" |>
  write_file och
```

We can try to compile it (see the target comp_compiler).

Obviously, we need an implementation of the Asm interface: see asm.ml. It realizes the abstract types instr, register and operand as mere strings, and takes some care to print the code prettily. The implementation is a good place to take care of the differences between Unix/Linux/WSL and MacOS platforms. These platforms have different executable code formats (ELF and Mach-O, resp.) and slightly different ABI. The main differences are: the MacOS assembler does not accept the .type directive; the names of global symbols must begin with an underscore. These differences are isolated in asm.ml; the rest of the compiler does not need to know about them.

How to find what platform we are compiling for? We may try to discover via a run-time test (e.g., uname −s). The easiest, however, is to set this information at the configuration time – as done in all compilers to my knowledge. To this end, we add the file config.ml with the relevant configuration data, prepared by a configuration tool: at present, by the compiler writer.

Finally, we need to arrange to invoke ti_main and to implement print_int. That is the job of the 'run-time' system, so to speak, the file init.c that we talked about in §4.1.1. We also have to assemble (invoke assembler on) our emitted assembly code, and link it with init.o and the code to initialize the C standard library that we are using. It is a lot of work. Luckily, we can leave all of that to gcc (OCaml does this too: it is a popular technique in general):

```
gcc compiled_code.s init.o
```

Finally, we need the driver.ml that puts everything together: accepts arguments from the command line, opens needed files, invokes the compile function and arranges the build of the final executable. It has lots of error handling: when the input file is not given, when the input file does not exist, when a syntax error is detected, when the file to output the assembly code could not be opened, or when the build failed for some reason.

The target tigerc in the build script (see §4.1.4) links everything together and builds the compiler: Build/tigerc. If we write the string "-42" into a file prog1.tg and invoke

```
Build/tigerc prog1.tg
```

we obtain the executable file Build/a.out, executing which prints −42.

If we examine the produced a.out using nm a.out or objdump −x −d a.out we see ti_main that we generated. We also see *a lot* of other stuff, needed to make the program to run. Note _start, which is invoked by the OS kernel to start the program. After a lot of initialization, it eventually calls main, which calls our ti_main. Luckily all this other stuff can be entrusted to gcc (the toolchain), and we only have to concentrate on generating the assembly code. Most of other compilers take a similar approach.

4.1.3 Testing a compiler

Needless to say, we must test the compiler. We need both positive tests (correct programs should be accepted, compiled and run correctly) and negative tests (wrong programs should be rejected with an appropriate error message).

The first thing to test is the compiler invocation itself. The compiler, the tigerc command, expects one argument, the file name with the source program. Therefore, tigerc should complain if invoked without arguments (or if invoked with a non-existent file, for example). Let's try: Build/tigerc.

Mostly we will be testing compilation. For example, the program 0 is correct and should compile. To verify, we create a temporary file, say, /tmp/a1.tg containing 0 and pass it to the compiler:

```
Build/tigerc /tmp/a1.tg
```

The command should finish without errors, producing Build/a.out, running which should print 0 followed by Done. On the other hand, the program xxx should clearly be rejected.

Running the tests by hand is very cumbersome. The file util/expect.ml implements a simple testing framework, in OCaml, with four main functions:

test_command ***cmd*** Execute the command *cmd* and return its output or the failure indicator, to be analyzed by expect or expect_fail below. Here, *cmd* is a list of strings: the head is the command itself (the file name), followed by arguments, if any.

test_it ***inp cmdf*** Execute the given command on the given input and return its its output or the failure indicator, to be analyzed by expect or expect_fail below. Here, *cmdf* is a function that accepts a file name and returns a list of strings: the command to run and its arguments; *inp* is a string. The function test_it creates a temporary file, writes *inp* to it and passes the file name to *cmdf*. It then runs the resulting command (specified as a list of string) as test_command above.

expect ***expected res*** Check that *res*, which is the result of test_it or test_command, indicates the successful completion of the command, and check that its output matches the string *expected*.

expect_fail ***res*** Check that *res*, which is the result of test_it or test_command, indicates the failure of the command.

The functions expect and expect_failure crash the program if their check fails.

The earlier check that 0 is the correct program is hence automated as follows:

