CSE 401 – Compilers

Overview and Administrivia

Hal Perkins

Autumn 2010

Credits

- Some direct ancestors of this quarter:
  - UW CSE 401 (Chambers, Snyder, Notkin...)
  - UW CSE PMP 582/501 (Perkins)
  - Cornell CS 412-3 (Teitelbaum, Perkins)
  - Rice CS 412 (Cooper, Kennedy, Torczon)
  - Many books (Appel; Cooper/Torczon; Aho, [Lam,] Sethi, Ullman [Dragon Book], Fischer, Cytron , LeBlanc; Muchnick, ...)

Agenda

- Introductions
- Administrivia
- What’s a compiler?

CSE 401 Personnel

- Instructor: Hal Perkins
  - CSE 548; perkins[at]cs
  - Office hours: tbd in CSE lab + dropins, &c.
- TA:
  - Hadi Esmaeilzadeh; hadianeh[at]cs

Course Meetings

- Lectures
  - MWF 12:30-1:20, EE 045
- Sections Thursdays
  - AA: 1:30 (MEB 237)
  - AB: 2:30 (MEB 250), but...
  - Will try to move sections to the same room
  - No sections this week – not far enough along yet

Communications

- Course web site
- Discussion board
  - For anything related to the course
  - Join in! Help each other out
- Mailing list
  - You are automatically subscribed if you are enrolled
  - Will keep this fairly low-volume; limited to things that everyone needs to read

Prerequisites (old version)

- CSE 326: Data structures & algorithms
- CSE 322: Formal languages & automata
- CSE 378: Machine organization
  - particularly assembly-level programming for some machine (not necessarily x86)
- CSE 341: Programming Languages

Prerequisites (the future)

- One of:
  - CSE 326 and CSE 378, or
  - CSE 332 and CSE 351

- What's your background?

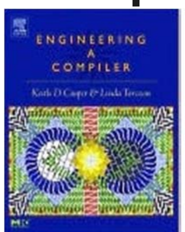
CSE 401 Course Project

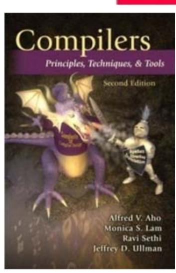
- Best way to learn about compilers is to build (at least parts of) one
- Course project
  - Core Java compiler: classes, objects, etc.
    - But cut down to essentials
  - Generate executable x86 code & run it
  - Completed in steps through the quarter

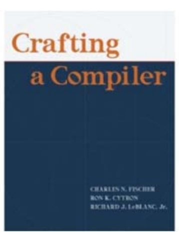
Project Groups

- You should work in pairs
  - Pair programming strongly encouraged
- Space for group SVN repositories & other shared files will be provided
- Pick partners by end of the week & send email to instructor with “401 partner” in the subject

Books







- Four good books:
  - Cooper & Torczon, *Engineering a Compiler*
  - Appel, *Modern Compiler Implementation in Java*, 2nd ed.
  - Aho, Lam, Sethi, Ullman, “Dragon Book”, 2nd ed (but 1st ed is also fine)
  - Fischer, Cytron, LeBlanc, *Crafting a Compiler*
- Cooper/Torczon is the “official” text
- Original minijava project taken from Appel

Requirements & Grading

- Roughly
  - 40% project
  - 15% individual written homework
  - 15% midterm exam (date tba*)
  - 25% final exam
  - 5% other

  We reserve the right to adjust as needed
- Midterm date: Nov 12 (day after Thur. holiday) or Nov. 4 (day after Thur. section)? Whadda ya like?

Academic Integrity

- We want a cooperative group working together to do great stuff!
- But: you must never misrepresent work done by someone else as your own, without proper credit
- Know the rules – ask if in doubt or if tempted

And the point is...

- How do we execute this?

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

- The computer only knows 1's & 0's

Interpreters & Compilers

- Interpreter
  - A program that reads a 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*)

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> }

Interpreter

- Interpreter
  - 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: immediate execution, good debugging & interaction, etc.

