CSE P 501 – Compilers

Overview and Administrivia

Hal Perkins

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Credits

- Some direct ancestors of this course
  - Cornell CS 412-3 (Teitelbaum, Perkins)
  - Rice CS 412 (Cooper, Kennedy, Torczon)
  - UW CSE 401 (Chambers, Ruzzo, et al)
  - Many grad compiler courses, some papers
  - Many books (Appel; Cooper/Torczon; Aho, [Lam,] Sethi, Ullman [Dragon Books], Muchnick [Advanced Compiler …])

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Agenda

- Introductions
- What's a compiler?
- Administrivia

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CSE P 501 Personel

- Instructor: Hal Perkins
  - CSE 548; perkins@cs
  - Office hours: after class + drop in when you're around + appointments
    - (& before class if I'm not swamped)
- TA: Jonathan Beall
  - jibb@cs
  - Office hours: Tue 5:30-6:20; CSE 218

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And the point is…

- Execute this!

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

- How?

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Interpreters & Compilers

- Interpreter
  - A program that reads an source program and produces the results of executing that program
- Compiler
  - A program that translates a program from one language (the *source*) to another (the *target*)

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Common Issues

- Compilers and interpreters both must read the input – a stream of characters – and "understand" it; *analysis*

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> }

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Interpreter

- Interpreter
  - Execution engine
  - Program execution interleaved with analysis

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

  - Usually need repeated analysis of statements (particularly in loops, functions)
  - But: immediate execution, good debugging & interaction

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Compiler

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

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Typical Implementations

- Compilers
  - FORTRAN, C, C++, Java, COBOL, etc. etc.
  - Strong need for optimization in many cases
- Interpreters
  - PERL, Python, Ruby, awk, sed, shells, Scheme/Lisp/ML, postscript/pdf, Java VM
  - Particularly effective if interpreter overhead is low relative to execution cost of individual statements

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Hybrid approaches

- Classic example: Java
  - Compile Java source to byte codes – Java Virtual Machine language (.class files)
  - Execution
    - Interpret byte codes directly, or
    - Compile some or all byte codes to native code
      - Just-In-Time compiler (JIT) – detect hot spots & compile on the fly to native code – standard these days
- Variations used for .NET (compile always) & in high-performance compilers for dynamic languages, e.g., JavaScript

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Why Study Compilers? (1)

- Become a better programmer(!)
  - Insight into interaction between languages, compilers, and hardware
  - Understanding of implementation techniques
  - What is all that stuff in the debugger anyway?
  - Better intuition about what your code does

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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)

Why Study Compilers? (3)

- Fascinating blend of theory and engineering
  - Direct applications of theory to practice
    - Parsing, scanning, static analysis
  - Some very difficult problems (NP-hard or worse)
    - Resource allocation, "optimization", etc.
    - Need to come up with good-enough approximations/heuristics

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Why Study Compilers? (4)

- 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

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Why Study Compilers? (5)

- You might even write a compiler some day!
  - You'll almost certainly write parsers and interpreters for little languages

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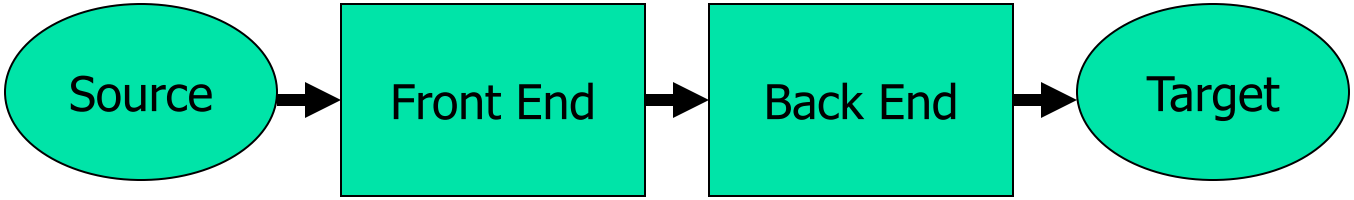
Structure of a Compiler

