CSE P 501 – Compilers

Overview and Administrivia

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Autumn 2019

Agenda

- Introductions
- What's a compiler?
- Administrivia

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- What's a compiler?
- Administrivia

Who: Course staff

- Instructor:
  - Hal Perkins: UW faculty for quite a while now; veteran of many compiler courses (among other things)

- Teaching Assistant:
  - Fatemeh Ghezloo, CSE grad student

- Office hours: Fatemeh, Tue. before class, 5:30-6:20, CSE2 152; can adjust if needed
  Hal, after class – lecture room or CSE 548 office

- Get to know us – we're here to help you succeed!

Credits

- Some direct ancestors of this course:
  - UW CSE 401 (Chambers, Snyder, Notkin, Perkins, Ringenburg, Henry, …)
  - UW CSE PMP 582/501 (Perkins, Hogg)
  - Rice CS 412 (Cooper, Kennedy, Torczon)
  - Cornell CS 412-3 (Teitelbaum, Perkins)
  - Other compiler courses, papers, …
  - 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

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- What’s a compiler?
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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

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)
    - Hybrid approaches can avoid some of this overhead
  - But: immediate execution, good debugging, interactive, etc.

Often implemented with interpreters

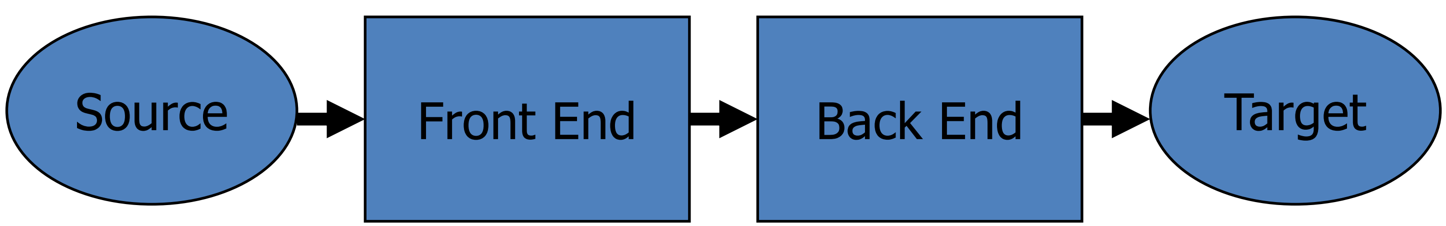
- Javascript, PERL, Python, Ruby, awk, sed, shells (bash), Scheme/Lisp/ML/OCaml, postscript/pdf, machine simulators
- Particularly efficient if interpreter overhead is low relative to execution cost of individual statements
  - But even if not (machine simulators), flexibility, immediacy, or portability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

Hybrid approaches

- Compiler generates intermediate language, e.g. compile Java source to Java Virtual Machine .class files (byte codes), 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
- Widely use for Javascript, many functional and other languages (Haskell, ML, Ruby), Java, C# and Microsoft CLR, others

