CS4212: Compiler Design

Ilya Sergey

ilya@nus.edu.sg

ilyasergey.net/CS4212/

Why Compilers?

https://www.youtube.com/watch?v=kil2Z3ij-JA

(From Episode 6 of the classic 1983 television series, Bits and Bytes)

Week 1: Introduction

Why learn about compiler design?

- You will learn:
  - How programs we write end up being executed
  - Lexing/Parsing/Interpreters
  - How high-level languages are implemented in machine language
  - (A subset of) Intel x86 architecture
  - More about common compilation tools like GCC and LLVM
  - How to better understand program code
  - A little about programming language semantics & types (*math* behind programs)
  - Practical applications of Programming Language theory
  - Advanced functional programming in OCaml (yay!)
  - How to manipulate complex data structures
  - How to be a better programmer

- Expect this to be a *very challenging*, implementation-oriented course (duh!)
  - Programming projects can take *tens* of hours per week…

Administrivia

- **Instructor:** Ilya Sergey
  Lectures (F2F): Mondays, 3:00pm-6:00pm, LT18
- **E-mail:** ilya@nus.edu.sg
- **Web site:** https://ilyasergey.net/CS4212
- **GitHub:** https://github.com/cs4212

Please, email me your GitHub name to access the code!

Course Policies

Prerequisites:
Significant programming experience

- Familiarity with Data Structures
- HW1 will introduce you to / refresh your knowledge of OCaml

Grading:

- 60%: coding projects: *Compiler*
  - Groups of 2 students (except the 1st one)
  - Implemented in OCaml
- 40%: written final exam (2 hours)
- Lecture attendance is crucial
  - Active participation (asking questions, etc.) is encouraged

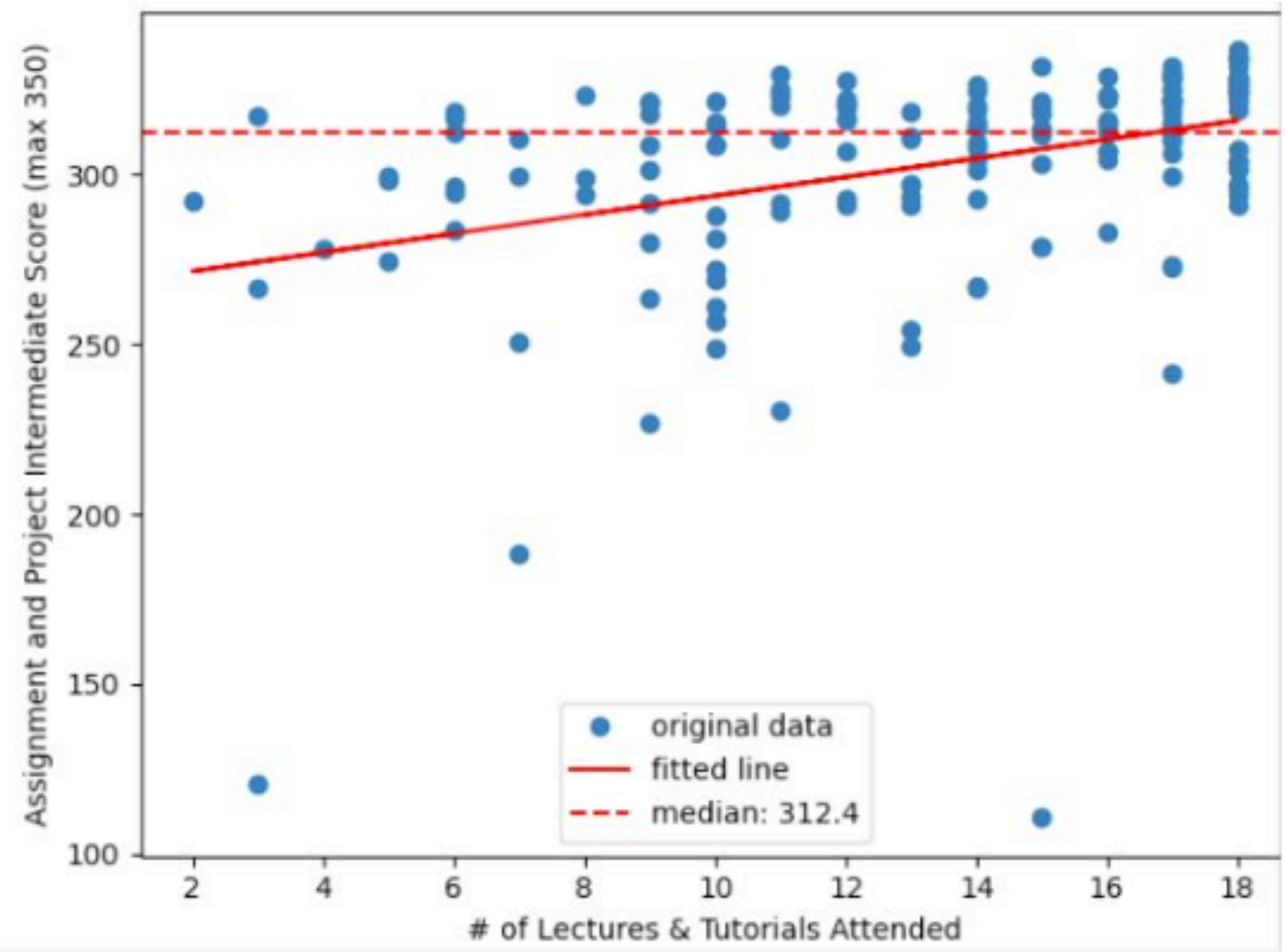
Homework Projects

- Six homework assignments (each graded out of 100 points)
  - HW1: OCaml Programming
  - HW2: X86lite interpreter
  - HW3: LLVMlite compiler
  - HW4: Lexing, Parsing, simple compilation
  - HW5: Higher-level Features
  - HW6: Analysis and Optimisations
- Goal: build a **complete compiler** from a high-level, type-safe language to x86 assembly.

General Advice

- 3-hours afternoon class (!!)
  Try to make class livelier by asking questions and participating in discussions!

On physical/virtual attendance



Homework Policies

- Homework (except HW1) should be done *individually* or *in pairs*
- Late projects:
  - up to 24 hours late: 10 point penalty
  - up to 48 hours late: 20 point penalty
  - after 48 hours: not accepted (sorry)

- Submission policy:
  - Projects that **don't compile will get no credit**
  - Partial credit will be awarded according to the guidelines in the project description

- Fair work-split policy:
  - In group projects it is expected each member to contribute non-trivial amount of code (not comments, blank lines or trivial code permutations);
  - I will use GitHub contribution tracking for this; please, make sure your email is properly configure with GitHub so this accounting would work;
  - "Free-loaders" will be penalised at my discretion.

