Lecture 1

CS131: COMPILERS

Slides adapted from UPenn CIS 3410 by Steve Zdancewic

Administrivia

- **Instructor: 陈浩贤**
- **Office hours:** Wednesday 4:00-5:00pm & by appointment.
  SIST 1A503.A

- **TAs:**
  - 尤存翰 Monday 7:00 - 8:00 pm
  - 郑嘉业 Thursday 7:00 – 8:00 pm

- **Course Website:** https://faculty.sist.shanghaitech.edu.cn/cs131/
  - HW instructions
  - Course schedule and materials

- **Projects:** submit on Blackboard

Why CS131?

- You will learn:
  - Practical applications of theory
  - 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
  - A deeper understanding of code
  - A little about programming language semantics & types
  - Functional programming in OCaml
  - How to manipulate complex data structures
  - How to be a better programmer

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

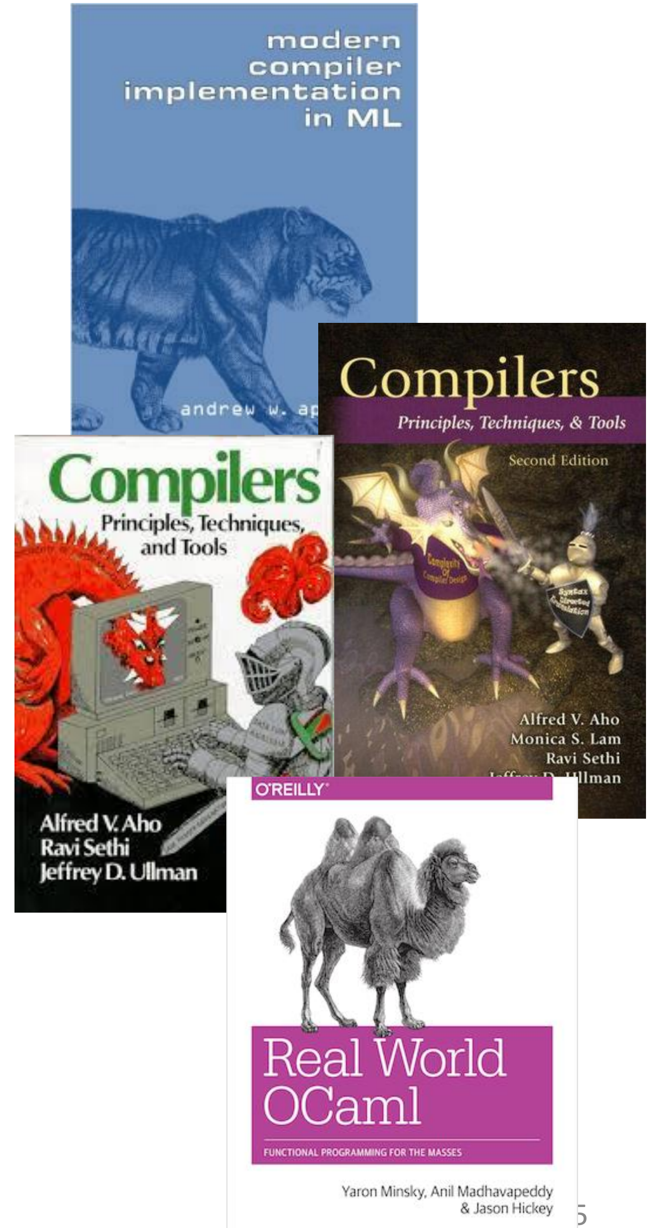
The CS131 Compiler

- Course projects
  - HW1: Hellocaml! (OCaml programming)
  - HW2: X86lite interpreter
  - HW3: LLVMlite compiler
  - HW4: Lexing, Parsing, simple compilation
  - HW5: Higher-level Features
  - HW6: Analysis and Optimizations

- Goal: build a complete compiler from a high-level, type-safe language to x86 assembly.

