CSE 401/M501 – Compilers

Overview and Administrivia

Hal Perkins

Autumn 2019

Agenda

- Introductions
- Administrivia
- What’s a compiler?
- Why you want to take this course

Who: Course staff

- Instructor: Hal Perkins: UW faculty for a while; CSE 401 veteran (+ other compiler courses)
- TAs: Aaron Johnston, Miya Natsuhara, Kory Watson, and Sam Wolfson
  - With consulting help from Fatemeh Ghezloo (CSEP501 TA)
- Get to know us – we're here to help you succeed!
- Office hours start next week. Watch for schedule on the course web

Credits

- Some direct ancestors of this course:
  - UW CSE 401 (Chambers, Snyder, Notkin, Perkins, Ringenburg, Henry, …)
  - UW CSE PMP 582/501 (Perkins)
  - Rice CS 412 (Cooper, Kennedy, Torczon)
  - Cornell CS 412-3 (Teitelbaum, Perkins)
  - Many books (Appel; Cooper/Torczon; Aho, [[Lam,] Sethi,] Ullman [Dragon Book]; Fischer, [Cytron ,] LeBlanc; Muchnick, …)
- Won't attempt to attribute everything – and some of the details are lost in the haze of time

CSE M 501

- Enhanced version for 5th-year Master's students.

- M501 students will have to do a significant addition to the project, or some other extra work if agreed with instructor (papers, reports, ???)
  - More details later

- Otherwise 401 and M501 are the same (lectures, sections, assignments, infrastructure, …)

So whadda ya know?

- Official prerequisites:
  - – CSE 332 (data abstractions)
    - and therefore CSE 311 (Foundations)
  - – CSE 351 (hardware/software interface, x86_64)
- Also useful, but not required:
  - – CSE 331 (software design & implementation)
  - – CSE 341 (programming languages)
  - – Who's taken these?

Lectures & Sections

- Both required
- All material posted, but they are visual aids
  - Arrive punctually and pay attention (& take notes!)
  - If doing so doesn't save you time, one of us is messing up! Let us know so we can try to fix.
- Sections: additional examples and exercises plus project details and tools
  - This week (tomorrow!): start regexps/scanners – no reason to wait until Friday! Be there!!
  - AA, AB sections in SAV 131 (AA moved), AC still in SIG 228 but might move next week – check time roster before class to be sure

Staying in touch

- Course web site
- Discussion board –new this quarter: ed!
  - You will get login credentials sent to your UW email later today
  - For anything related to the course
  - Join in! Help each other out. Staff will contribute.
- Mailing list
  - You are automatically subscribed if you are registered
  - Will keep this fairly low-volume; limited to announcements or things that everyone must read

Requirements & Grading

- Roughly
  - 50% project, done with a partner
  - 15% individual written homework
  - 15% midterm exam
  - 20% final exam

  We reserve the right to adjust as needed

Academic Integrity

- We want a collegial group helping each other succeed!
- But: you must never misrepresent work done by someone else as your own, without proper credit if appropriate, or assist others to do the same
- Read the course policy carefully
- We trust you to behave ethically
  - I have little sympathy for violations of that trust
  - Honest work is the most important feature of a university (or engineering or business or life). Anything less disrespects your instructor, your colleagues, and yourself

Course Project

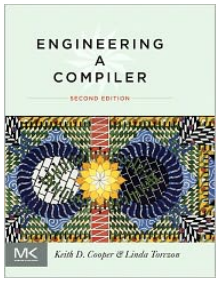
- Best way to learn about compilers is to build one!
- Course project
  - MiniJava compiler: classes, objects, etc.
    - Core parts of Java – essentials only
    - Originally from Appel textbook (but you don't need that)
  - Generate executable x86-64 code & run it
  - Completed in steps through the quarter
    - Where you wind up at the end is the most important part, but there are intermediate milestones to keep you on schedule and provide feedback at important points
  - Additional work for CSE M 501 students – details later

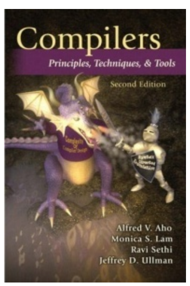
Project Groups

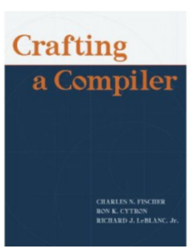
- You should work in pairs
  - Pick a partner now to work with throughout quarter – we need this info by early next week
  - If you are in CSE M 501 you should pair up with someone else in that group

- We’ll provide accounts on department gitlab server for groups to store and synchronize their work & we’ll get files from there for grading / feedback
  - Anybody new to CSE Gitlab/Git?

