CSE 401/M501 – Compilers

Overview and Administrivia

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Autumn 2024

Agenda

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

Welcome back!

- This has been a strange world for the last few years and we're still dealing with lingering effects.

- Please speak up if things aren't (or are!) going well
  - We can often help if we know about problems, so stay in touch with TAs, instructor, advising, friends and peers, others
  - Don't try to "tough it out" or pretend it will get better if you just ignore it – speak up! Don't wait until it's too late!!

- We're all in this together but not all in the same way, so please show understanding and compassion for each other and help when you can – both in and outside of class

- Stay healthy! If you do come down with something, please stay home until recovered and not contagious
  - Lectures are on panopto if you do need to miss (but this is not a remote-learning class)

- Please be realistic about your workload – it's up to you to be sure you have the time and energy to handle your academic and other commitments
  - Do NOT "Ghost" your project partner!! 👻

Who: Course staff

- Instructor: Hal Perkins: UW faculty for a while; CSE 401 veteran (+ other compiler courses)
- TAs: Eric Chen, Karen Haining,
  Connor Reinholdtsen, and Richard Tran
- Get to know us – we're here to help you succeed!
- Office hours start soon! – watch for postings on main website calendar. Mostly in-person but may add some hybrid and zoom-only hours (use canvas calendar to access zoom links)

Credits

- Some direct ancestors of this course:
  - UW CSE 401 (Chambers, Snyder, Notkin, Perkins, Ringenburg, Henry, …)
  - UW CSE PMP 582/501 (Perkins & others)
  - 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 (many?) of the details are lost in the haze of time

CSE M 501

- Enhanced version for 5th-year BS/MS 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 very 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
  - Be here! Take notes! (& do better in class!!)
  - Panopto lecture recordings intended for review and unavoidable absences only
- Sections: additional examples and exercises plus project details and tools
  - We will have sections this week (tomorrow!) – don't miss!
    - Some section rooms have changed – be sure to check

Gadgets in class

- Gadgets reduce focus and learning
  - Bursts of info (*e.g.* notifications, IMs, etc.) are *addictive*
  - Heavy multitaskers have more trouble focusing and shutting out irrelevant information (lots of research results and news stories about this in recent years)
- So how should we deal with laptops/phones/etc.?
  - Just say no!
  - No open gadgets during class (really!)
    - Unless you are actually using a device to take notes or for other appropriate uses….
  - Urge to search? – ask a question! Everyone benefits!!
  - You may close/turn off non-notetaking electronics now
  - Pull out a piece of paper and pen/pencil instead ☺

Communications

- Course web site (www.cs.uw.edu/401)
- Discussion board – ed
  - For (almost) anything related to the course
  - Join in! Help each other out. Staff will contribute.
  - Also use for private messages with too-specific-to-post questions, code, etc.
  - Staff will also use to post announcements
- Gradescope regrades for questions about written assignment feedback
- Email to cse401-staff[at]cs for project feedback questions, unexpected or personal situations, things that need a followup, not appropriate for ed, …

Requirements & Grading

- We will have a midterm and final exam
  – It's an important review/reflection part we need
  – Dates are on the course calendar now
- Roughly:
  – 50% project, done with a partner
    - Half of this is the final result, other half from intermediate steps
  – 25% individual written homework
  – 10% midterm
  – 15% final

  We reserve the right to adjust as needed/appropriate
- Deadlines: 11:59 pm for everything

Academic Integrity

- We want a collegial group helping each other succeed!
- But: you must never misrepresent work done by someone (or something) else as your own, without proper credit if appropriate, or assist others to do the same (do not attempt to bypass learning by avoiding work)
- Read the course policy carefully
- We trust you to behave ethically
  - We 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

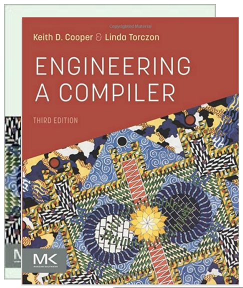
- Best way to learn about compilers is to build one!
- Course project
  - MiniJava compiler: classes, objects, etc.
    - Core parts of Java – essentials only
    - Originally from Appel textbook (but you don’t need that)
  - Generate executable x86-64 code & run it
  - Completed in steps through the quarter
    - Where you wind up at the end is by far 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, but usually: add some interesting feature to MiniJava

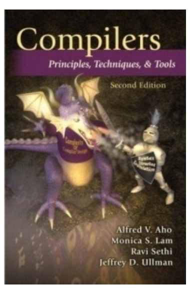
Project Groups

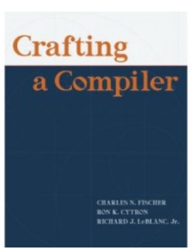
- You should work in pairs
  - Pick a partner now to work with throughout quarter – we need this info by early next week
    - Be sure you agree on work strategy, attitudes about deadlines, etc.
  - If you are in CSE M 501 you should pair up with someone else in that group (401 → M 501 switches are possible if it makes sense for individual(s) involved)
  - Partnering over networks works surprisingly well even if you don’t intend to hang out together in the labs regularly