Academic Integrity

- Learning Materials are Copyrighted by NUS / Original Authors
  - Do not re-distribute the code of the assignments!
  - Do not dump the content of "hidden tests" (yes, we know this can be done)

- "low level" and "high level" discussions across groups are fine
  - **"Low level"**: "how do you debug your LLVM output?", "what is the meaning of this x86 operation?"
  - **"High level"**: "What is a lattice in a data flow analysis?", drawing boxes on a whiteboard.

- "mid level" discussions / code sharing between teams are **not permitted**
  - **"Mid-level":** "how does your type checker implementation work on lambdas?"

- Adopting/translating code parts from other teams or the internet is **not permitted** (I will know)

- General principle: *When in doubt, ask the instructor!*

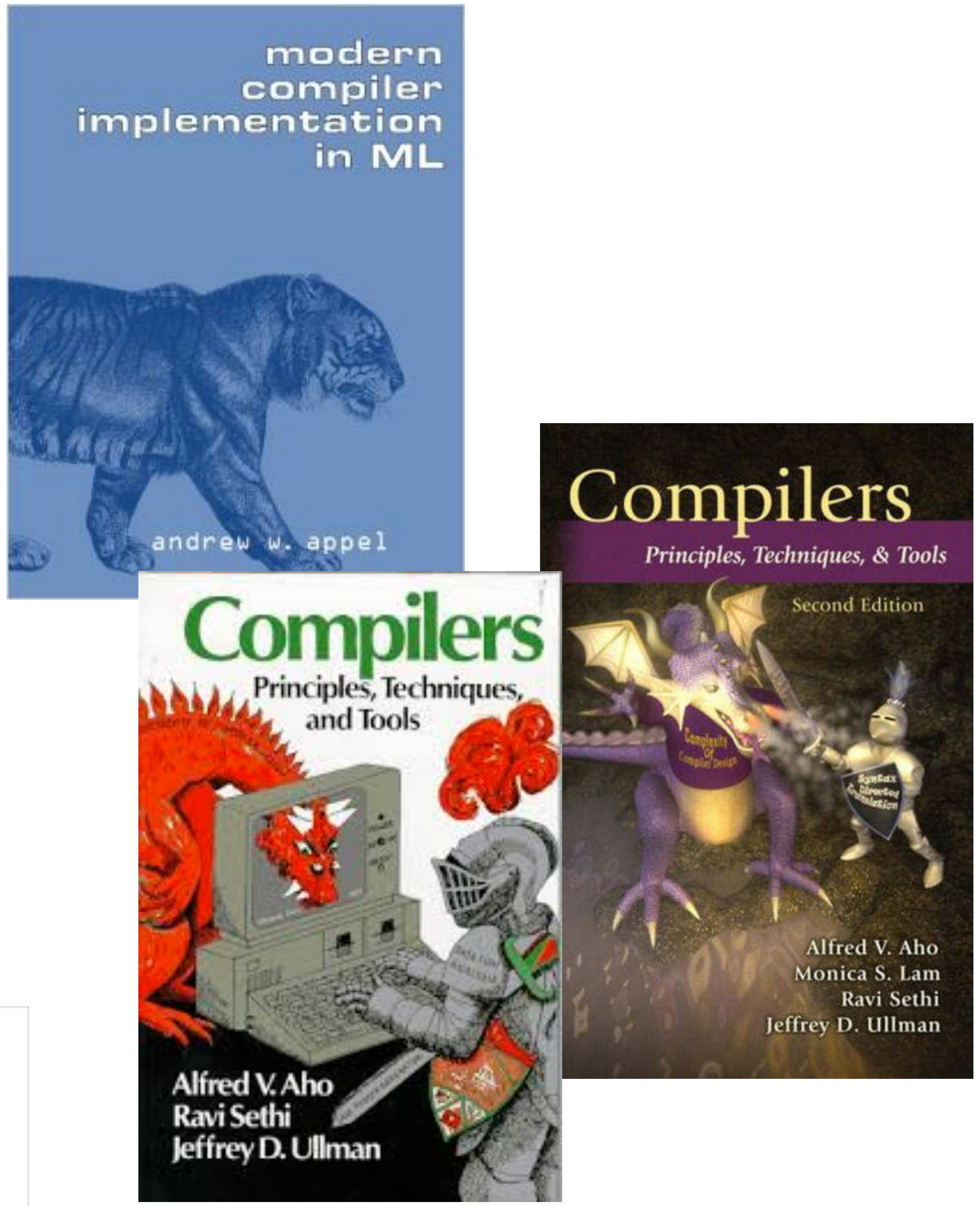
- Penalties for cheating:
  - First strike: 0 points to the whole team for the homework
  - Second strike: F for the module, case is passed to the Academic Integrity Committee

