CSE 401/M501 – Compilers

Overview and Administrivia

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Agenda

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

Who: Course staff

- Instructor: Hal Perkins: UW faculty for many years; CSE 401 veteran (+ other compiler courses)
- TAs: Aaron Johnston, Laura Vonessen, & Nate Yazdani
- Get to know us – we're here to help you succeed!
- Office hours tbd shortly – trying for most afternoons. Questions:
  – In the lab or separate TA room?
  – Right after class or later in the afternoon?

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 M501

- New this year – “enhanced” version for 5th-year Master’s students. Welcome!
- M501 will be an “official” course sometime during the quarter & everyone who should be in it will have their registration automagically changed.
- M501 students will have to do a significant addition to the project, or (maybe) some other extra work if agreed with instructor

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!
- Sections: additional examples and exercises plus project details and tools
- Additional project and other material posted

Staying in touch

- Course web site
- Discussion board – a google group
  - Uses your "UW Google identity" (not cse) because of how we sync with the UW registrar enrollment data
  - 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 things that everyone needs to read

Requirements & Grading

- Roughly
  - 50% project, done with a partner
    - (CSEM students should pair up with each other)
  - 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). Anything less disrespects your instructor, your colleagues, and yourself

Course Project

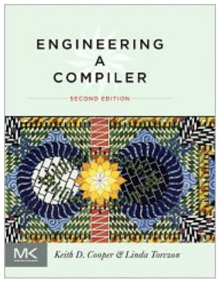
- Best way to learn about compilers is to build one
- Course project
  - MiniJava compiler: classes, objects, etc.
    - Core parts of Java – essentials only
    - Originally from Appel textbook (but you won't need that)
  - Generate executable x86-64 code & run it
  - Completed in steps through the quarter
    - Where you wind up at the end is the most important part, but there are intermediate milestone deadlines to keep you on schedule and provide feedback at important points
  - Additional work here for M501 students – details tba

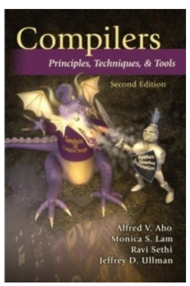
Project Groups

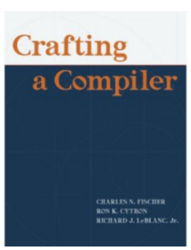
- You should work in pairs
  - Pick a partner now to work with throughout quarter – will need this info early next week
  - If you are in M501 you should pair up with someone else in that group

- 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 put on reserve in the engineering library if anyone wants:
  - Cooper & Torczon, *Engineering a Compiler.* "Official text" & we'll have 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*

And the point is…

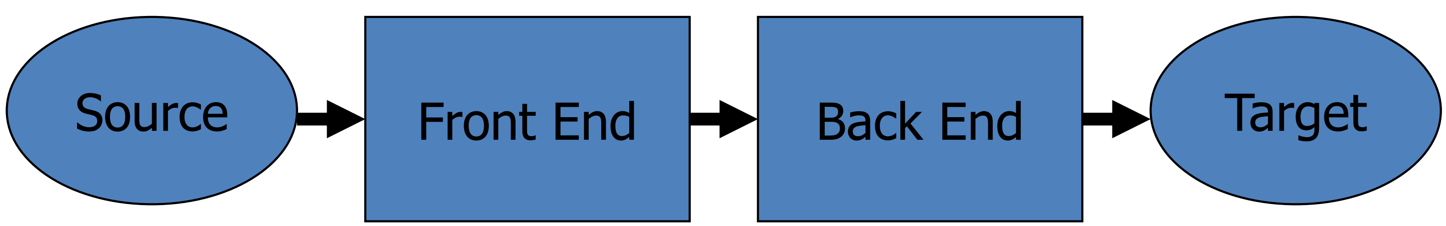
- How do we execute something like this?