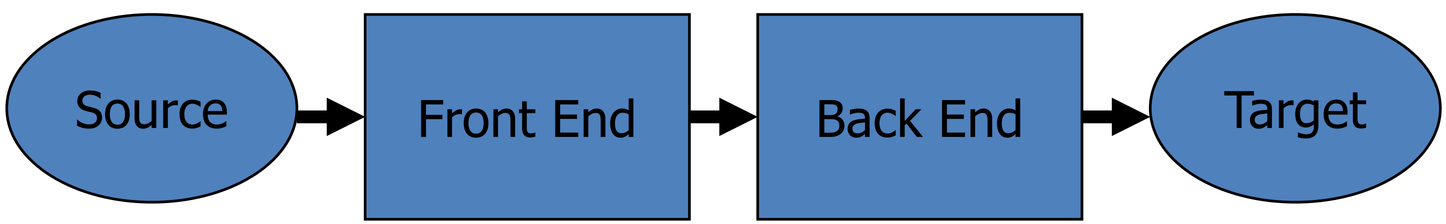
Structure of a Compiler

- 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



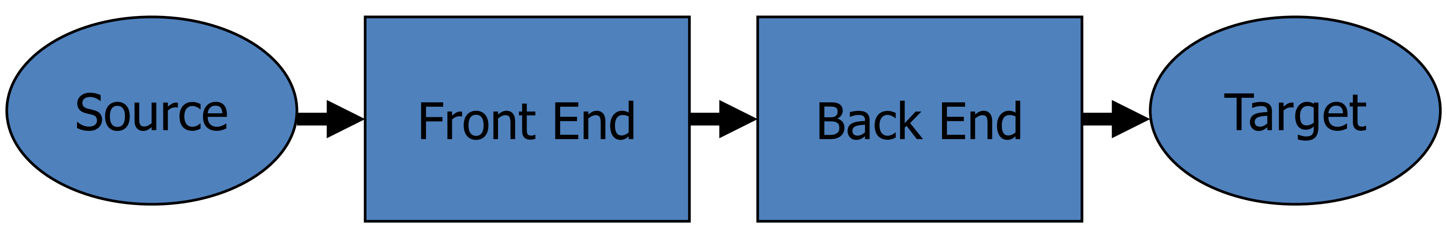
Compiler must…

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

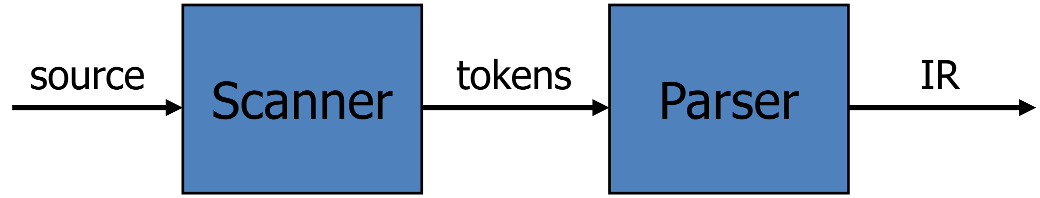


Implications

- 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: Convert character stream to token stream: keywords, operators, variables, constants, …
    - Also: strip out white space, comments
  - Parser: Read token stream; generates IR (AST or other)
- Scanner & parser 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)
    - Tokens can 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 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 have changed over time
  - Tradeoffs (and IRs) can often vary between different phases of a single compiler