```
let tigerc = Filename.concat "Build" "tigerc"
let execf = Filename.concat "Build" "a.out"
let cmd fname = [tigerc; fname]
let _ =
  expect "" @@ test_it "0" cmd;
  expect "0\nDone" @@ test_command [execf]
```

This OCaml code does exactly what we did before by hand: creates a temporary file; writes the string "0" into it; runs Build/tigerc passing the file name as the argument; tests that command finishes successfully with no output; runs the command Build/a.out with no arguments; checks that it finishes successfully and outputs 0 and and Done.

The following OCaml code verifies that the program xxx is indeed rejected:

```
let _ =
  expect_fail @@ test_it "xxx" cmd
```

The file test_script.ml is the test script containing the above tests (and a few more). It is executed by the build target test (see below). It should finish without errors, printing “All Done” at the end.

4.1.4 Build system

In this class we will be using a dedicated build system, which one may think of as a version of make: with all the needed facilities (such as build directory, dealing with the source code spread around many directories, etc.) but without their complexities. One may read the rationale in the file util/build.ml, which is the implementation.

To use the build system, first compile all the code in the util directory.

In our build system, all the built artifacts – compiled code such as .cmi and .cmo files, tigerc itself, etc. – are stored in a special build directory, called Build.

Check that your copy of the compiler code (e.g., step1 directory) contains Build as a subdirectory. If not, make it.

The build script is an OCaml script build.ml. It is meant to be invoked as is: ./build.ml. On some platforms, invoking the script like this may cause errors. In this case, run this script as ocaml build.ml.

The interface is the same as make: the script accepts the list of targets to make, and makes them in the specified sequence. For example:

```
./build.ml tigerc test
```

or, on some platforms

```
ocaml build.ml tigerc test
```

The list of targets may be empty, in which case the default target is built (which is usually tigerc). In this class, we typically use three targets: tigerc to build the compiler and the run-time system, test to run the tests, and clean to clean everything up.

The build script build.ml is a regular OCaml file, and can be edited as such. One should particularly note three definitions. First, compiler_manifest lists all the source files needed to build the compiler, and how to build them. *The order is important.* (In fact, the order is the linking order of the files).

```
let compiler_manifest = build_all [
  existent "../util/util.cmo";
  ocaml "config.ml";
  ocaml "asm.mli";
  ocaml "asm.ml";
  ocaml "compiler.ml";
  ocaml "driver.ml";
 ]
```

The argument of build_all is a list of rules. The rule existent checks to see that the file (../util/util.cmo in the above example) already exist, reporting an error if does not. The rule ocaml is to compile the given .ml or .mli file by the OCaml compiler. Later we shall see that the rule has the optional argument ~rename, used as:

```
  ocaml "../step21/lang.mli" ~rename:"lang_21"
  ocaml "../step21/pp_ast.ml" ~rename:"pp_ast_21"
```

For example, the former first renames ../step21/lang.mli to Build/lang_21.mli before compiling it (which produces Build/lang_21.cmi: all built artifacts go to the Build directory). Further rules include ocamllex, ocamlyacc (for lexer and parser generation, resp.), cc for compiling C code and link for linking. For example,

```
let tigerc = link ~out:"tigerc" compiler_manifest
```

is the rule to link all files built by compiler_manifest into the executable named tigerc. The earlier build_all is also a rule: collecting several rules into one.

Another important definition in the build script is

```
let runtime_manifest = build_all [
  cc "init.c";
 ]
```

which is the rule to compile the files that make the Tiger' run-time system. Finally,