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

- The computer only knows 1's & 0's - i.e., encodings of instructions and data

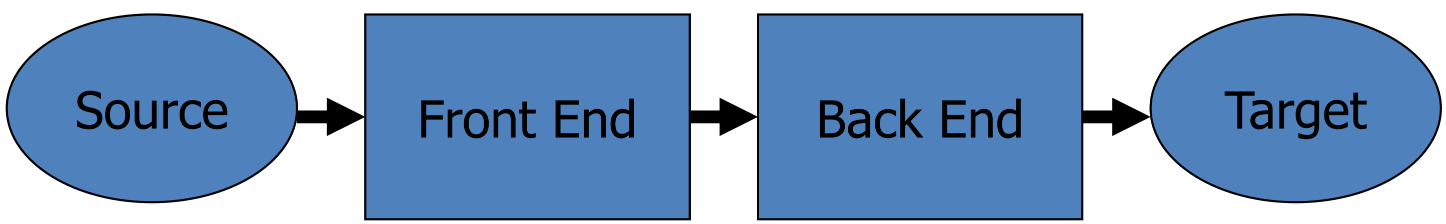
Structure of a Compiler

- 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



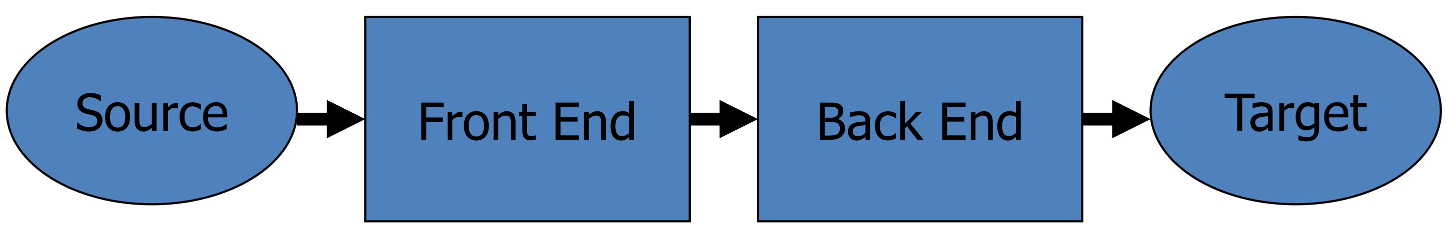
Compiler must…

- 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

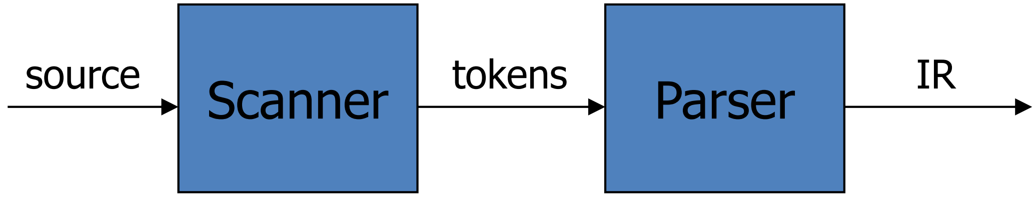


Implications

- 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 newlines)
    - Tokens may carry associated data (e.g., int 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 output from a parser is an abstract syntax tree
  - Essential meaning of program without syntactic noise
  - Nodes are operations, children are operands
- Many different forms
  - Engineering tradeoffs have changed over time
  - Tradeoffs (and IRs) can also vary between different phases of a single compiler