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

Typical Implementations

- Compilers
  - FORTRAN, C, C++, Java, COBOL, (La)TeX, SQL (databases), VHDL, etc., etc.
  - Particularly appropriate if significant optimization wanted/needed

Typical Implementations

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

Hybrid approaches

- Best-known example: Java
  - Compile Java source to byte codes – Java Virtual Machine (JVM) 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
- Variation: .NET/Common Language Runtime
  - All IL compiled to native code before execution
- More recently: Javascript & other scripting languages – compile for efficiency

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

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

Why Study Compilers? (4)

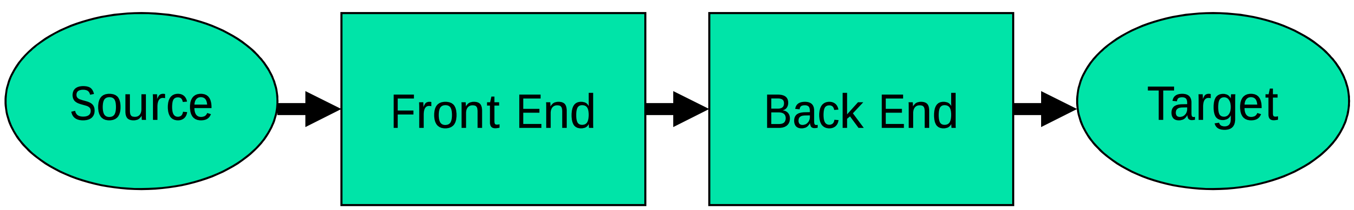
- Ideas from many parts of CSE
  - AI: Greedy algorithms, heuristic search
  - Algorithms: graph algorithms, dynamic programming, approximation algorithms
  - Theory: Grammars, DFAs and PDAs, pattern matching, fixed-point algorithms
  - Systems: Allocation & naming, synchronization, locality
  - Architecture: pipelines, instruction set use, memory hierarchy management, locality

Why Study Compilers? (5)

- You might even write a compiler some day!
  - You ***will*** write parsers and interpreters for little ad-hoc languages, if not bigger things

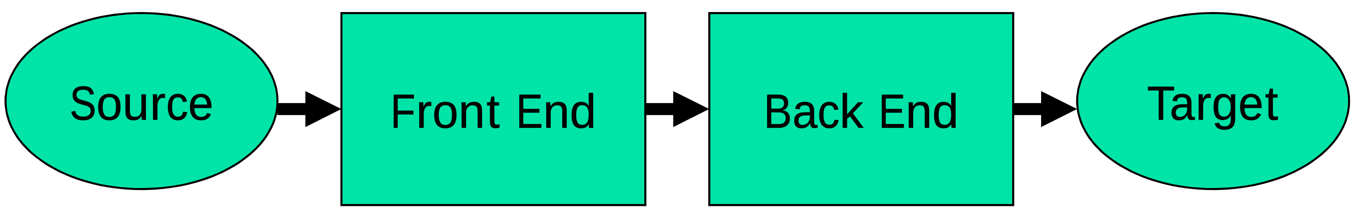
Structure of a Compiler

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



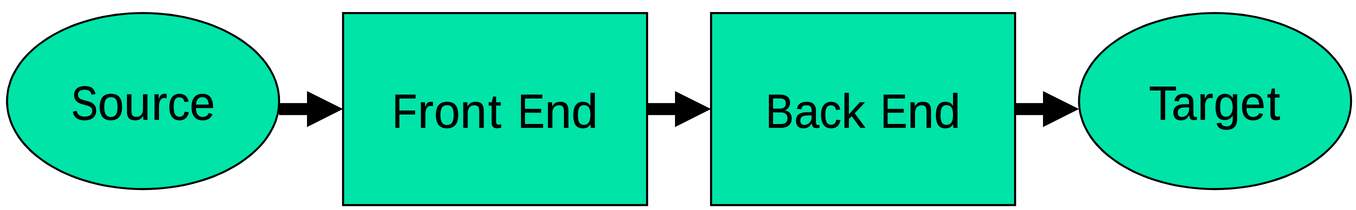
Implications

- 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

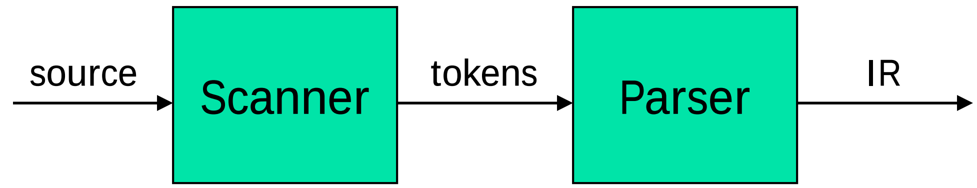


More Implications

- 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



Front End



- Usually 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)