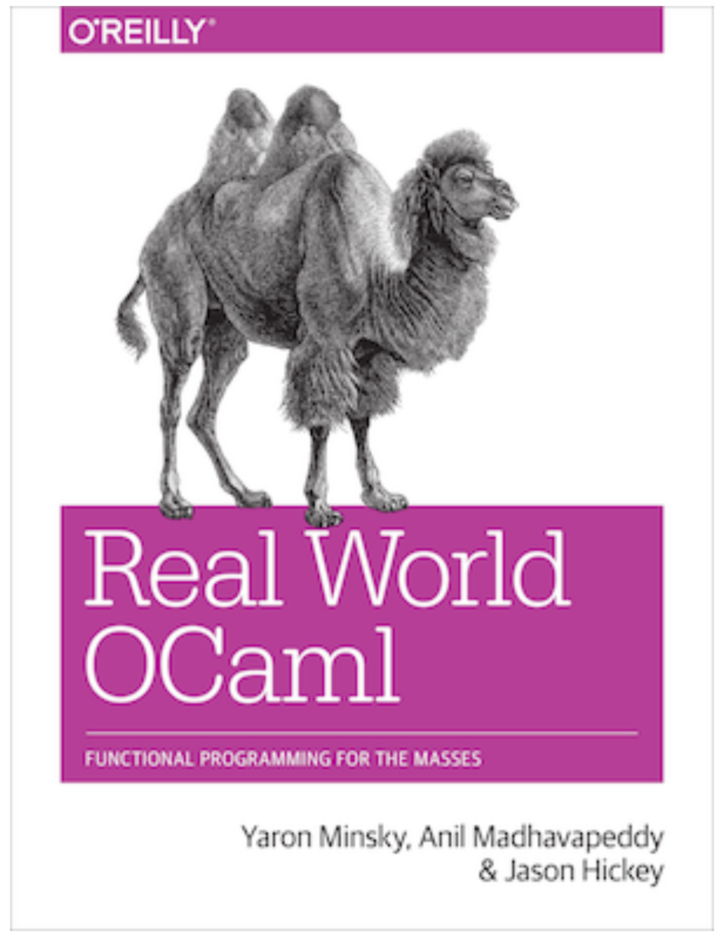
Getting Help

- **Office Hours**: get in touch by email if you have questions
- **E-mail policy**: questions about homework assignments sent less than 24 hours before submission deadline won't be answered.
- **Slack policy:** timely (or any) responses from the instructor are not guaranteed. Ask the TA or other students on public channels. **Do not** share (parts of) your solution on public channels on Slack!
- **Exception**: bug reports.
- **HW submission extensions:** only if MC is provided.

Resources

- Course textbook: (recommended, not required)
  - *Modern compiler implementation in ML* (Appel)
- Additional compilers books:
  - *Compilers – Principles, Techniques & Tools* (Aho, Lam, Sethi, Ullman)
    - *a.k.a. "The Dragon Book"*
  - *Advanced Compiler Design & Implementation* (Muchnick)
- About Ocaml:
  - *Real World Ocaml* (Minsky, Madhavapeddy, Hickey)
    - realworldocaml.org
  - *Introduction to Objective Caml* (Hickey)





Hello, OCaml

- OCaml is a dialect of ML – “Meta Language”
  - It was designed to enable easy manipulation *abstract syntax trees*
  - Type-safe, mostly pure, functional language with support for polymorphic (generic) algebraic datatypes, modules, and mutable state
  - The OCaml compiler itself is well engineered
    - you can study its source!
  - It is the right tool for this job
- O-wat?
  - First two projects will help you get up to speed programming
  - See “Introduction to Objective Caml” by Jason Hickey
    - book available on the module web page, referred to in HW1

HW1: HelloCaml

- Homework 1 is available on Canvas
  - Individual project – no groups (the only in this module)
  - Due: *Sunday, 25 August 2024 at 23:59*
  - Topic: OCaml programming, an introduction to basic interpreters
  - Those who took CS4215 or any Prof. Danvy's classes will find it *very* familiar

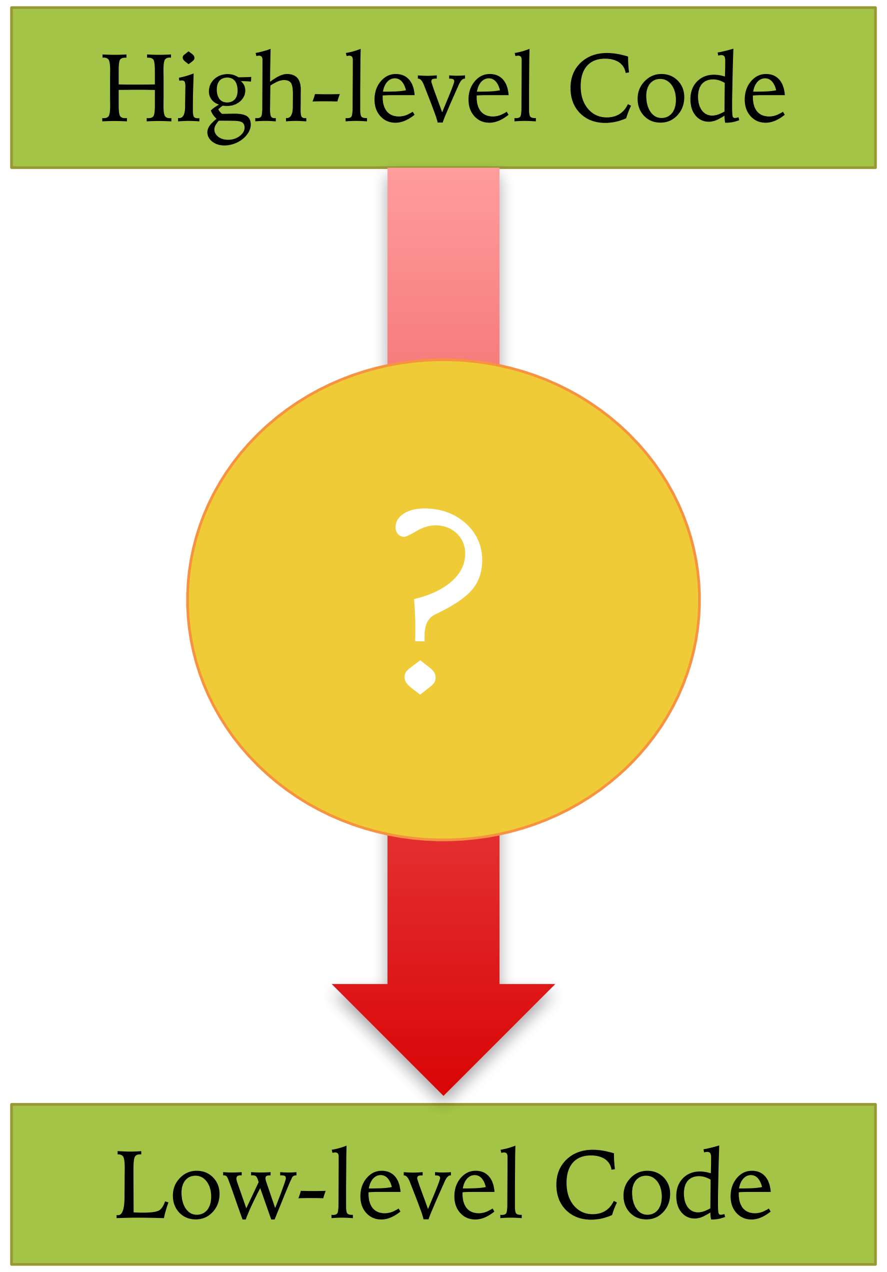
- Recommended software:
  - VSCode + OCaml extension
  - See the prerequisites page for the full setup

Any questions?

What is a Compiler, formally?

What is a Compiler?