```
let tests = test [
  "test_script.ml";
  ]
```

is the rule that runs the listed test scripts, invoked in building the target test. As we extend the compiler, we add new files to compiler_manifest, runtime_manifest, and tests lists. Typically, one would not modify anything else in the build.ml script.

4.2.6 Types

In Ex. 7, you must have faced two problems. First, how to print the result, which could be either a number or true/false. How to chose which format to use? Second, what to do about Tiger' programs like - true, not 1, — is_zero x? They are all well-formed according to the grammar, can be parsed and pretty-printed. Evaluating or compiling them, however, is puzzling. Do they even make sense? To be sure, one may try to give them some sense (e.g., to treat true as 1 and false as 0, as C or APL do). On the other hand, second-guessing the programmer tends to produce surprising results and sweep bugs under the rug, where they are quite more difficult to find.[13] It is not for nothing that most programming languages do distinguish booleans and integers.

Sentences that are well-formed yet meaningless are common in natural languages as well. Everyone probably had an experience in high school of a teacher marking a sentence as not making any sense, despite being grammatically correct. The sentence probably did make sense to you when you wrote it. 'Making sense' is a tough topic; in a Computing Theory class you will learn that there is no, and cannot be, a definite procedure (algorithm) to decide if sentences or programs make sense (except for very simple languages).

What we are left with, it seems, is to try to evaluate a given sentence anyway – perform its computation. If we encounter a roadblock such as trying to apply an operation to something outside of its range – e.g., dividing by zero, applying an integer operation to not-an-integer – report an error and exit. Although this strategy works quite well – after all, rebooting is uncannily effective in solving many computer problems – there are many situations where it is detrimental, harmful or even disastrous. An impressive example of the latter is the first test flight of the Ariane 5 rocket. The guidance computer obtained a result that did not fit within allocated 16-bits and raised an overflow exception. The system was rebooted. When the rocket is ascending with engines at full thrust, it is not a good time for rebooting the guidance system.[14]

Therefore, it becomes important to *anticipate* roadblocks and take countermeasures *before starting the execution*. At the beginning of the 20th century, Bertrand Russell faced a similar problem with some logical formulas which, although well-formed, were paradoxical. He wanted to find a way to rule out such a formula by just 'looking over it', without getting bogged down in its possible meaning. In 1903 (with further development in 1908) he introduced a formalism for so-called "range of significance" of logical predicates and for deciding, at a glance, when a predicate is applied outside of its range. He called this "range of significance" *type*.

It is important to realize that 'anticipation' is rarely perfect. An anticipated rain may not happen, or rain may still fall with a sunny forecast. Types are designed to eliminate the latter error – continuing our analogy, if no rain is anticipated, no rain shall fall.

[13] For a concrete, and rather scary example, see the entry DWIM in *The Jargon File* http://www.catb.org/~esr/jargon/html/D/DWIM.html.

[14] https://www.bugsnag.com/blog/bug-day-ariane-5-disaster/

Figure 3: Ariane 501: Ariane 5 first flight. Debris raining down after the self destruction, 4 June 1996. European Space Agency (ESA) Historic Photo Archive.

> In a well-typed program, particular (explicitly specified) classes of errors shall not occur, *no matter what the input*:
>
> *“Well-typed programs do no wrong.”*

The cost however is conservativity: some programs that make sense (or could make sense on some inputs) are judged problematic.[15]