Scannner/Parser Example

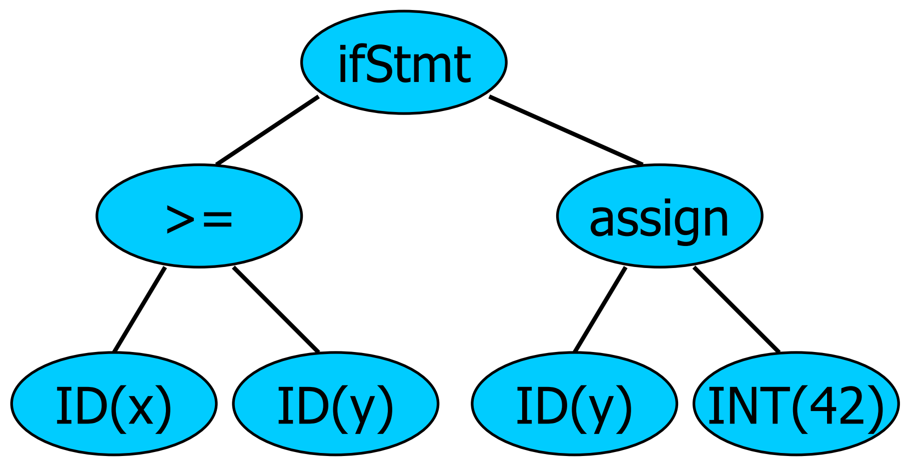
Original source program:

```
// 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
- Context-dependent checks that cannot be captured in a context-free grammar
  - Type checking (e.g., int x = 42 + true, number and types of arguments in method call)
  - Check language requirements like proper declarations, etc.
  - Preliminary resource allocation
  - Collect other information needed for back end analysis and code generation
- Key data structure: Symbol Table(s)
  - Maps names -> meanings/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

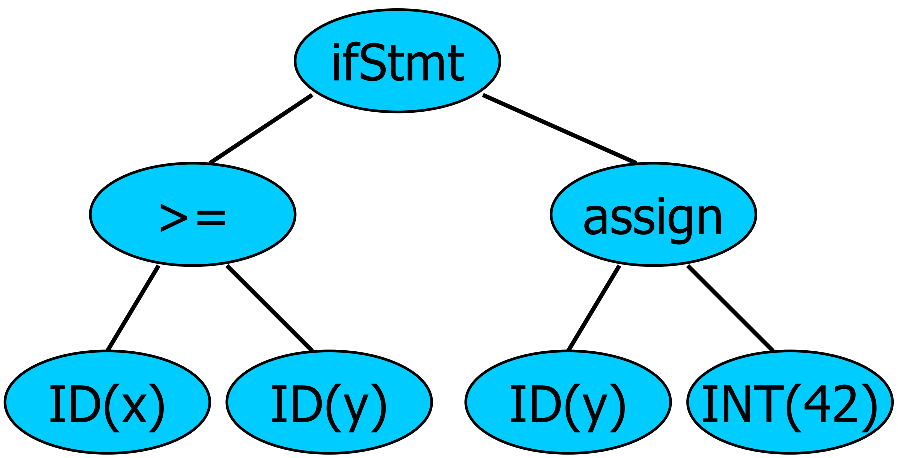
- Typically two major parts
  - "Optimization" – code improvement – change correct code into semantically equivalent "better" code
    - Examples: common subexpression elimination, constant folding, code motion (move invariant computations outside of loops), function inlining (replace call with function body)
    - Optimization phases often interleaved with analysis
  - Target Code Generation (machine specific)
    - Instruction selection & scheduling, register allocation
    - Machine-specific optimizations (peephole opt., …)
  - Optimization usually done on lower-level linear code produced by walking AST

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
    - Avoid wasting time on source “optimizations” that the compiler will do better; avoid “clever” code that confuses the compiler and makes things worse

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: graph, 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…

Some History (1)

- 1950's. Existence proof
  - FORTRAN I (1954) – competitive with hand-optimized code
- 1960's
  - New languages: ALGOL, LISP, COBOL, SIMULA
  - Formal notations for syntax, esp. BNF
  - Fundamental implementation techniques
    - Stack frames, recursive procedures, etc.

Some History (2)

- 1970's
  - Syntax: formal methods for producing compiler front-ends; many, many theorems
- Late 1970's, 1980's
  - New languages (functional; object-oriented, especially Smalltalk)
  - New architectures (RISC machines, parallel machines, memory hierarchy issues)
  - More attention to back-end issues

Some History (3)

- 1990s
  - Techniques for compiling objects and classes, efficiency in the presence of dynamic dispatch and small methods (Self – precursor of JavaScript, Smalltalk; techniques now common in JVMs, etc.)
  - Just-in-time compilers (JITs)
  - Compiler technology critical to effective use of new hardware (RISC, parallel machines, complex memory hierarchies)

Some History (4)

- 21st Century:
  - Compilation techniques in many new places
    - Software analysis, verification, security
  - Phased compilation – blurring the lines between “compile time” and “runtime”
  - Dynamic languages – e.g., JavaScript, …
  - Domain-specific languages (DSL)
  - Etc. …

Some History (5)

- 21st Century (more):
  - Optimization techniques for power, approximate computing, …
  - Memory models, concurrency, multicore, …
  - Full stack proofs/verification; secure OS/compilers
  - Language implementations for novel, heterogenous hardware architectures (dealing with the end of Moore's law, etc.)
    - How do we program these things? Need software tools – languages, compilers, …
  - Etc. etc.

Compiler (and related) Turing Awards

- 1966 Alan Perlis
- 1972 Edsger Dijkstra
- 1974 Donald Knuth
- 1976 Michael Rabin and Dana Scott
- 1977 John Backus
- 1978 Bob Floyd
- 1979 Ken Iverson
- 1980 Tony Hoare
- 1984 Niklaus Wirth
- 1987 John Cocke
- 1991 Robin Milner
- 2001 Ole-Johan Dahl and Kristen Nygaard
- 2003 Alan Kay
- 2005 Peter Naur
- 2006 Fran Allen
- 2008 Barbara Liskov
- 2013 Leslie Lamport
- 2018 John Hennessy & David Patterson

Agenda

- Introductions
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What's in CSE P 501?

- In past years most P501 students either have never taken a compiler course or what was covered was a mixed bag, so…
- We will cover the basics, but fairly quickly…
- Then coverage of more advanced topics
- If you have some background, some of this will be review, but most everyone will pick up new things

Expected background

- Assume undergraduate courses or equiv. in:
  - Data structures and algorithms