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)



Why 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

- Never used it?
  - Next couple lectures will introduce it
  - First two projects will help you get up to speed programming
  - See "Introduction to Objective Caml" by Jason Hickey
    - book available on the course web pages, referred to in HW1

HW1: Hellocaml

- Homework 1 available soon on Blackboard.
  - **Individual** project – no groups
  - Due: *September 30th . 2024 at 11:59pm*
  - Topic: OCaml programming, an introduction to interpreters

- We recommend using VSCode + Docker
  - the projects will build a "dev container" for you
  - See the instruction tool chain to get started

- Quickstart guide:
  - open up the project in VSCode
  - start a “sandbox terminal” via OCaml Platform plugin
  - type make test at the command prompt

  - Please: Use Blackboard to report any troubles with the toolchain!

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
- Submission policy:
  - Projects that don't compile will get no credit
  - Partial credit will be awarded according to the guidelines in the project description
- Academic integrity: don't cheat
  - This course will abide by the University's Code of Academic Integrity
  - "low level" and "high level" discussions across groups are fine
  - "mid level" discussions / code sharing are not permitted
  - General principle: *When in doubt, ask!*

Course Policies

Prerequisites:

- Significant programming experience, familiarity with trees, graphs, low-level coding
- Some familiarity with computation models (automata, stack machines, etc.), is useful too!
- If HW01 is a struggle, this class might not be a good fit for you (HW01 is significantly simpler than the rest…)

Grading:

- 60% Projects: *Compiler*
  - Groups of 2 students (except for HW01)
  - Implemented in OCaml

- 20% Midterm: in class … tentatively November 12th
- 20% Final exam

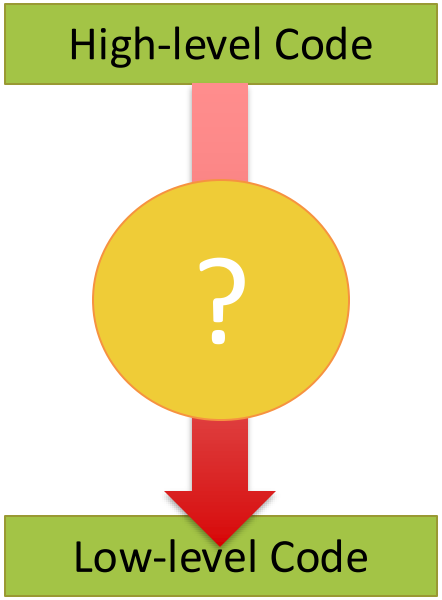
- Lecture attendance is crucial
  - Active participation (asking questions, etc.) is encouraged

What is a compiler?

COMPILERS

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.
- 1951—1952: Grace Hopper
  - developed the A-0 system 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
- 1970's: language/compiler design blossomed

1980s: ML / LCF
1984: Standard ML
1987: Caml
1991: Caml Light
1995: Caml Special Light
1996: Objective Caml
2005: F# (Microsoft)
2015: Reason ML
2020: OCaml Platform

- Today: *thousands* of languages (most little used)
  - Some better designed than others...