Types hence play a *negative role*: rejecting programs that make no sense – or, to be more precise, rejecting programs that could not be judged meaningful and safe. One comes across many complaints about a type system restricting programmer’s flexibility and ‘freedom’. This is like complaining about a fire alarm being annoying: annoying is what a fire alarm is designed to be.

Types play also a *positive role*. “Well-typed programs do no wrong” is a strong positive statement, and hence very valuable. Since we are sure particular errors shall not occur in our program once it passed the type check, we do not to have to guard against such errors, and do not have to think about recovery. For example, the code generator does not have to worry about compiling successor on booleans: such case is simply impossible. The code generator may also

[15] Therefore, common type systems may be called ‘pessimistic’: they err on the side of rejecting programs. If a program can “do wrong” even on a single input, it is judged ill-typed. There are also ‘optimistic’ type systems, quite less common. Somehow they are limited to logic programming and Erlang.

assume that a register that contains a boolean has only two possible pre-defined bit patterns, and generate optimal instruction sequences accordingly. Types hence lead to simpler, and more efficient code.

Returning to Ex. 7: the result of an integer Tiger' program is to be printed as an integer; a boolean result is to be printed as "true" or "false". It helps performance if the choice which function to call at the end of the program – print_int or print_bool – were done at compile-time. Types help make this choice. Using types to guide the selection of instructions in a compiler is the reason types were first introduced in programming languages: see Martini [2016].

To emphasize, types are used at compile time, to guide code generation and reject programs deemed unsafe or meaningless. They are not represented at run-time.[16] Unsafe may mean liable to raise a run-time exception – or interfering with another program or misusing data. This broadly-speaking "security" point of view is expressed in the slogan of types as a "syntactical discipline for enforcing level of abstraction" Reynolds [1974] (see Martini [2016] for the development of this point of view, mainly due to J.H.Morris).

It took quite a while to realize that classification of values to select instructions, and the rejection of meaningless/unsafe programs are two aspects of the same notion: types. It is quite surprising therefore that there was a person who recognized these connections, back in late 1940s: logician H.B. Curry. The first technical use of "type" in programming, in 1949, was also due to him Curry [1949]. Deeply unfortunately, his papers seem to have been forgotten. It is not until nine years later, in 1958, that the term 'type' as classes of values started to be used Martini [2016]. The connection to logic had to wait another decade to be rediscovered.

Types are similar to grammar: both give a procedure to judge and accept a sentence, or reject it as being ill-formed (or ill-typed). Crucially, in both cases the procedure is 'superficial': the judgement is done only by looking at the shape or form of sentences without deeply considering their meaning. In principle, type judgments may be incorporated into a grammar. It is rarely a good idea, because the resulting grammar becomes very difficult to understand, and also to slow to parse.[17] [18] Just like separating lexing from parsing, it makes sense to perform type checking as a separate step.

4.2.7 Compiling integer and boolean unary expressions

All the code for this section is in the directory step22 in the class repo.

Overall, compilation now looks as in Fig. 4. We have added the compiler phase: which is another interpreter for Lang, performing type-checking, and then passing the parsed expression to the code generator.

[16] Formally, this is called "type erasure".