    - Linked lists, trees, hash tables, dictionaries, graphs
  - Machine organization
    - Assembly-level programming of some architecture (not necessarily x86-64)
  - Formal languages & automata
    - Regular expressions, NFAs/DFAs, context-free grammars, maybe a little parsing
- We will review basics and gaps can be filled in but might take some extra time/work

CSE P 501 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
  - Every legal MiniJava program is also legal regular Java – compare results from your project with javac/java

Project Scope

- Goal: large enough to be interesting and capture key concepts; small enough to do in 10 weeks
- Completed in steps through the quarter
  - Where you wind up at the end is the most important
  - Intermediate milestone deadlines to keep you on schedule and provide feedback at important points
  - Evaluation is weighted towards final results but milestone results count
- Core requirements, then open-ended if you have time for extensions

Project Implementation

- Default is Java 11 with JFlex, CUP scanner/parser tools
  – Choice of editors/environments up to you
- Somewhat open to alternatives – check with course staff – but you assume risk of the unknown
  – Have had successful past projects using C#, F#, Haskell, ML, others (even Python & Ruby!)
  – You need to be sure there are Lex/Yacc, Flex/Bison work-alike compiler tools available
  – Your compiler has to "work" the same as the regular ones (startup, command options, etc.)
  – Course staff will help as best we can but no guarantees

Project Groups & Repositories

- You should work in groups of two
  - Pick a partner now to work with throughout quarter
    - How? Mingle during breaks, discussion board, …
  - Have had some people do the project solo, but easy to underestimate effort needed. Very helpful to have partner to talk to about details. Pairs strongly recommended.
- All groups *must* use course repositories on CSE GitLab server to store their projects. We'll access files from there for evaluation (& to help with project)
- By early next week, fill out partner info form linked on course web so we can set up groups and repositories

Requirements & Grading

- Roughly
  - 50% project
  - 20% individual written homework
  - 25% exam (extra class session late in quarter – need to figure this out shortly)
    - i.e., let's look at the calendar! 🦃🦃🦃
  - 5% other/discretionary

  We reserve the right to adjust as needed

- Deadlines – would like to be able to hand out sample solutions in class right after assignment is due. How best to manage this?

Lectures

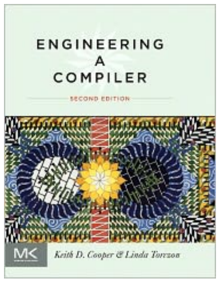
- Tuesdays, 6:30-9:20
- Lecture slides posted on course calendar by mid-afternoon before each class

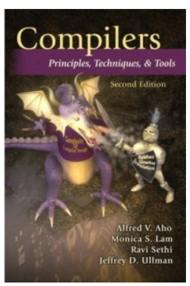
- Strongly recommend no laptops / devices in class unless you are actually using a tablet to take notes
  - Something confusing? Don't search; ask a question!
    - Your colleagues will be grateful! 🙂

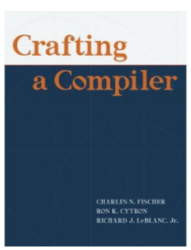
Staying in touch

- Course web site
- Discussion board – new this quarter: ed!
  - Login credentials sent to your UW email before class
  - 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

Books







- Four good books – use at least one; all on reserve in the engineering library
  - Cooper & Torczon, *Engineering a Compiler.* “Official text”, 1st edition should be ok too.
  - Appel, *Modern Compiler Implementation in Java*, 2nd ed. MiniJava is from here.
  - Aho, Lam, Sethi, Ullman, “Dragon Book”
  - Fischer, Cytron, LeBlanc, *Crafting a Compiler*

Academic Integrity

- We want a collegial group helping each other succeed!
- But: you must never misrepresent work done by someone else as your own or assist others to do the same (for compiler project, your group's work should be done collaboratively by you and your partner)
- Read the course policy carefully (on the web)
- 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

Any questions?

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

Coming Attractions

- Quick review of formal grammars
- Lexical analysis – scanning
  – Background for first part of the project
- Followed by parsing …

- Start reading: ch. 1, 2.1-2.4 in EAC or corresponding chapters in other books