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

Books







- Four good books…
  - Cooper & Torczon, *Engineering a Compiler.* “Official text” & we’ll take some assignment questions fr … e free online throu … ks login. See syllabus.
  - Appel, *Modern Compiler Implementation in Java*, 2nd ed. MiniJava is from here.
  - Aho, Lam, Sethi, Ullman, “Dragon Book”
  - Fischer, Cytron, LeBlanc, *Crafting a Compiler*

New 3rd edition early last year!
Either 2nd or 3rd ed. should be fine

And the point is…

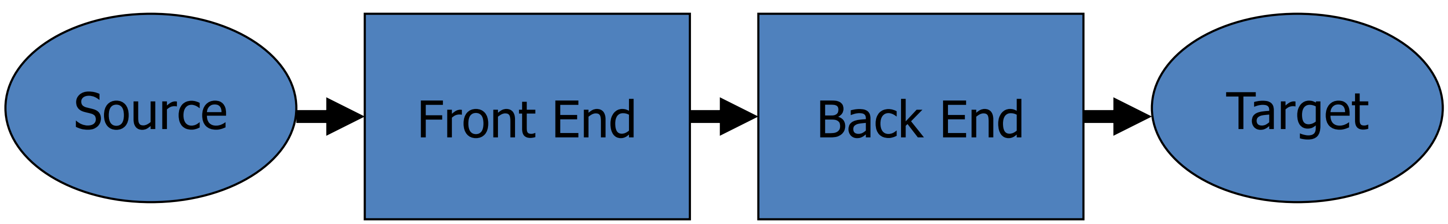
- How do we execute something like this?

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

- Or, more concretely, how do we program a computer to understand and carry out a computation written as text in a file? The computer only knows 1’s & 0’s: encodings of instructions and data (cf CSE 351)

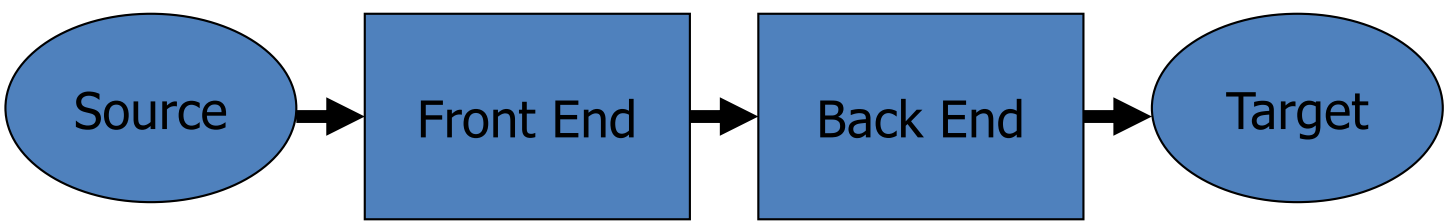
Structure of a Compiler

- 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



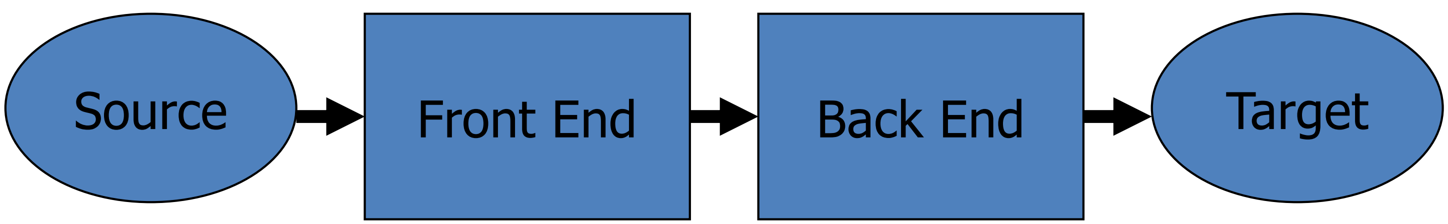
Compiler must…

- 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

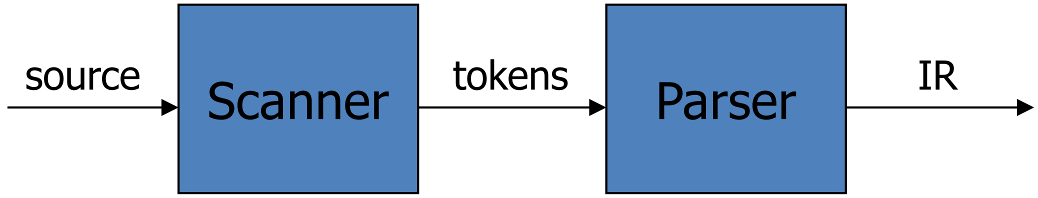


Implications

- 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, equivalent tools for almost all major langauges)

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)