- A compiler is a program that translates from one programming language to another.
- Typically: *high-level source code* to *low-level machine code* (object code)
  - Not always: Source-to-source translators, Java bytecode compiler, GWT Java ⇒ Javascript



Historical Aside

- This is an old problem!
- Until the 1950's: computers were programmed in assembly.
  - Assembly is a textual representation of machine codes
- 1951—1952: Grace Hopper
  - developed the A-0 system (Arithmetic Language version 0) for the UNIVAC I
  - She later contributed significantly to the design of COBOL
- 1957: FORTRAN compiler built at IBM
  - Team led by John Backus
- 1960's: development of the first bootstrapping compiler for LISP

  See https://en.wikipedia.org/wiki/Tombstone_diagram
- 1970's: language/compiler design blossomed
- Today: *thousands* of languages (most little used)
  - Some better designed than others...

1980s: ML / LCF
1984: Standard ML
1987: Caml
1991: Caml Light
1995: Caml Special Light
1996: Objective Caml
2005: F# (Microsoft)
2015: Rust

Source Code

- Optimised for human readability
  - *Expressive*: matches human ideas of grammar / syntax / meaning
  - *Redundant*: more information than needed (why?)
  - *Abstract*: exact computation on CPU possibly not fully determined by code
- Example C source:

```c
#include <stdio.h>

int factorial(int n) {
  int acc = 1;
  while (n > 0) {
    acc = acc * n;
    n = n - 1;
  }
  return acc;
}
```

```c
int main(int argc, char *argv[]) {
  printf("factorial(6) = %d\n", factorial(6));
}
```

Low-Level Code

```
_factorial:
## BB#0:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $8, %esp
        movl    8(%ebp), %eax
        movl    %eax, -4(%ebp)
        movl    $1, -8(%ebp)
LBB0_1:
        cmpl    $0, -4(%ebp)
        jle     LBB0_3
## BB#2:
        movl    -8(%ebp), %eax
        imull   -4(%ebp), %eax
        movl    %eax, -8(%ebp)
        movl    -4(%ebp), %eax
        subl    $1, %eax
        movl    %eax, -4(%ebp)
        jmp     LBB0_1
LBB0_3:
        movl    -8(%ebp), %eax
        addl    $8, %esp
        popl    %ebp
        retl
```

- Optimised for Hardware
  - Mimics the logic of a particular processor (CPU): x86, Arm
  - Machine code hard for people to read
  - Redundancy, ambiguity reduced
  - Abstractions & information about intent is lost
- Assembly language
  - strong correspondence between the instructions in the language and the architecture's machine code instructions
  - text representation of the machine language
  - Etymology: internal instructions of a computer are “assembled” into the actual form used by the machine
- Figure at left shows (unoptimised) 32-bit code for the factorial function written in x86 assembly

How to translate?

- Source code – Machine code mismatch
- Some languages are farther from machine code than others:
  - Consider: C, C++, Java, Lisp, ML, Haskell, R, Python, JavaScript

- Goals of translation:
  - Source level expressiveness for the task
  - Best performance for the concrete computation
  - Reasonable translation efficiency ($< O(n^3)$)
  - Maintainable code
  - Correctness!

Correct Compilation

- Programming languages describe computation precisely…
  - therefore, *translation* can be precisely described
  - a compiler *must* be correct with respect to the source and target language semantics.

- Correctness is important!
  - Broken compilers generate broken code.
  - Hard to debug source programs if the compiler is incorrect.
  - Failure has dire consequences for development cost, security, etc.

- This course: some techniques for building correct compilers
  - *Finding and Understanding Bugs in C Compilers,*
    Yang et al. PLDI 2011
  - There is much ongoing research about *proving* compilers correct.
    (search for CompCert, Verified Software Toolchain, or Vellvm)