Books







- Four good books; will be on reserve in the engineering library:
  - Cooper & Torczon, *Engineering a Compiler.* “Official text” & we’ll take some assignments from here
  - Appel, *Modern Compiler Implementation in Java*, 2nd ed. MiniJava is from here.
  - Aho, Lam, Sethi, Ullman, “Dragon Book”
  - Fischer, Cytron, LeBlanc, *Crafting a Compiler*

Gadgets

- Gadgets reduce focus and learning
  - Bursts of info (*e.g.* emails, IMs, etc.) are *addictive*
  - Heavy multitaskers have more trouble focusing and shutting out irrelevant information
    - http://www.npr.org/2016/04/17/474525392/attention-students-put-your-laptops-away
  - Seriously, you will learn more if you use **paper** instead!!!
- So how should we deal with laptops/phones/etc.?
  - Just say no!
  - No open gadgets during class (really!)
  - Urge to search? – ask a question! Everyone benefits!!
  - You may close/turn off your electronic devices now
  - Pull out a piece of paper and pen/pencil instead ☺

And the point is…

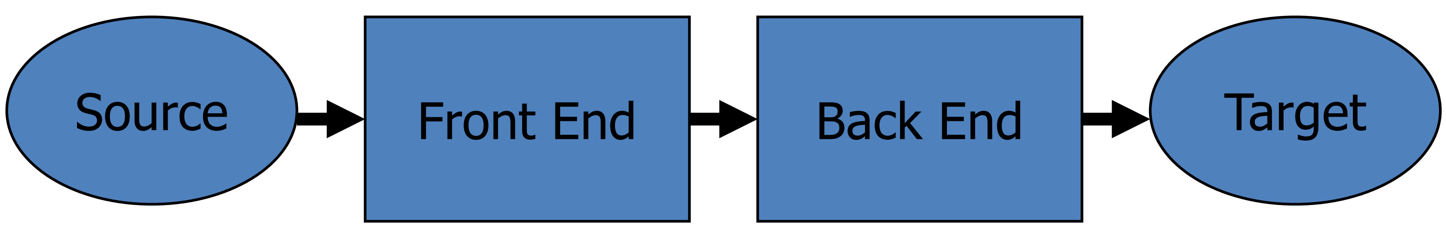
- How do we execute something like this?

```
int nPos = 0;
int k = 0;
while (k < length) {
  if (a[k] > 0) {
    nPos++;
  }
}
```

- The computer only knows 1's & 0's: encodings of instructions and data

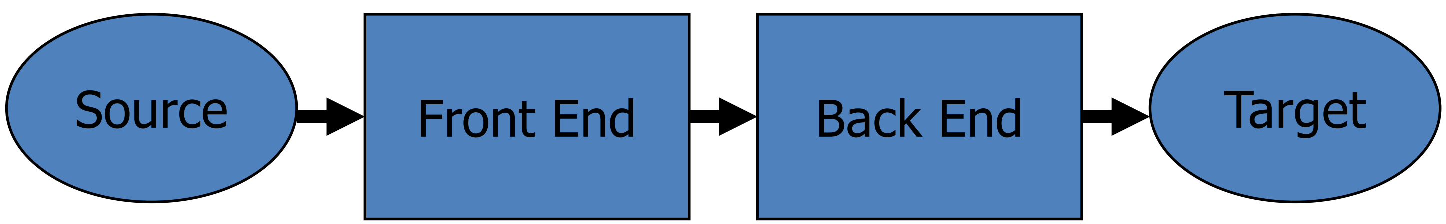
Structure of a Compiler

- At a high level, a compiler has two pieces:
  - Front end: analysis
    - Read source program and discover its structure and meaning
  - Back end: synthesis
    - Generate equivalent target language program



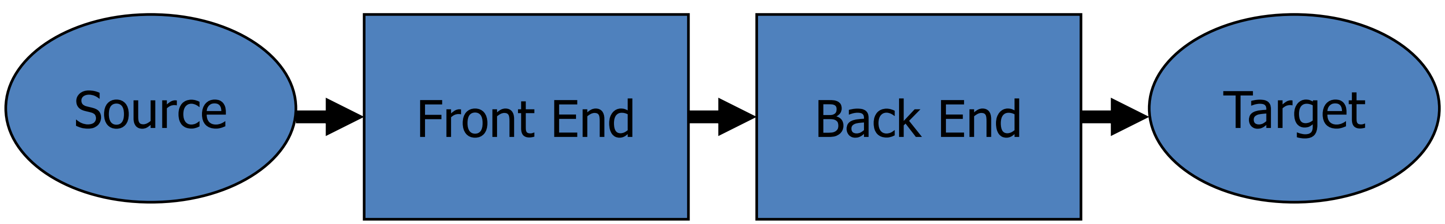
Compiler must…

- Recognize legal programs (& complain about illegal ones)
- Generate correct code
  - Compiler can attempt to improve ("optimize") code, but must not change behavior (meaning)
- Manage runtime storage of all variables/data
- Agree with OS & linker on target format