Tokens

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

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 – counterexample: Python)

Parser Output (IR)

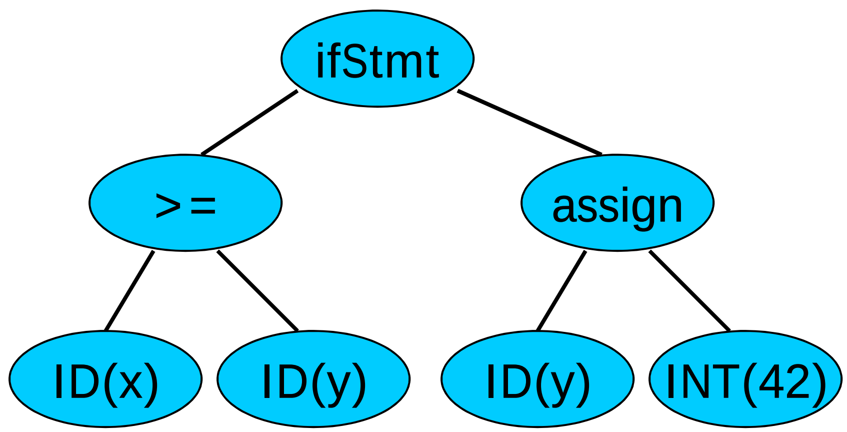
- Many different forms
  - Engineering tradeoffs have changed over time (e.g., memory is (almost) free these days)
- Common output from a parser is an abstract syntax tree
  - Essential meaning of the program without the syntactic noise

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
- Key data structure: Symbol Table
  - Maps names -> meaning/types/details
  - Often a logical table per method/class/block/scope

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
    - Memory hierarchy

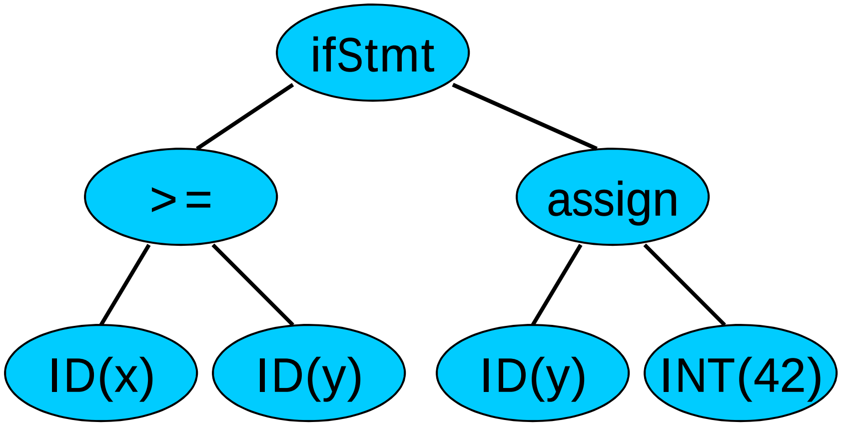
Back End Structure

- Typically split into two major parts
  - “Optimization” – code improvements
  - Code generation – usually two phases
    - Intermediate (lower-level) code generation
      - Typically source-language and target-machine independent
      - Usually precedes optimization
    - Target Code Generation (machine specific)
      - Instruction selection & scheduling
      - Register allocation

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.

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, 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)

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

Compiling (or related) Turing Awards

- 1966 Alan Perlis
- 1972 Edsger Dijkstra
- 1976 Michael Rabin and Dana Scott
- 1977 John Backus
- 1978 Bob Floyd
- 1979 Bob Iverson
- 1980 Tony Hoare
- 1984 Niklaus Wirth
- 1987 John Cocke
- 2001 Ole-Johan Dahl and Kristen Nygaard
- 2003 Alan Kay
- 2005 Peter Naur
- 2006 Fran Allen

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