Parser Example

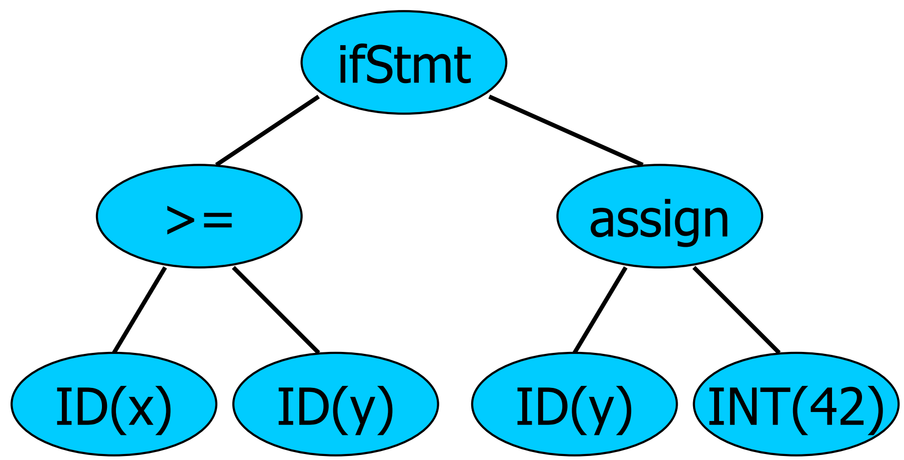
Original source program:

```
// 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 after parsing, check that the program is legal and collect info for the back end
  - Type checking
  - Check 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 machine code
  - Should produce “good” code
    - “good” = fast, compact, low power (pick some)
    - Optimization phase translates correct code into semantically equivalent “better” code
  - Should use machine resources effectively
    - Registers
    - Instructions
    - Memory hierarchy

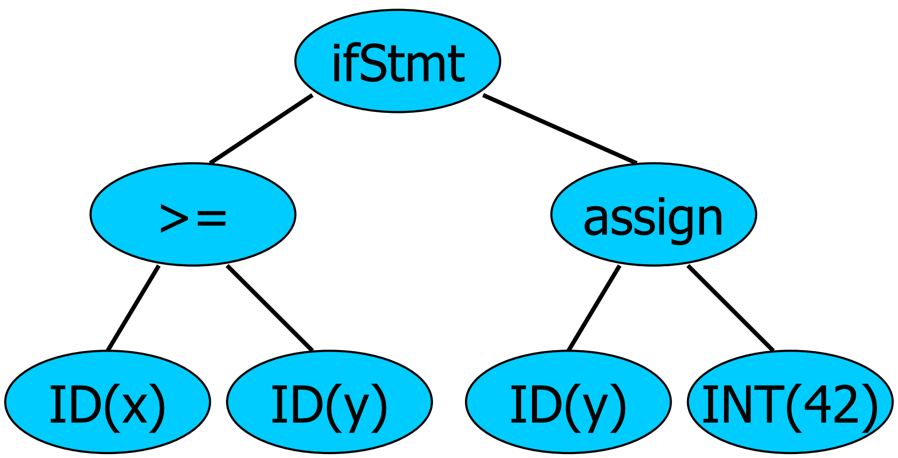
Back End Structure

- Typically split into two major parts
  - "Optimization" – code improvement
    - Examples: common subexpression elimination, constant folding, code motion (move invariant computations outside of loops)
    - Optimization phases often interleaved with analysis
  - Target Code Generation (machine specific)
    - Instruction selection & scheduling, register allocation
  - Usually walk the AST to 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:
```

Interpreters & Compilers

- Programs can be compiled or interpreted (or sometimes both)
- Compiler
  - A program that translates a program from one language (the *source*) to another (the *target*)
    - Languages are sometimes even the same(!)
- Interpreter
  - A program that reads a source program and produces the results of executing that program on some input

Common Issues

- Compilers and interpreters both must read the input – a stream of characters – and "understand" it: front-end analysis phase

w h i l e (k < l e n g t h) { <nl> <tab> i f (a [k] > 0
) <nl> <tab> <tab>{ n P o s + + ; } <nl> <tab> }

Compiler

- Read and analyze entire program
- Translate to semantically equivalent program in another language
  - Presumably easier or more efficient to execute
- Offline process
- Tradeoff: compile-time overhead (preprocessing) vs execution performance

Typically implemented with Compilers

- FORTRAN, C, C++, COBOL, many other programming languages, (La)TeX, SQL (databases), VHDL, many others
- Particularly appropriate if significant optimization wanted/needed

Interpreter

- Interpreter
  - Typically implemented as an "execution engine"
  - Program analysis interleaved with execution:

```
running = true;
while (running) {
   analyze next statement;
   execute that statement;
}
```

  - Usually requires repeated analysis of individual statements (particularly in loops, functions)
    - But hybrid approaches can avoid some of this overhead
  - But: immediate execution, good debugging/interaction, etc.

Often implemented with interpreters

- Javascript, PERL, Python, Ruby, awk, sed, shells (bash), Scheme/Lisp/ML/OCaml, postscript/pdf, machine simulators
- Particularly efficient if interpreter overhead is low relative to execution cost of individual statements
  - But even if not (machine simulators), flexibility, immediacy, or portability may be worth it

Hybrid approaches

- Compiler generates byte code intermediate language, e.g. compile Java source to Java Virtual Machine .class files, then
- Interpret byte codes directly, or
- Compile some or all byte codes to native code
  - Variation: Just-In-Time compiler (JIT) – detect hot spots & compile on the fly to native code
- Also wide use for Javascript, many functional and other languages (Haskell, ML, Racket, Ruby), C# and Microsoft Common Language Runtime, others

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 as well or better – particularly if you don’t try to get too clever

Why Study Compilers? (2)

- Compiler techniques are everywhere
  - Parsing ("little" languages, interpreters, XML)
  - 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, 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
  - Background for first part of the project
- 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

- Familiarize yourself with the course web site

- Read syllabus and academic integrity policy

- Find a partner!
  – And meet other people in the class too!! ☺