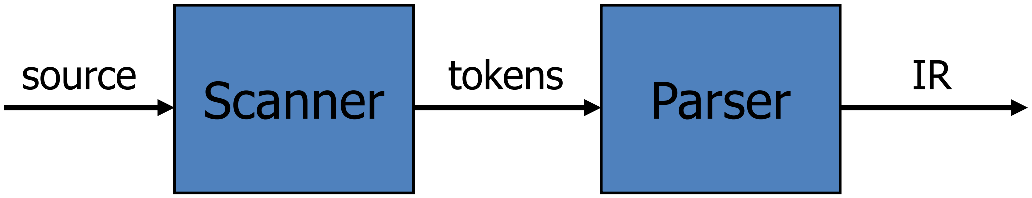


Implications

- Phases communicate using some sort of Intermediate Representation(s) (IR)
  - Front end maps source into IR
  - Back end maps IR to target machine code
  - Often multiple IRs – higher level at first, lower level in later phases



Front End



- Usually split into two parts
  - Scanner: Responsible for converting character stream to token stream: keywords, operators, variables, constants, …
    - Also: strips out white space, comments
  - Parser: Reads token stream; generates IR
    - Either here or shortly after, perform semantics analysis to check for things like type errors, etc.
- Both of these can be generated automatically
  - Use a formal grammar to specify the source language
  - Tools read the grammar and generate scanner & parser (lex/yacc or flex/bison for C/C++, JFlex/CUP for Java)

Scanner Example

- Input text

```
// this statement does very little
if (x >= y) y = 42;
```

- Token Stream

IF	LPAREN	ID(x)	GEQ	ID(y)

RPAREN	ID(y)	BECOMES	INT(42)	SCOLON

  - Notes: tokens are atomic items, not character strings; comments & whitespace are *not* tokens (in most languages – counterexamples: Python indenting, Ruby and JavaScript newlines)
    - Token objects sometimes carry associated data (e.g., numeric value, variable name)

Parser Output (IR)

- Given token stream from scanner, the parser must produce output that captures the meaning of the program
- Most common parser output is an abstract syntax tree (AST)
  - Essential meaning of program without syntactic noise
  - Nodes are operations, children are operands
- Many different forms
  - Engineering tradeoffs change over time
  - Tradeoffs (and IRs) can also vary between different phases of a single compiler

Scanner/Parser Example

Original source program:

```
// this statement does very little
if (x >= y) y = 42;
```

- Token Stream

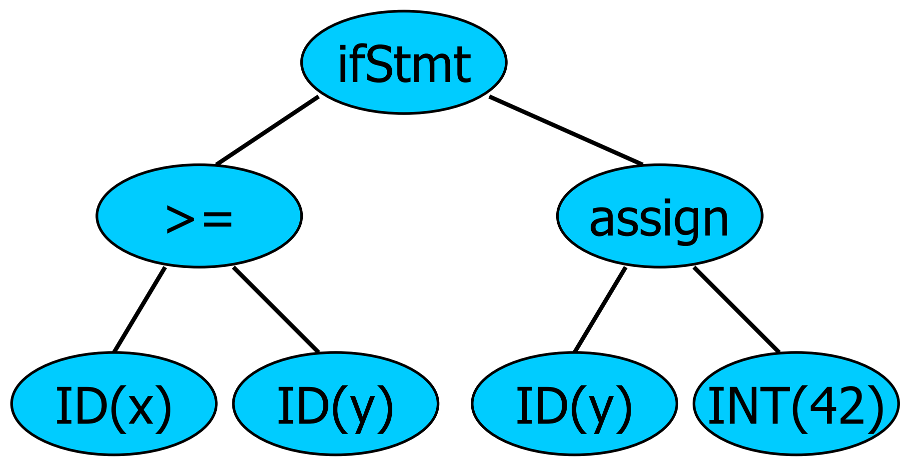
IF | LPAREN | ID(x)

GEQ | ID(y) | RPAREN

ID(y) | BECOMES

INT(42) | SCOLON

- Abstract Syntax Tree



Static Semantic Analysis

- During or (usually) after parsing, check that the program is legal and collect info for the back end
  - Type checking
  - Verify language requirements like proper declarations, etc.
  - Preliminary resource allocation
  - Collect other information needed by back end analysis and code generation
- Key data structure: Symbol Table(s)
  - Maps names -> meaning/types/details

Back End

- Responsibilities
  - Translate IR into target code
  - Should produce "good" code
    - "good" = fast, compact, low power (pick some)
  - Should use machine resources effectively
    - Registers
    - Instructions
    - Memory hierarchy