- First approximation
  - Front end: analysis
    - Read source program and understand its structure and meaning
  - Back end: synthesis
    - Generate equivalent target language program



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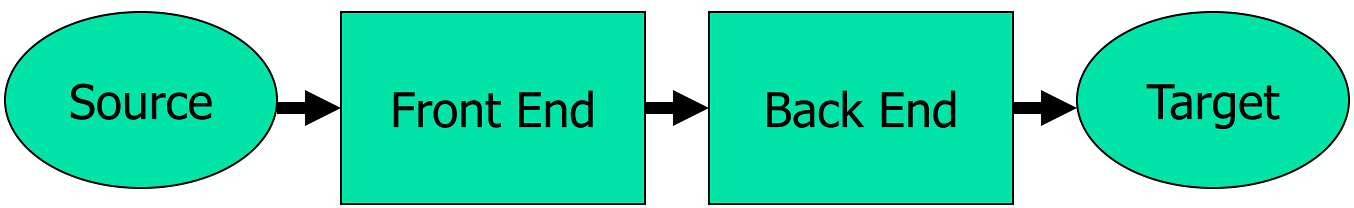
Implications

- Must recognize legal programs (& complain about illegal ones)
- Must generate correct code
- Must manage storage of all variables/data
- Must agree with OS & linker on target format



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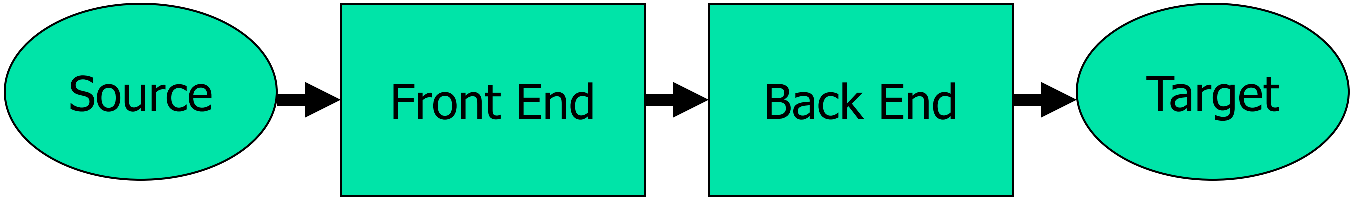
More Implications

- Need 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



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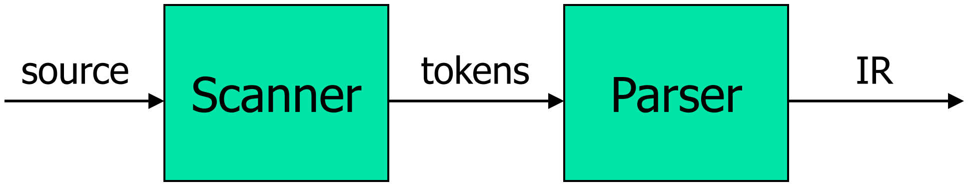
Front End



- Normally split into two parts
  - Scanner: Responsible for converting character stream to token stream
    - Also strips out white space, comments
  - Parser: Reads token stream; generates IR
- Both of these can be generated automatically
  - Source language specified by a formal grammar
  - Tools read the grammar and generate scanner & parser (either table-driven or hard-coded)

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Tokens

- Token stream: Each significant lexical chunk of the program is represented by a token
  - Operators & Punctuation: {}[]!+-=*;: …
  - Keywords: if while return goto
  - Identifiers: id token + actual name
  - Constants: kind + value; int, floating-point character, string, …

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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 (not true of all languages, cf. Python)

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Parser Output (IR)

- Many different forms
  - Engineering tradeoffs have changed over time (e.g., memory is (almost) free these days)
- Common output from a parser is an abstract syntax tree
  - Essential meaning of the program without the syntactic noise