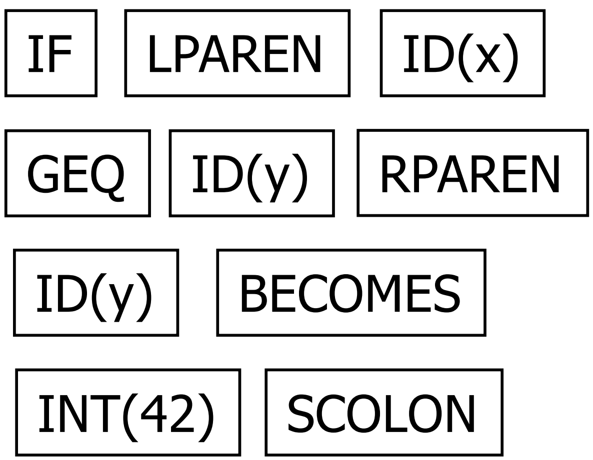
- Given token stream from scanner, the parser must produce output that captures the meaning of the program
- Most common parser output is an abstract syntax tree (AST)
  - Essential meaning of program without syntactic noise
  - Nodes are operations, children are operands
- Many different forms
  - Engineering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

Scanner/Parser Example

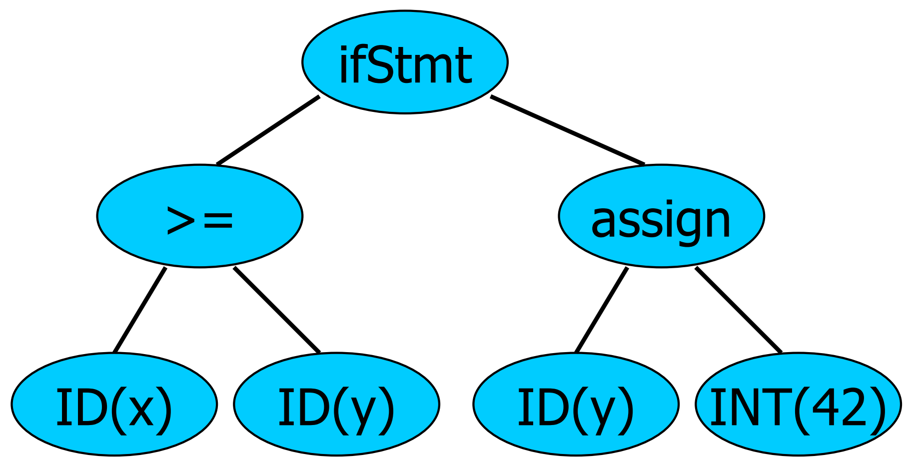
Original source program:

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

- Token Stream



- 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

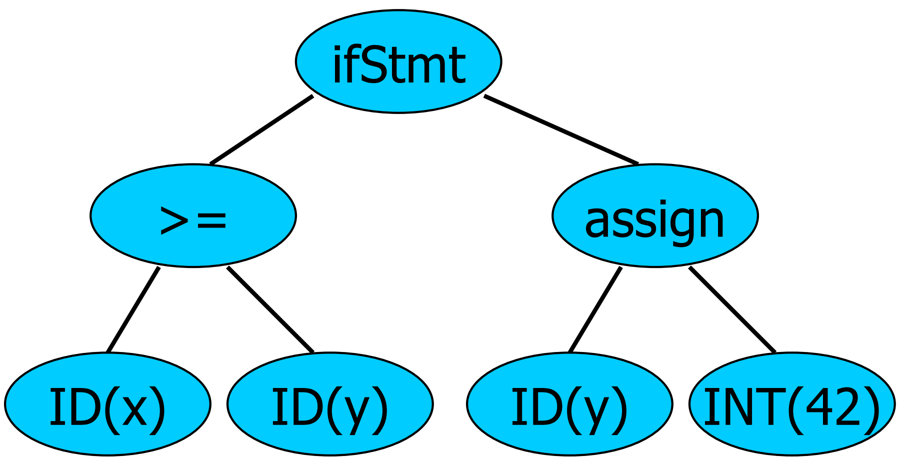
Back End Structure

- 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 source "optimizations" that the compiler ~~can~~ 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 (SQL, …)
  - Domain-specific languages, ML, data science
  - 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 for optimizations (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, semi-structured data, …
- And if you like working with compilers there are many jobs available…
  - Novel languages / architectures for ML/AI, massive data science, etc. need effective implementations

Any questions?

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

Coming Attractions

- Quick review of formal grammars
- Lexical analysis – scanning, regular expressions, DFAs, (starting in sections tomorrow!)
  - Background for first part of the project
- Followed by parsing …
- Start reading: ch. 1, 2.1-2.4
  - Entire 2^{nd} ed. book available through Safari Online to UW community – see syllabus for link

Before next time…

- Familiarize yourself with the course web site
- Read syllabus and academic integrity policy
- Find a partner!
  - And meet other people in the class too!! ☺
- Go to sections tomorrow! Essential stuff
  - And be sure to go to the right room ☺