Specifying Compilers

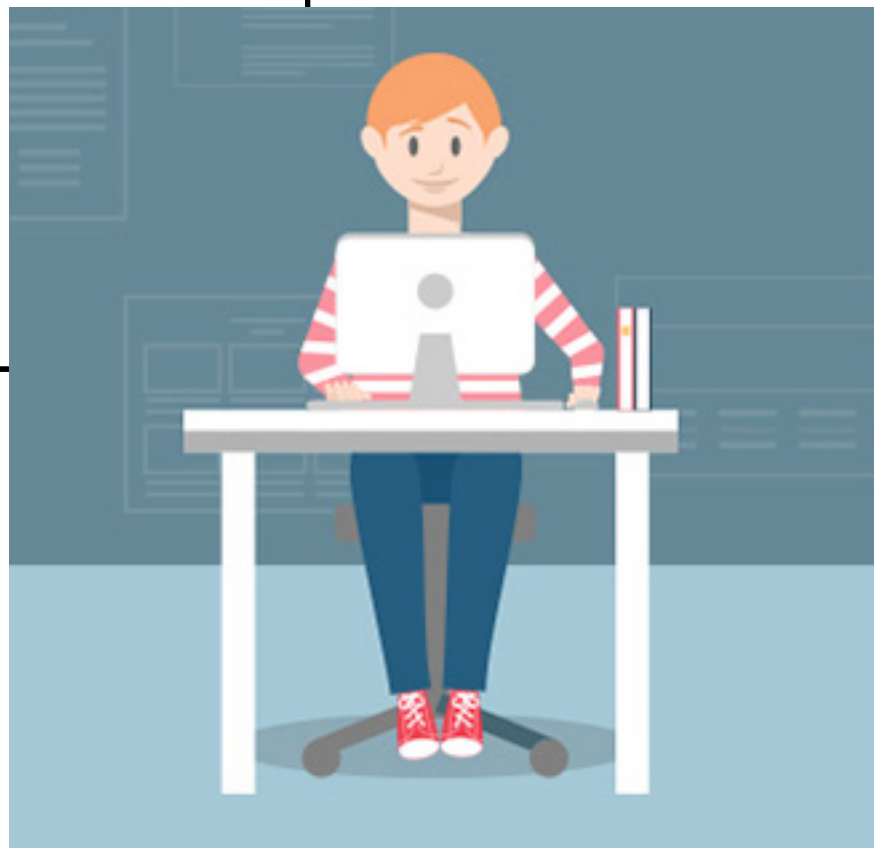
Program in C

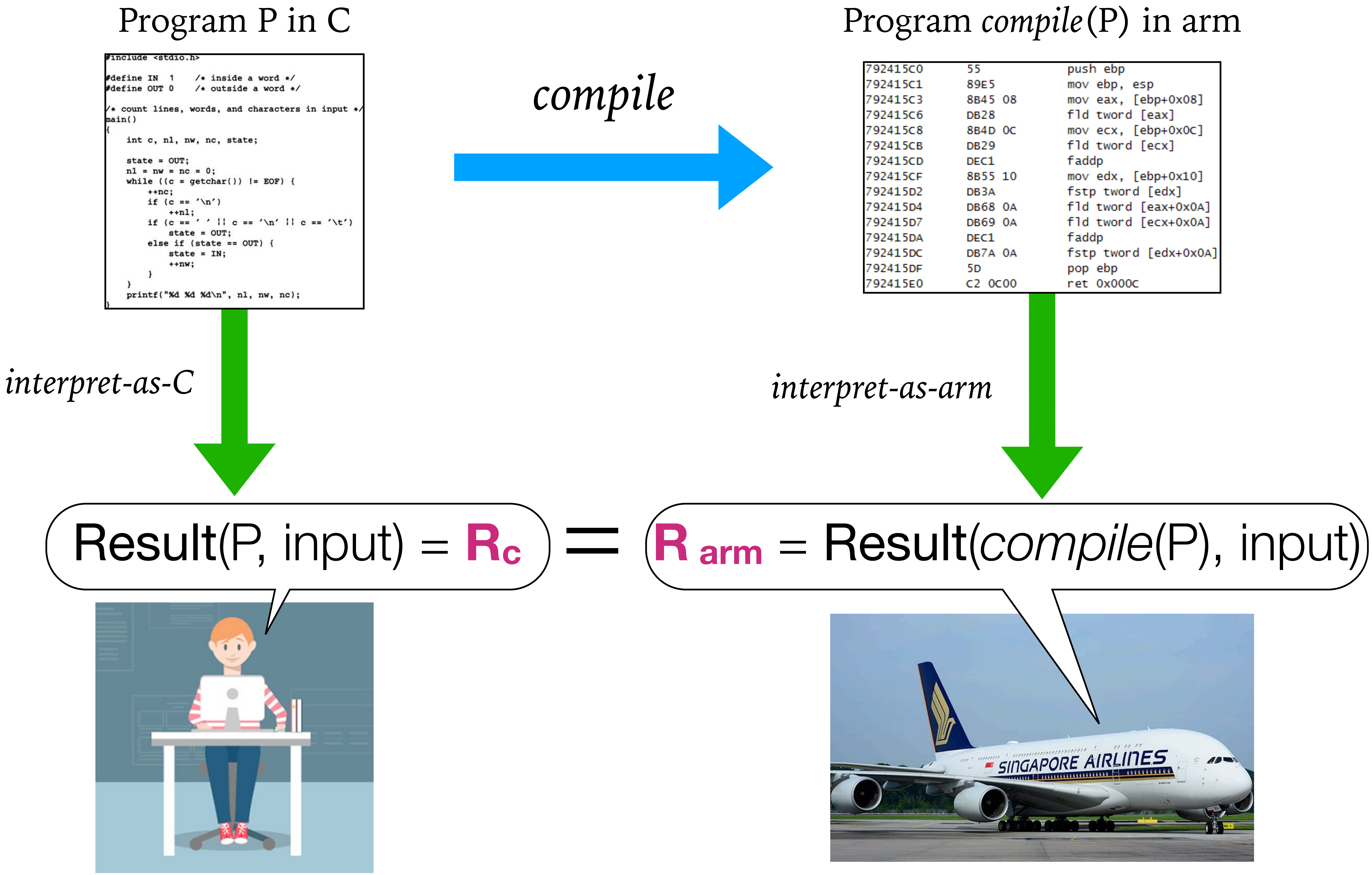
```c
#include <stdio.h>

#define IN  1   /* inside a word */
#define OUT 0   /* outside a word */

/* count lines, words, and characters in input */
main()
{
    int c, nl, nw, nc, state;

    state = OUT;
    nl = nw = nc = 0;
    while ((c = getchar()) != EOF) {
        ++nc;
        if (c == '\n')
            ++nl;
        if (c == ' ' || c == '\n' || c == '\t')
            state = OUT;
        else if (state == OUT) {
            state = IN;
            ++nw;
        }
    }
    printf("%d %d %d\n", nl, nw, nc);
}
```

compile

Program in arm assembly

```
792415C0    55        push ebp
792415C1    89E5      mov ebp, esp
792415C3    8B45 08   mov eax, [ebp+0x08]
792415C6    DB28      fld tword [eax]
792415C8    8B4D 0C   mov ecx, [ebp+0x0C]
792415CB    DB29      fld tword [ecx]
792415CD    DEC1      faddp
792415CF    8B55 10   mov edx, [ebp+0x10]
792415D2    DB3A      fstp tword [edx]
792415D4    DB68 0A   fld tword [eax+0x0A]
792415D7    DB69 0A   fld tword [ecx+0x0A]
792415DA    DEC1      faddp
792415DC    DB7A 0A   fstp tword [edx+0x0A]
                      pop ebp
                      ret 0x000C
```





Program P in C
#include <stdio.h>
#define IN 1 /* inside a word */
#define OUT 0 /* outside a word */
/* count lines, words, and characters in input */
main()
{
int c, nl, nw, nc, state;
state = OUT;
nl = nw = nc = 0;
while ((c = getchar()) != EOF) {
++nc;
if (c == '\n')
++nl;
if (c == ' ' || c == '\n' || c == '\t')
state = OUT;
else if (state == OUT) {
state = IN;
++nw;
}
}
printf("%d %d %d\n", nl, nw, nc);
}
compile
Program compile(P) in arm
792415C0 55 push ebp
792415C1 89E5 mov ebp, esp
792415C3 8B45 08 mov eax, [ebp+0x08]
792415C6 DB28 fld tword [eax]
792415C8 8B4D 0C mov ecx, [ebp+0x0C]
792415CB DB29 fld tword [ecx]
792415CD DEC1 faddp
792415CF 8B55 10 mov edx, [ebp+0x10]
792415D2 DB3A fstp tword [edx]
792415D4 DB68 0A fld tword [eax+0x0A]
792415D7 DB69 0A fld tword [ecx+0x0A]
792415DA DEC1 faddp
792415DC DB7A 0A fstp tword [edx+0x0A]
792415DF 5D pop ebp
792415E0 C2 0C00 ret 0x000C
interpret-as-C
interpret-as-arm
Result(P, input) = Rc
=
R arm = Result(compile(P), input)
SINGAPORE AIRLINES

Compiler **Specification:**

For *any* program P, and *any* input,
the result of *interpreting* P with input in **C** is the same as
the result of *executing compilation* of P with input in **arm assembly**.