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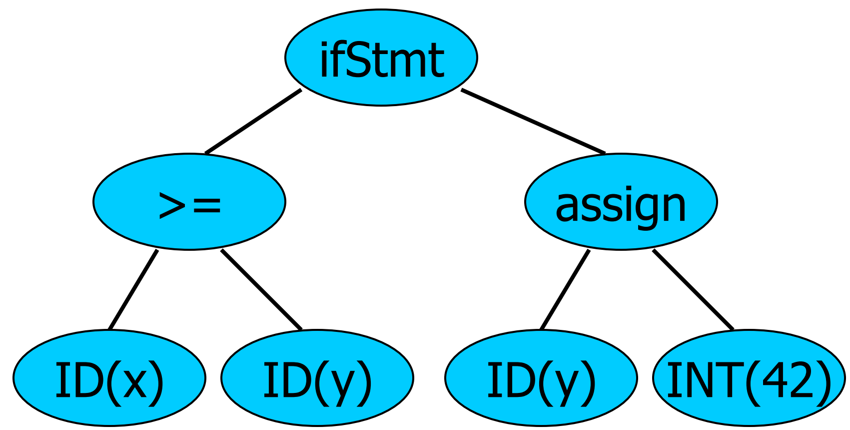
Parser Example

- Token Stream Input

IF LPAREN ID(x)
GEQ ID(y) RPAREN
ID(y) BECOMES
INT(42) SCOLON

- Abstract Syntax Tree



Static Semantic Analysis

- During or (more common) after parsing
  - Type checking
  - Check language requirements like proper declarations, etc.
  - Preliminary resource allocation
  - Collect other information needed by back end analysis and code generation

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Back End

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

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Back End Structure

- Typically split into two major parts with sub phases
  - “Optimization” – code improvements
    - Usually works on lower-level IR than AST
  - Code generation
    - Instruction selection & scheduling
    - Register allocation

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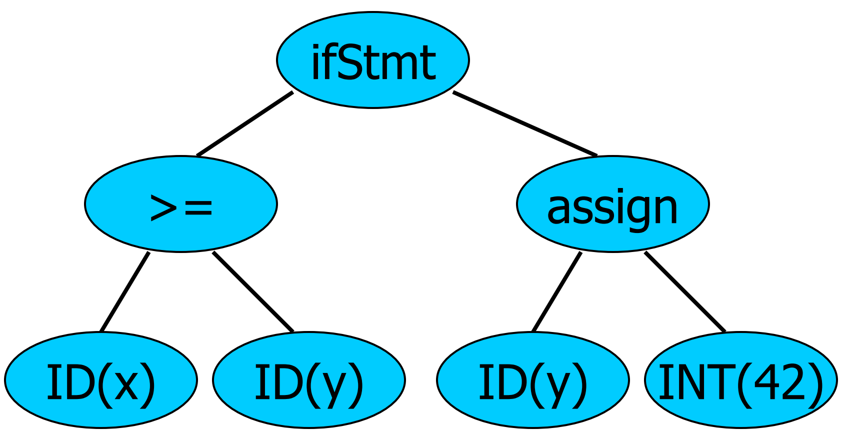
The Result

- Input

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



- Output

```
    mov    eax,[ebp+16]
    cmp    eax,[ebp-8]
    jl     L17
    mov    [ebp-8],42
L17:
```

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.

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Some History (2)

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

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Some History (3)

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

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Some History (4)

- This decade
  - Compilation techniques in many new places
    - Software analysis, verification, security
  - Phased compilation – blurring the lines between “compile time” and “runtime”
    - Using machine learning techniques to control optimizations(!)
  - Dynamic languages – e.g., JavaScript, …
  - The new 800 lb gorilla - multicore

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CSE P 501

- So what will this course cover?
  - Only about 1/5th of you said “yes” for having had a compiler course, and what was covered was mixed, so…
  - we will cover the basics, but quickly, then…
  - we’ll explore more advanced things.
  - If you are in that 1/5th, enjoy the review – but I’m guessing that everyone will pick up some new things

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CSE P 501 Course Project

- Best way to learn about compilers is to build one
- CSE P 501 course project: Implement an x86 compiler in Java for an object-oriented programming language
  - MiniJava subset of Java from Appel book
  - Includes core object-oriented parts (classes, instances, and methods, including subclasses and inheritance)
  - Basic control structures (if, while, method calls)
  - Integer variables and expressions

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Project Details

- Goal: large enough language to be interesting; small enough to be tractable
- Project due in phases
  - Final result is the main thing, but timeliness and quality of intermediate work counts for something
  - Final report & short conference at end of the course
- Core requirements, then open-ended
- Reasonably open to alternatives; let's discuss
  - Most likely would be a different implementation language (C#, ML, Ocaml, F#, ?) or target (MIPS/SPIM, x86-64, …), maybe optimizations?