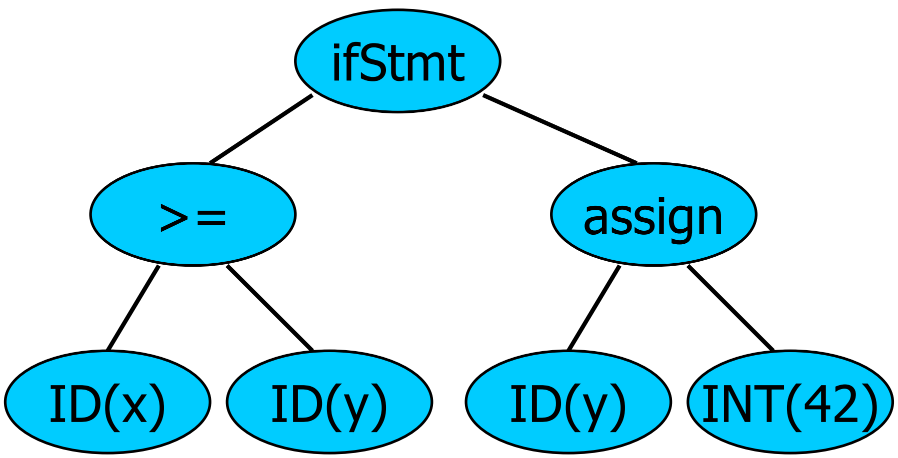
Back End Structure

- Typically two major parts
  - "Optimization" – code improvement – change correct code into semantically equivalent "better" code
    - Examples: common subexpression elimination, constant folding, code motion (move invariant computations outside of loops), function inlining (replace call with body of function)
    - Optimization phases often interleaved with analysis
  - Target Code Generation (machine specific)
    - Instruction selection & scheduling, register allocation
- Usually walk the AST and generate lower-level intermediate code before optimization

The Result

- Input

```
if (x >= y)
   y = 42;
```



- Output

```
  movl  16(%rbp),%edx
  movl  -8(%rbp),%eax
  cmpl   %eax, %edx
  jl       L17
  movl  $42, -8(%rbp)
L17:
```

Why Study Compilers? (1)

- Become a better programmer(!)
  - Insight into interaction between languages, compilers, and hardware
  - Understanding of implementation techniques, how code maps to hardware
  - Better intuition about what your code does
  - Understanding how compilers optimize code helps you write code that is easier to optimize
    - And avoid wasting time doing “optimizations” that the compiler will do better, and avoid “clever” code that confuses the compiler and makes thing worse

Why Study Compilers? (2)

- Compiler techniques are everywhere
  - Parsing (“little” languages, program input, scripts,…)
  - Software tools (verifiers, checkers, …)
  - Database engines, query languages
  - Domain-specific languages
  - Text processing
    - Tex/LaTex -> dvi -> Postscript -> pdf
  - Hardware: VHDL; model-checking tools
  - Mathematics (Mathematica, Matlab, SAGE)

Why Study Compilers? (3)

- Fascinating blend of theory and engineering
  - Lots of beautiful theory around compilers
    - Parsing, scanning, static analysis
  - Interesting engineering challenges and tradeoffs, particularly in optimization (code improvement)
    - Ordering of optimization phases
    - What works for some programs can be bad for others
  - Plus some very difficult problems (NP-hard or worse)
    - E.g., register allocation is equivalent to graph coloring
    - Need to come up with "good enough" approximations / heuristics

Why Study Compilers? (4)

- Draws ideas from many parts of CSE
  - AI: Greedy algorithms, heuristic search
  - Algorithms: graphs, dynamic programming, approximation
  - Theory: Grammars, DFAs and PDAs, pattern matching, fixed-point algorithms
  - Systems: Allocation & naming, synchronization, locality
  - Architecture: pipelines, instruction set use, memory hierarchy management, locality

Why Study Compilers? (5)

- You might even write a compiler some day!

- You ***will*** write parsers and interpreters for little languages, if not bigger things
  - Command languages, configuration files, XML, JSON, network protocols, …

- And if you like working with compilers and are good at it there are many jobs available…

Any questions?

- Your job is to ask questions to be sure you understand what's happening and to slow me down
  - Otherwise, I'll barrel on ahead ☺

Coming Attractions

- Quick review of formal grammars
- Lexical analysis – scanning & regular expressions – starts in sections *tomorrow*!
  - Background for first part of the project
  - All sections in SAV 131 (but check time schedule…)
- Followed by parsing …

- Start reading: ch. 1, 2.1-2.4

Before next time…

- If you are trying to add the class please watch for an opening and grab one when it shows up
  - Go to any section tomorrow
- Familiarize yourself with the course web site
- Read syllabus and academic integrity policy
- Find a partner!
  - And meet other people in the class too!! ☺