[17] Programming language grammars are usually context-free or mostly context-free. Type systems, however, are often context-sensitive.

[18] For example, one may compare for equality two integer or two boolean expressions, but not an integer with a boolean. Expressing this constraint in a grammar leads to the explosion of non-terminals.

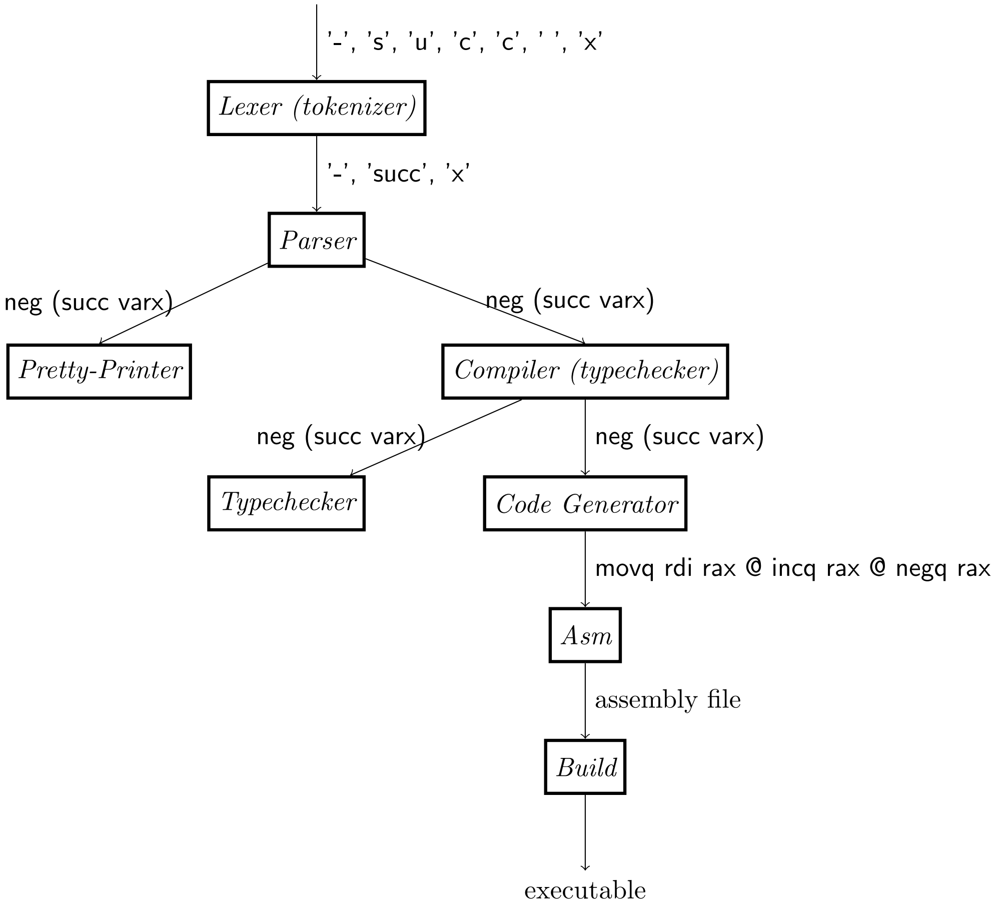


Figure 4: Data flow after adding type checker

Type checking can be performed as a sort of evaluation: Abstract Interpretation Jones and Nielson [1994]. The type checker ('compiler' in Fig. 4) is hence written as an interpreter, of Lang. Actually, the compiler of Fig. 4 is a product[19] of two interpreters: the type-checking interpreter and code-generation interpreter, or the higher-level assembly (what used to be called 'compiler' in Fig. 1.) They interpret the same expression in 'parallel' so to speak (or, in lockstep). The compiler code `compiler.ml` shows the two roles of types clearly: the type checking interpreter checks that operations receive the arguments in their 'range of significance'. The result, the type of the whole program, is used at the end, in observe, to select the function to print the result: either print_int or print_bool.

[19] that is, a pair

6 Projects

1. Take a signature like Lang (actually, the compiled `lang.cmi` file) and automatically build a parser for that language. The signature needs to be annotated with the names of terminals. This is what yacc grammar essentially does. One needs to draw the distinction between concrete and abstract syntaxes. See §4.2.1.

2. Change `asm.ml` to output the assembly code in Intel format

3. Currently we represent a boolean value as a 64-bit word: 0 meaning false and 1 meaning true. GCC on x86-64 uses a slightly different representation: still a 64-bit word, but only the least significant 8 bits are taken into account. Do you see the advantage of it? Change the compiler to use this representation. All earlier tests should pass. As an extra challenge, think of (micro- and medium-size) benchmarks to test how much of a difference this new representation makes.

4. Much better memory allocation. One particular direction: notice the similarity between unique variable renaming (Ex. 15,16) and allocating memory for those variables.

5. A better representation for strings, such as Phil Bagwell's persistent data structures. See §4.8.

6. Functions returning multiple arguments

7. Implement the lambda-lifting technique. See §4.11.3.

8. Implement various micro-optimizations. First, when loading an immediate value into a register, say, rax, and that value happens to be zero, instead of movq $0,%rax emit xorq %rax,%rax, which is *far* more efficient. Intel CPU recognizes such instruction already during decoding (it is not even need to be executed, strictly speaking). Second, multiplication by constants is often done without imul instruction: see, for example, how GCC compiles $x * (-7)$. Division by a constant is always done without using the division instruction, which is slow and quite awkward to use. Implement such optimizations. As a further challenge, discover other micro-optimizations (e.g., by analyzing GCC assembly output or search the Web) and implement them. Ideally you will come up with a framework which makes implementing (and adding) micro-optimizations easy.

References

Andrew W. Appel. *Modern Compiler Implementation in ML*. Cambridge University Press, 1998. ISBN 0-521-52745-1. doi: 10.1017/CBO9780511811449. URL http://www.cs.princeton.edu/~appel/modern/ml/.

Michael R. Clarkson. OCaml programming: Correct + Efficient + Beautiful. https://cs3110.github.io/textbook/cover.html, 2022. Cornell U. course; videos available.

Félix Cloutier (Ed.). x86 and amd64 instruction reference. https://www.felixcloutier.com/x86/index.html, 9 September 2022.

staff CS107. CS107 x86-64 reference sheet. https://web.stanford.edu/class/cs107/resources/x86-64-reference.pdf, 2021a.