or, equivalently

Correctness Theorem:

$$\forall\ P, \text{input},\ \textit{interpret}_{C}(P, \text{input}) = \textit{execute}_{\text{arm}}(\textit{compile}(P), \text{input})$$

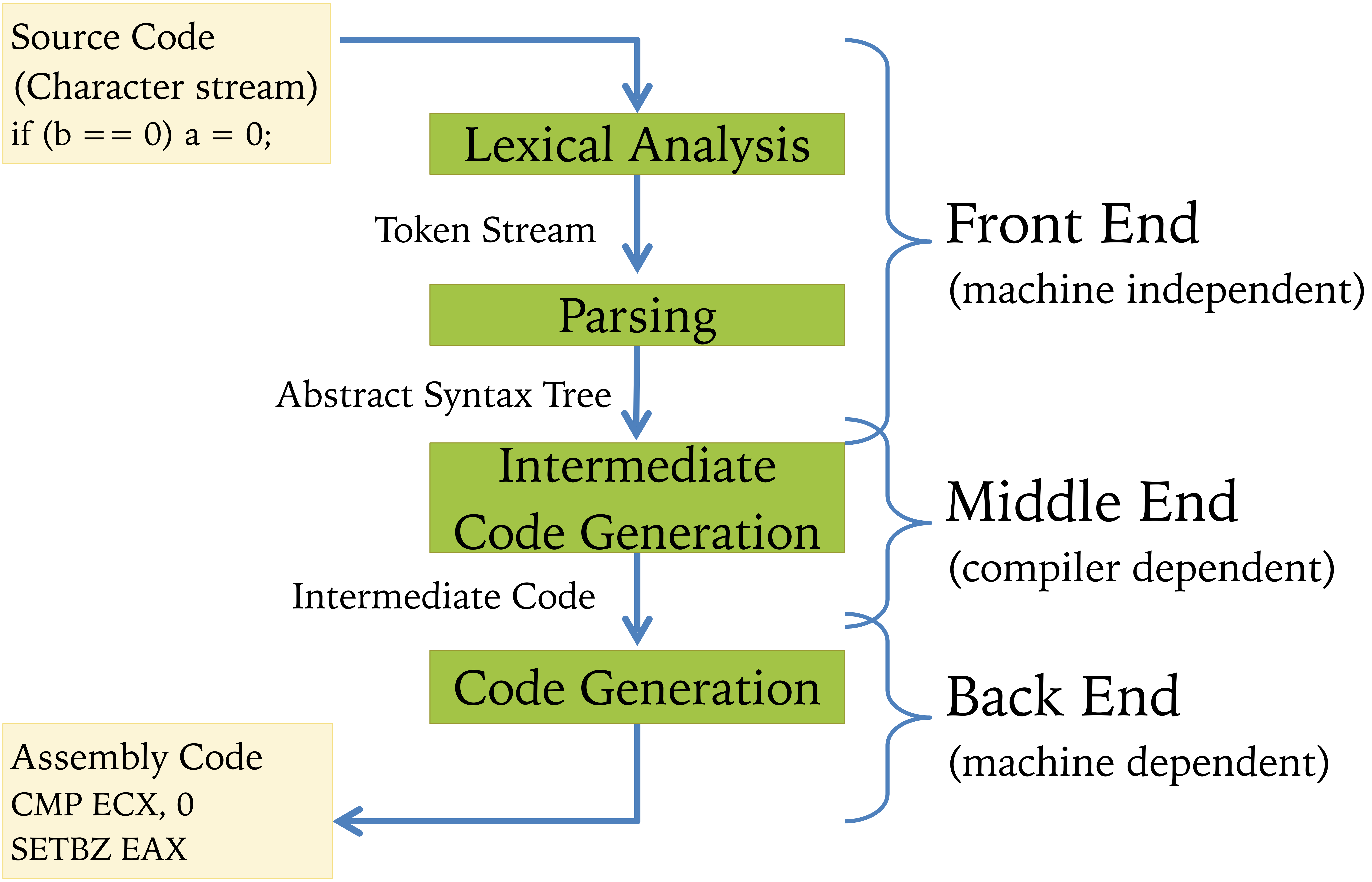
Idea: Translate in Steps

- Compile via a series of program representations

- Intermediate representations are optimised for program manipulation of various kinds:
  - Semantic analysis: type checking, error checking, etc.
  - Optimisation: dead-code elimination, common subexpression elimination, function inlining, register allocation, etc.
  - Code generation: instruction selection

- Representations are more machine specific, less language specific as translation proceeds