Source Code

- Optimized for human readability
  - *Expressive*: matches human ideas of grammar / syntax / meaning
  - *Redundant*: more information than needed to help catch errors
  - *Abstract*: exact computation possibly not fully determined by code
- Example C source:

```
#include <stdio.h>

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

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

Low-level code

- Optimized for Hardware
  - Machine code hard for people to read
  - Redundancy, ambiguity reduced
  - Abstractions & information about intent is lost

- Assembly language
  - then machine language

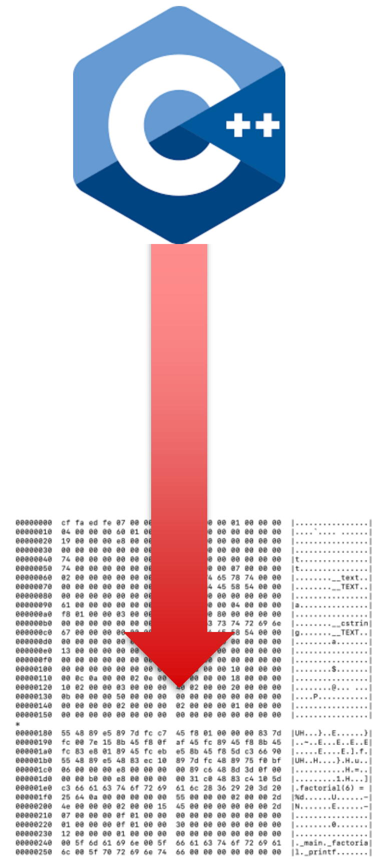
- Figure at right shows (unoptimized) 32-bit code x86 for the factorial function