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Prerequisites

- Assume undergrad courses in:
  - Data structures & algorithms
    - Linked lists, dictionaries, trees, hash tables, graphs, &c
  - Formal languages & automata
    - Regular expressions, finite automata, context-free grammars, maybe a little parsing
  - Machine organization
    - Assembly-level programming for some machine (not necessarily x86)
- Gaps can usually be filled in
  - But be prepared to put in extra time if needed

Project Groups

- You are encouraged to work in groups of 2-3
  - Suggestion: use class discussion board to find partners
- Space for SVN or other repositories + other shared files available on UW CSE machines
  - Use if desired; not required
  - Mail to instructor if you want this

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Programming Environments

- Whatever you want!
  - But if you're using Java, your code should compile & run using standard Sun javac/java
  - If you use C# or something else, you assume some risk of the unknown
    - We'll provide what pointers we can, but…
    - Work with other members of the class on infrastructure
    - Class discussion list can be very helpful here
  - If you're looking for a Java IDE, try Eclipse
    - Or netbeans, or <name your favorite>
    - javac/java + emacs for the truly hardcore

Requirements & Grading

- Roughly
  - 50% project
  - 20% individual written homework
  - 25% exam (tentative: Thursday evening, week after Thanksgiving; does that work?)
  - 5% other
- Homework submission online with graded work returned via email

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CSE 582 Administrivia

- 1 lecture per week
  - Tuesday 6:30-9:20, CSE 305 + MSFT
  - Carpools?
- Office Hours
  - Perkins: after class, drop-ins, CSE 548
  - Beall: Tue. 5:30-6:20, CSE 218
  - Also appointments
  - Suggestions for other times/locations?

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CSE P 501 Web

- Everything is (or will be) at
  - www.cs.washington.edu/csep501
- Lecture slides will be on the course web by mid-afternoon before each class
  - Printed copies available in class at UW, but you may want to read or print in advance
- Live video during class
  - But do try to join us (questions, etc.) – it's lonely talking to an empty room! (& not as good for you)
- Archived video and slides from class will be posted a day or two later

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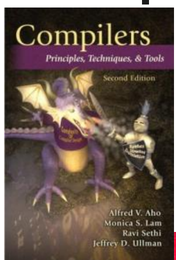
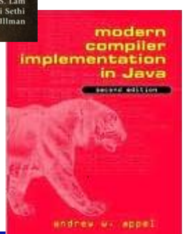
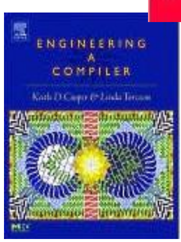
Communications

- Course web site
- Mailing list
  - You are automatically subscribed if you are enrolled
  - Will try to keep this fairly low-volume; limited to things that everyone needs to read
  - Link is on course web page
- Discussion board
  - Also linked from course web
  - Use for anything relevant to the course – let's try to build a community
  - Can configure to have postings sent via email

Books







- Three good books:
  - Aho, Lam, Sethi, Ullman, "Dragon Book", 2^{nd} ed (but 1^{st} ed is also fine)
  - Appel, *Modern Compiler Implementation in Java*, 2^{nd} ed.
  - Cooper & Torczon, *Engineering a Compiler*
- Cooper/Torczon book is the "official" text, but all would work & we'll draw on all three (and more)

Academic Integrity

- We want a cooperative group working together to do great stuff!
  - Possibilities include bounties for first person to solve vexing problems
- But: you must never misrepresent work done by someone else as your own, without proper credit
  - OK to share ideas & help each other out, but your project should ultimately be created by your group & solo homework / test should be your own

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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 ☺

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Coming Attractions

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

- Good time to read the first couple of chapters of (any of) the book(s)

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