Simplified Compiler Pipeline

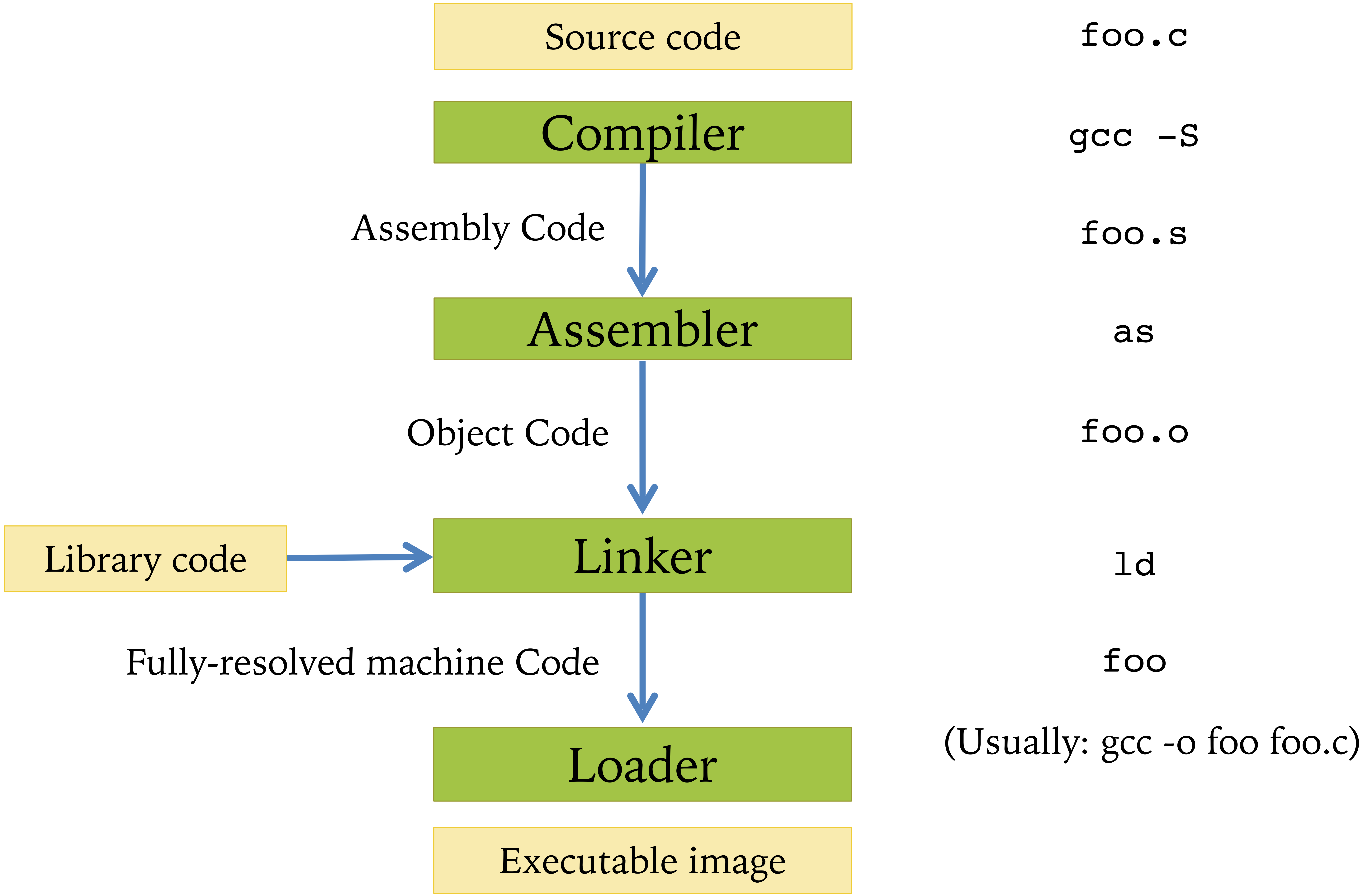


Typical Compiler Stages

Compiler Passes		Representations of the program
Lexing	→	token stream
Parsing	→	abstract syntax
Disambiguation	→	abstract syntax
Semantic analysis	→	annotated abstract syntax
Translation	→	intermediate code
Control-flow analysis	→	control-flow graph
Data-flow analysis	→	interference graph
Register allocation	→	assembly
Code emission		

- Optimisations may be done at many of these stages
- Different source language features may require more/different stages
- Assembly code is not the end of the story (processors may optimise, too)

Compilation and Execution



Compiler Demo

https://github.com/cs4212/week-01-simple-2024

See `factorial.c` in the project root

(use `hexdump` to see binary files)

Short-term Plan

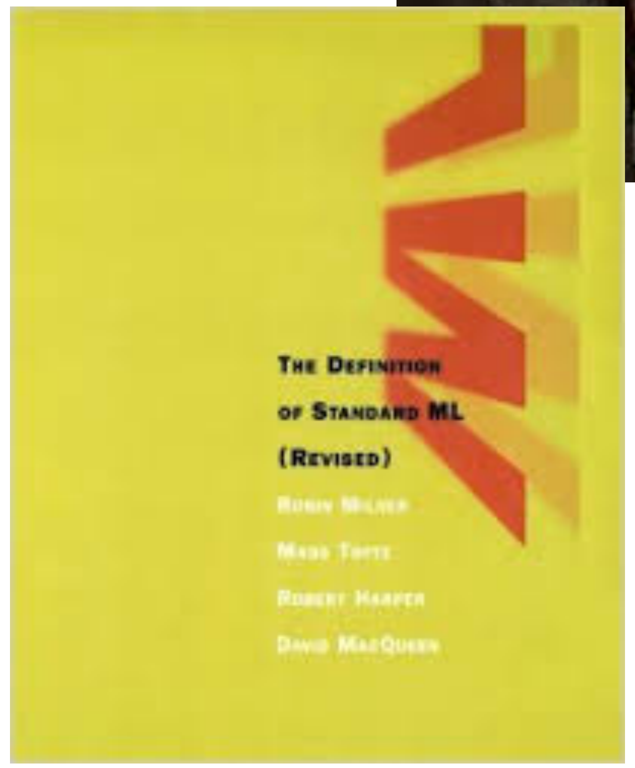
- Rest of today:
  - Refresher / background on OCaml
  - “object language” vs. “meta language”
  - Build a simple interpreter

- Next week:
  - Diving into x86 Assembly programming

OCaml for Compiler Hackers

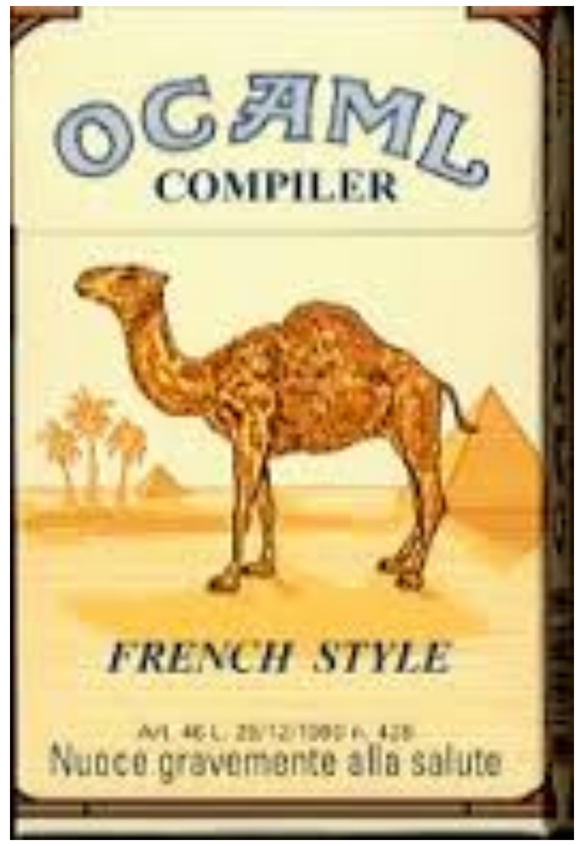
ML's History

- **1971: Robin Milner** starts the LCF Project at Stanford
  - "logic of computable functions"
- **1973:** At Edinburgh, Milner implemented his theorem prover and dubbed it "Meta Language" – ML
- **1984:** ML escaped into the wild and became "Standard ML"
  - SML '97 newest version of the standard
  - There is a whole family of SML compilers:
    - SML/NJ – developed at AT&T Bell Labs
    - MLton – whole program, optimizing compiler
    - Poly/ML
    - Moscow ML
    - ML Kit compiler
    - MLj – SML to Java bytecode compiler
- ML 2000: failed revised standardization
- sML: successor ML – discussed intermittently
- **2014:** sml-family.org + definition on GitHub