staff CS107. Guide to x86-64. https://web.stanford.edu/class/archive/cs/cs107/cs107.1224/guide/x86-64.html, 2021b.

Haskell B. Curry. On the composition of programs for automatic computing. Technical Report Memorandum 10337, Naval Ordnance Laboratory, 1949.

Andrei Petrovich Ershov. On programming arithmetic operators. *Doklady Akademii Nauk*, 118(3):427–430, 1958a.

Andrei Petrovich Ershov. On programming of arithmetic operations. *Comm. ACM*, 1(8):3–6, August 1958b.

Agner Fog. Calling conventions: for different C++ compilers and operating systems. http://agner.org/optimize/calling_conventions.pdf, 5 August 2022.

Abdulaziz Ghuloum. An incremental approach to compiler construction. In Robert Bruce Findler, editor, *Proceedings of the 7th Workshop on Scheme and Functional Programming*, number TR-2006-06 in Tech. Rep., pages 27–37. University of Chicago, 17 September 2006. URL http://scheme2006.cs.uchicago.edu/.

Michael Gordon, Robin Milner, L. Morris, M. Newey, and C. Wadsworth. A metalanguage for interactive proof in LCF. In *Conference Record of the Fifth Annual ACM Symposium on Principles of Programming Languages*, pages 119–130, Tucson, Arizona, January 23–25, 1978. ACM SIGACT-SIGPLAN. URL http://www-public.tem-tsp.eu/~gibson/Teaching/CSC4504/ReadingMaterial/GordonMMNW78.pdf.

C. A. R. Hoare. Hints on programming language design. Technical Report STAN-CS-73-403, Department of Computer Science, Stanford University, December 1973. URL http://flint.cs.yale.edu/cs428/doc/HintsPL.pdf. https://purl.stanford.edu/vr655dy1064.

Paul Hudak. Building domain-specific embedded languages. *ACM Computing Surveys*, 28(4es):196, December 1996.

K. Jensen and N. Wirth. *Pascal User Manual and Report*. Springer-Verlag, Berlin, 1975.

Neil D. Jones and Flemming Nielson. Abstract interpretation: a semantics-based tool for program analysis. In *Handbook of Logic in Computer Science*, pages 527–629. Oxford University Press, 1994. http://www.diku.dk/forskning/topps/bibliography/1994.html#D-58.

Oleg Kiselyov. Free variable as effect, in practice, 27 December 2023. URL http://arxiv.org/abs/2312.16446. HOPE Workshop 2023.

Oleg Kiselyov. Tagless-final style. https://okmij.org/ftp/tagless-final/, 2024.

Charles H. Lindsey. A history of ALGOL 68. In John A. N. Lee and Jean E. Sammet, editors, *History of Programming Languages Conference (HOPL-II), Preprints, Cambridge, Massachusetts, USA, April 20-23, 1993*, pages 97–132. ACM, 1993. doi: 10.1145/154766.155365.

Simone Martini. Several types of types in programming languages. In *History and Philosophy of Computing, HAPOC 2015*, volume 487 of *IFIP Advances in Information and Communication Technology*, pages 216–227. Springer, 2016. URL https://arxiv.org/abs/1510.03726.

Fernando C. N. Pereira and David H. D. Warren. Parsing as deduction. In *Proceedings of the 21th Annual Meeting of the Association for Computational Linguistics*, pages 137–144, Somerset, NJ, 1983. Association for Computational Linguistics. URL http://www.aclweb.org/anthology/P83-1021.

John C. Reynolds. Towards a theory of type structure. In Bernard Robinet, editor, *Programming Symposium: Proceedings, Colloque sur la Programmation*, number 19 in Lecture Notes in Computer Science, pages 408–425, Berlin, 9–11 April 1974. Springer.

Stuart M. Shieber, Yves Schabes, and Fernando C. N. Pereira. Principles and implementation of deductive parsing. *Journal of Logic Programming*, 24(1–2):3–36, 1995. URL http://arxiv.org/abs/cmp-lg/9404008http://www.eecs.harvard.edu/~shieber/Distrib/Sources/deductive-parser/.

John Whitington. *OCaml from the Very Beginning*. Coherent Press, 2013. ISBN ISBN-13: 978-0957671102; ISBN-10: 0957671105. URL https://ocaml-book.com/.

Xuejun Yang, Yang Chen, Eric Eide, and John Regehr. Finding and understanding bugs in C compilers. In Mary W. Hall and David A. Padua, editors, *Proceedings of the 32nd ACM SIGPLAN Conference on Programming Language Design and Implementation, PLDI 2011, San Jose, CA, USA, June 4-8, 2011*, pages 283–294. ACM, 2011. doi: 10.1145/1993498.1993532.