CSE P 501 – Compilers

Overview and Administrivia

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Agenda

• Introductions
• What’s a compiler?
• Administrivia
Who: Course staff

• Instructor:
  – Hal Perkins: UW faculty for quite a while now; have taught various compiler courses many times

• TA:
  – Erin Peach, CSE grad student

• Office hours: Erin, Tue. before class, 5:30-6:20, CSE218; Hal, after class, CSE305 or CSE548 office.
  – Could also add a “virtual office hour” later in the week or on the weekend. What would be helpful?

• Get to know us – we’re here to help you succeed!
Credits

• Some direct ancestors of this course:
  – UW CSE 401 (Chambers, Snyder, Notkin, Ringenburg, Henry, ...)
  – UW CSE PMP 582/501 (Perkins, Hogg)
  – Cornell CS 412-3 (Teitelbaum, Perkins)
  – Rice CS 412 (Cooper, Kennedy, Torczon)
  – 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.]
And the point is...

• How do we execute something like this?

```c
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

\[
\text{while}(k < \text{length}) \{ \text{nl} \text{ <tab>} \text{if}(a[k] > 0) \text{nl} \text{ <tab}> \{ \text{nPos}++; \} \text{nl} \text{ <tab>} \}
\]
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

• 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: Responsible for converting character stream to token stream: keywords, operators, variables, constants, ...
    - Also: strips out white space, comments
  - Parser: Reads token stream; generates IR
- 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

```java
// 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:

```c
// 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

```
ifStmt

  >=

  ID(x) ID(y) ID(y) INT(42)
```

Static Semantic Analysis

- During or 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 split into two major parts
  – “Optimization” – code improvements
    • 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
    • Machine-specific optimizations (peephole opt., ...)
  – Optimization usually done on lower-level linear code produced by walking AST
The Result

- **Input**
  
  \[
  \text{if } (x \geq y) \\
  y = 42;
  \]

- **Output** (Intel/masm format)
  
  \[
  \begin{align*}
  \text{mov} & \quad \text{eax,[ebp+16]} \\
  \text{cmp} & \quad \text{eax,[ebp-8]} \\
  \text{jl} & \quad \text{L17} \\
  \text{mov} & \quad [\text{ebp-8}],42 \\
  \text{L17:} & 
  \end{align*}
  \]
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” where the compiler could do as well or better – particularly if you don’t confuse it with code that is too clever
Why Study Compilers? (2)

• Compiler techniques are everywhere
  – Parsing (“little” languages, interpreters, XML)
  – Software tools (verifiers, checkers, …)
  – Database engines, query languages
  – AI, etc.: 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 for intractable “optimizations”
Why Study Compilers? (4)

• Draws ideas from many parts of CSE
  – AI: Greedy algorithms, heuristic search
  – Algorithms: graph algorithms, dynamic programming, approximation algorithms
  – 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...
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 theorems

• Late 1970’s, 1980’s
  – New languages (functional; object-oriented - 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)

• More recently:
  – 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, …
  – Optimization techniques for power, approximate computing, …
  – Memory models, concurrency, multicore, …
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
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
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 8 with JFlex, CUP scanner/parser tools
  – Choice of editors/environments up to you
• Reasonably open to alternatives – check with course staff – but you assume some 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
  – Course staff will help as best we can but no guarantees
  – Use discussion board to stay in touch with similar groups and help each other
Project Groups & Repositories

• You should work in groups of 2 (or maybe 3)
  – Pick a partner now to work with throughout quarter
    • Suggestion: use discussion board to locate partners?
    – Have had some people do the project solo, but it is easy to underestimate effort needed & it is real helpful to have someone to talk to about details
• 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 on course web so we can set up groups and repositories
Requirements & Grading

• Roughly
  – 50% project
  – 20% individual written homework
  – 25% exam (Thursday, March 3 – extra class session)
  – 5% other/discretionary

We reserve the right to adjust as needed
Lectures

• Tuesdays, 6:30-9:20
• Lecture slides posted on course calendar by mid-afternoon before each class
• Live video stream, but please join us – it’s lonely talking to an empty room & better for you if you’re here to ask questions & interact
• Archived video and slides posted a day or two later
Staying in touch

• Course web site
• Discussion board
  – For anything related to the course
  – Join in! Help each other out. Staff will contribute.
  – Post a followup to the “welcome” message today to get it to keep track of unread messages for you
• 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, others might be worth checking out:
  – Cooper & Torczon, *Engineering a Compiler*. “Official text” 1st edition should be ok too.
  – 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 your own)
• 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, I’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