```
_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
```

How to translate?

- Source code – Machine code mismatch
- Some languages are farther from machine code than others:
  - Consider: C, C++, Java, Lisp, ML, Haskell, Ruby, 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 can 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.

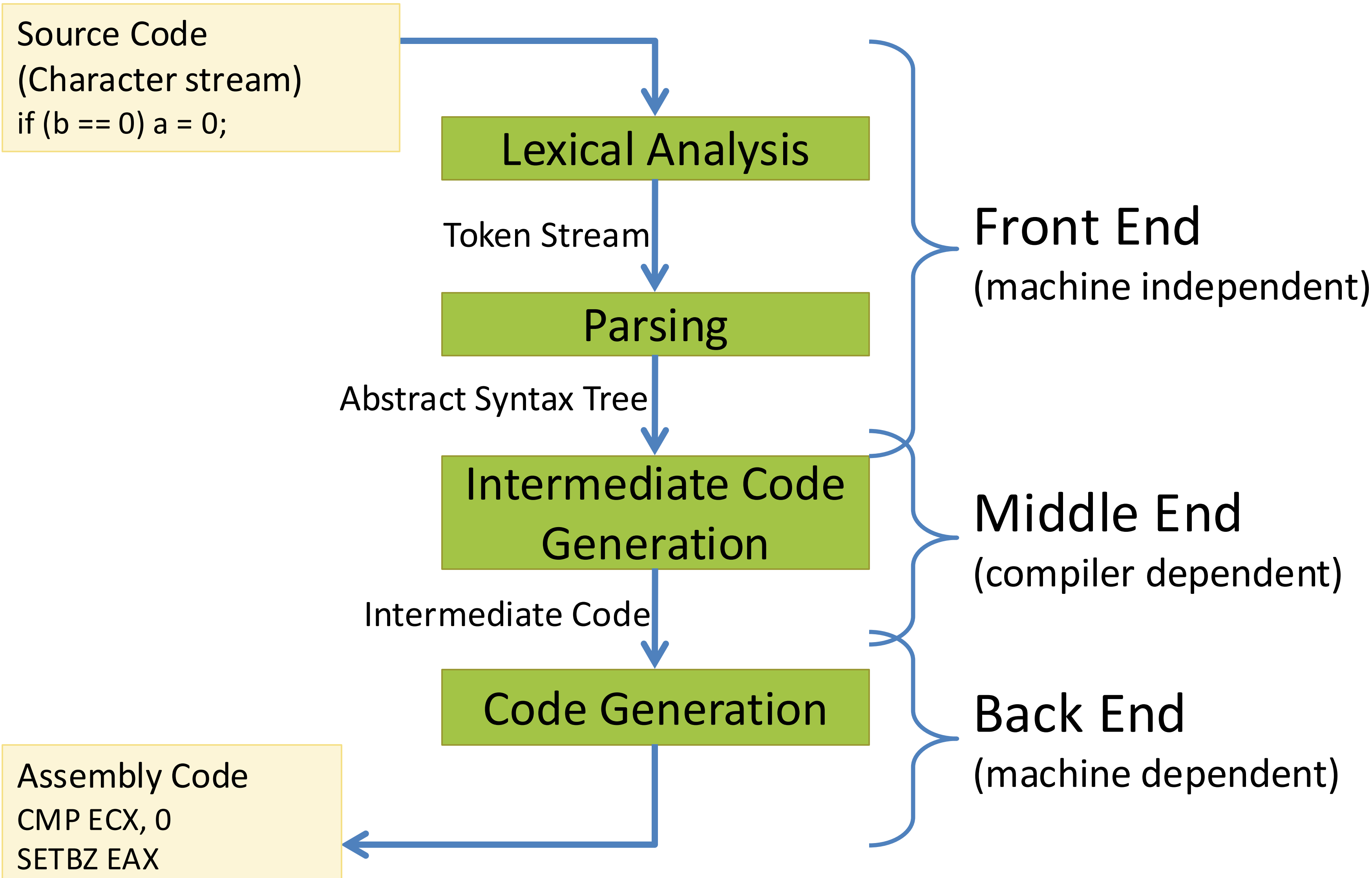
- This course: some techniques for building correct compilers
  - *Finding and Understanding Bugs in C Compilers,*
    Yang et al. PLDI 2011

  - There is much ongoing research about *proving* compilers correct.
    (Google for CompCert, Verified Software Toolchain, or Vellvm)

Idea: Translate in Steps

- Compile via a series of program representations
- Intermediate representations are optimized for program manipulation of various kinds:
  - Semantic analysis: type checking, error checking, etc.
  - Optimization: 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 Structure

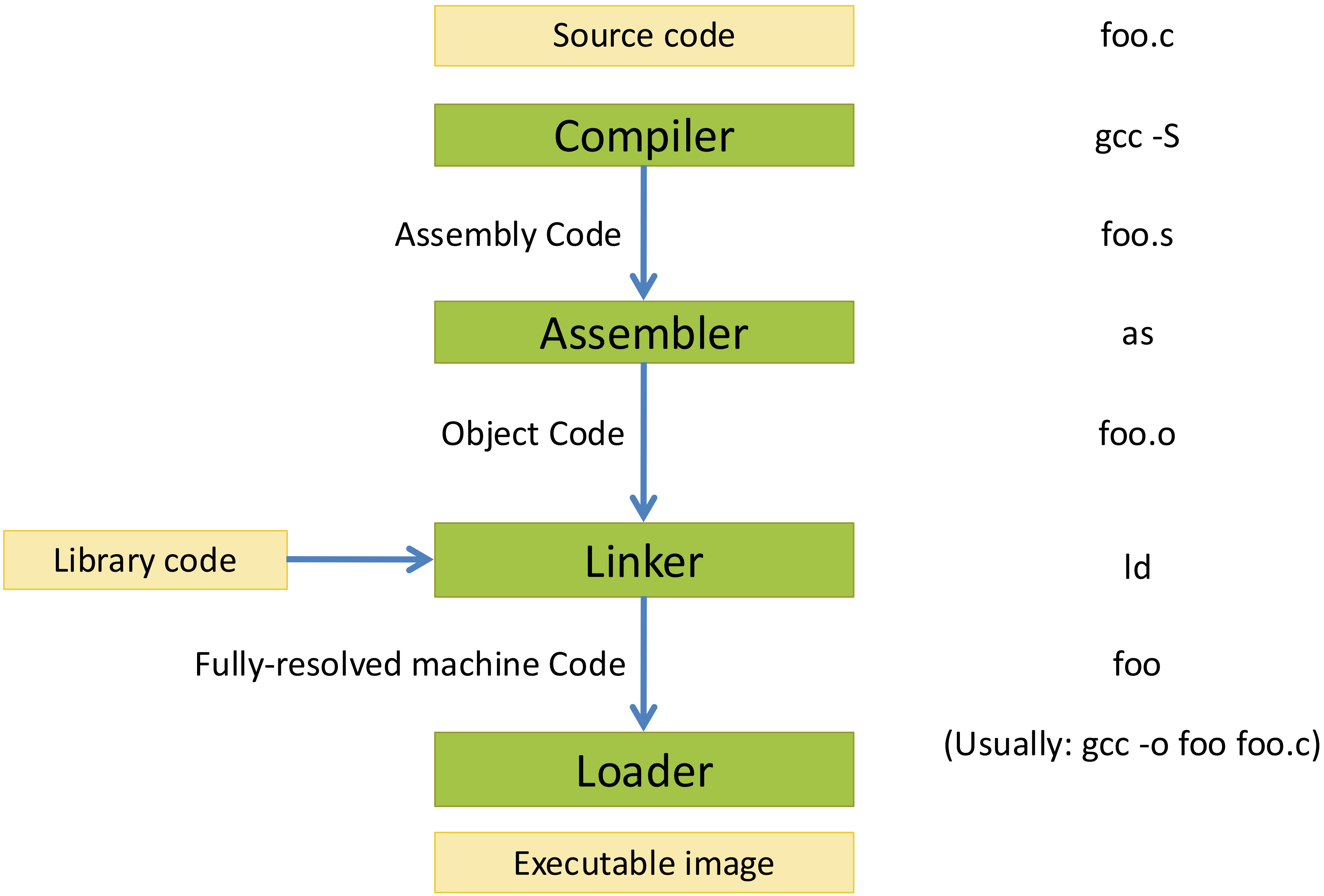


Typical Compiler Stages

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		

- Optimizations 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

Compilation & Execution



See lec01.zip

COMPILER DEMO

Short-term Plan

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

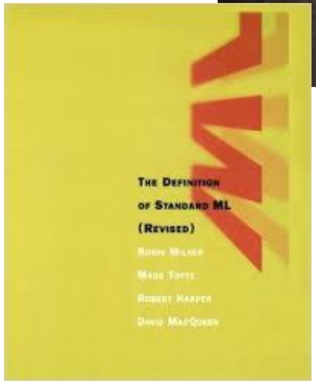
Introduction to OCaml programming

- A little background about ML
- Interactive tour of OCaml via UTop & VSCode
- Writing simple interpreters

OCAML

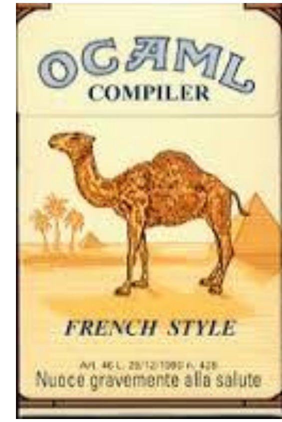
ML's History

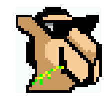
- **1971: Robin Milner** starts the LCF Project at Stanford
  - "logic of computable functions"
- **1973:** At Edinburgh, Milner implemented his theorem prover and dubbed it "Meta Language" – ML
- **1984:** ML escaped into the wild and became "Standard ML"
  - SML '97 newest version of the standard
  - 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
- **2020:** OCaml Platform
- **2022:** Multicore OCaml

OCaml Tools

- ocaml – the top-level interactive loop
- ocamlc – the bytecode compiler
- ocamlopt – the native code compiler
- ocamldep – the dependency analyzer
- ocamldoc – the documentation generator
- ocamllex – the lexer generator
- ocamlyacc – the parser generator

- menhir – a more modern parser generator
- dune – a compilation manager
- 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 typechecks 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

OCaml

Most Important Features for CS131

- 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

How to represent programs as data structures.

How to write programs that process programs.

INTERPRETERS

Factorial: 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 language
  - ***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 ⇒ x86_64	compiler written in OCaml

Clang compiler:

C/C++ ⇒ LLVM ⇒ x86_64	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 a simple imperative 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)

OCaml Demo

simple.ml