OCaml's History

- The Formel project at the Institut National de Rechereche en Informatique et en Automatique (INRIA)
- **1987:** Guy Cousineau re-implemented a variant of ML
  - Implementation targeted the "Categorical Abstract Machine" (CAM)
  - As a pun, "CAM-ML" became "CAML"
- **1991:** Xavier Leroy and Damien Doligez wrote Caml-light
  - Compiled CAML to a virtual machine with simple bytecode (much faster!)
- **1996:** Xavier Leroy, Jérôme Vouillon, and Didier Rémy
  - Add an object system to create OCaml
  - Add native code compilation
- Many updates, extensions, since…
- **2005:** Microsoft's F# language is a descendent of OCaml
- **2013:** ocaml.org



OCaml Toolchain

- ocaml – the top-level interactive loop
- ocamlc – the bytecode compiler
- ocamlopt – the native code compiler
- ocamldep – the dependency analyser
- ocamldoc – the documentation generator
- ocamllex – the lexer generator
- ocamlyacc – the parser generator
- ocamlbuild – a compilation manager

- menhir – a more modern parser generator
- dune – a more compilation manager (build tool)
- utop – a more fully-featured interactive top-level

- opam – package manager

Distinguishing Characteristics

- Functional & (Mostly) "Pure"
  - Programs manipulate values rather than issue commands
  - Functions are first-class entities
  - Results of computation can be "named" using let
  - Has relatively few "side effects" (imperative updates to memory)

- Strongly & Statically typed
  - Compiler type-checks every expression of the program, issues errors if it can't prove that the program is type safe
  - Good support for type inference & generic (polymorphic) types
  - Rich user-defined "algebraic data types" with pervasive use of *pattern matching*
  - Very strong and flexible module system for constructing large projects

Example: Imperative BST

```
type 'a node =
  | Node of (int * 'a ref * 'a tree * 'a tree)
  | Leaf
and 'a tree = ('a node) ref
let insert key value tree =
  let current = ref tree in
  let continue = ref true in
  while !continue do
    match !(!current) with
    | Leaf ->
      (!current) := Node (key, ref value, ref Leaf, ref Leaf)
    | Node (k, v, left, right) ->
      if k = key then begin
        v := value;
        continue := false;
      end else if k < key then
        current := left
      else
        current := right
  done
```

Example: Functional BST

```
type 'a tree =
  | Node of (int * 'a * 'a tree * 'a tree)
  | Leaf
let rec insert key value tree =
  match tree with
  | Leaf -> Node (key, value, Leaf, Leaf)
  | Node (k, v, left, right) ->
    if k = key then
      Node (k, value, left right)
    else if k < key then
      Node (k, v, insert key value left, right)
    else
      Node (k, v, left, insert key value right)
```

Most Important OCaml Features for the Class

- Types:
  - int, bool, int32, int64, char, string, built-in lists, tuples, records, functions
- Concepts:
  - Pattern matching
  - Recursive functions over algebraic (i.e. tree-structured) datatypes
- Libraries:
  - Int32, Int64, List, Printf, Format

Interpreters

- How to represent programs as data structures.
- How to write *programs* that *process programs*.

Olivier Danvy

Science (Computer Science)

Professor

Email: danvy@yale-nus.edu.sg

VIEW CURRICULUM VITAE

BIO | RESEARCH | PUBLICATIONS | TEACHING MODULES

Prof Danvy is interested in all aspects of programming languages, from their logic and semantics to their implementation, including programming, transforming programs, program transformations, and reasoning about programs and about program transformations (for one man's program is another program's data). As a Scheme programmer, he is familiar with parentheses and he is not afraid to use them. Also, for several years now, he has become convinced that the Coq Proof Assistant is the greatest thing since sliced bread and that it has the potential to transcend Computer Science college education, so watch this space. He is also interested in scientific communication.

Everyone's Favorite Function

- Consider this implementation of factorial in a hypothetical programming language that we'll call "SIMPLE"
  (Simple IMperative Programming LanguagE):

```
X = 6;
ANS = 1;
whileNZ (x) {
    ANS = ANS * X;
    X = X + -1;
}
```

- We need to describe the constructs of this SIMPLE
  - ***Syntax:*** which sequences of characters count as a legal "program"?
  - ***Semantics:*** what is the meaning (behavior) of a legal "program"?

”Object” vs. “Meta” language

Object language: the language (syntax / semantics) being described or manipulated	***Metalanguage***: the language (syntax / semantics) used to *describe* some object language
Today’s example: SIMPLE	interpreter written in OCaml
Course project: OAT ⇒ LLVM ⇒ x86asm	compiler written in OCaml
Clang compiler: C/C++ ⇒ LLVM ⇒ x86asm	compiler written in C++
Metacircular interpreter: lisp	interpreter written in lisp

Grammar for a Simple Language

```
<exp> ::=
    |   <X>
    |   <exp> + <exp>
    |   <exp> * <exp>
    |   <exp> < <exp>
    |   <integer constant>
    |   (<exp>)

<cmd> ::=
    |   skip
    |   <X> = <exp>
    |   ifNZ <exp> { <cmd> } else { <cmd> }
    |   whileNZ <exp> { <cmd> }
    |   <cmd>; <cmd>
```

BNF grammars are themselves domain-specific metalanguages for describing the syntax of other languages…

- Concrete syntax (grammar) for the Simple language:
  - Written in "Backus-Naur form"
  - <*exp*> and <*cmd*> are ***nonterminals***
  - '::=' , '|' , and <…> symbols are part of the *metalanguage*
  - keywords, like 'skip' and 'ifNZ' and symbols, like '{' and '+' are part of the *object language*

- Need to represent the ***abstract syntax*** (i.e. hide the irrelevant of the concrete syntax)

- Implement the ***operational semantics*** (i.e. define the behavior, or meaning, of the program)

Demo: Interpreters in OCaml

- https://github.com/cs4212/week-01-simple-2024
- Interpreting expressions
- Translating Simple programs to OCaml programs

Next Week

- Continuing with SIMPLE interpreter
- Basics X86 Assembly
- C memory layout
- Implementing calls and returns via call stacks