Compilers

CSE 413, Autumn 2005

Programming Languages

http://www.cs.washington.edu/education/courses/413/05au/

Credits

- Much of the material in the following lectures is derived from lectures taught by Hal Perkins for CSE 413 and CSE 582
- and previous classes ...
  - » Cornell CS 412-3 (Teitelbaum, Perkins)
  - » Rice CS 412 (Cooper, Kennedy, Torczon)
  - » UW CSE 401 (Chambers, Ruzzo, et al)

Books

- Primary Reference
  - » *Compilers: Principles, Techniques, and Tools*, by Aho, Sethi, Ullman
    - the "Dragon Book"
- Other references
  - » *Engineering a Compiler* by Keith Cooper & Linda Torczon
  - » *Modern Compiler Implementation in Java*, by Appel

Why are we doing this?

- Execute this ...

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

- How?
  - » many and varied are the ways ...

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*)

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 execution interleaved with analysis

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

  - » May involve repeated analysis of some statements (loops, functions)

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

Typical Implementations

- Compilers
  - » FORTRAN, C, C++, Java, C#, COBOL, etc. etc.
  - » Strong need for optimization, etc.
- Interpreters
  - » PERL, Python, awk, sed, sh, csh, postscript printer, Java VM
  - » Effective if interpreter overhead is low relative to execution cost of language statements
  - » Functional languages like Scheme and Smalltalk where the environment is dynamic

Hybrid approaches

- Well-known 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
      (particularly for execution hot spots)
      Just-In-Time compiler (JIT)
- Variation: VS.NET
  - » Compilers generate MSIL
  - » All IL compiled to native code before execution

Why Study Compilers? *Programmer*

- 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
- You might even write a compiler some day!
  - » You'll almost certainly write parsers and interpreters if you haven't already

Why Study Compilers? *Designer*

- Compiler techniques are everywhere
  - » Parsing (little languages, interpreters)
  - » Database engines
  - » AI: domain-specific languages
  - » Text processing
    - Tex/LaTex -> dvi -> Postscript -> pdf
  - » Hardware: VHDL; model-checking tools
  - » Mathematics (Mathematica, Matlab)

Why Study Compilers? *Theoretician*

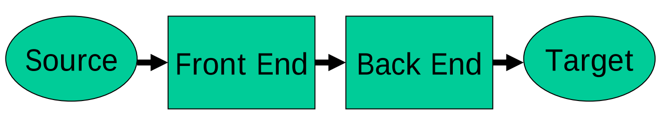
- Fascinating blend of theory and engineering
  - » Direct applications of theory to practice
    - Parsing, scanning, static analysis
  - » Some very difficult problems (NP-hard or worse)
    - Resource allocation, “optimization”, etc.
    - Need to come up with good-enough solutions

Why Study Compilers? *Education*

- 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 & hierarchy management, instruction set use
- Application to many other problem domains
  - » understanding what can be done expands your toolset

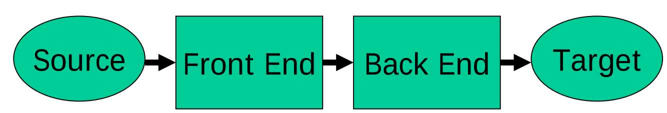
Structure of a Compiler

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



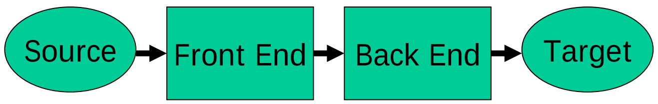
Implications

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

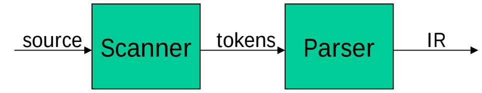


More Implications

- May need some sort of Intermediate Representation (IR)
- Front end maps source into IR
- Back end maps IR to target machine code
- Front and back may be mixed together with the interface between them implicitly defined



Front End



- 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 or by hand
  - » 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 line is a simple comment
if (x >= y) y = 42;
```

- Token Stream

IF | LPAREN | ID(x) | OP_GEQ | ID(y)

RPAREN | ID(y) | OP_ASSIGN | INT(42) | SCOLON

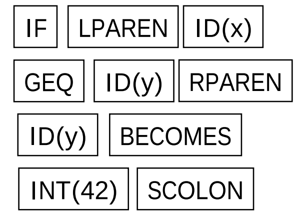
  - » Note: tokens are atomic items, not character strings
    - objects of class Token

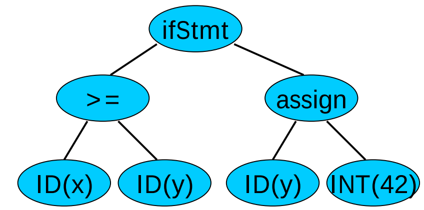
Parser Output (IR)

- Many different forms
  - » (Engineering tradeoffs)
- Common output from a parser is an abstract syntax tree
  - » Essential meaning of the program without the syntactic noise

Parser Example

- Token Stream Input
- Abstract Syntax Tree





Static Semantic Analysis

- During or (more common) after parsing
  - » Type checking
  - » Check for language requirements like “declare before use”, type compatibility
  - » Preliminary resource allocation
  - » Collect other information needed by back end analysis and code generation

Back End

- Responsibilities
  - » Translate IR into target machine code
  - » Should produce fast, compact code
  - » Should use machine resources effectively
    - Registers
    - Instructions
    - Memory hierarchy

Back End Structure

- Typically split into two major parts with sub phases
  - » "Optimization" – code improvements
    - May well translate parser IR into another IR
    - We won't do much with this part of the compiler
  - » Code generation
    - Instruction selection & scheduling
    - Register allocation

The Result

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

x86 assembly language

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

Java bytecode

```
4:   iload_1
5:   iload_2
6:   if_icmplt 12
9:   bipush  42
11:  istore_2
12:
```

Postscript

```
x y ge
{/y 42 def}
if
```


Some Ancient History

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

Some Later History

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

Some Recent History

- 1990's – now
  - » Compilation techniques appearing in many new places
    - Just-in-time compilers (JITs)
    - Whole program analysis
  - » Phased compilation – blurring the lines between "compile time" and "runtime"
  - » Compiler technology critical to effective use of new hardware (RISC, Itanium, complex memories)
- "May you study compilers in interesting times…", *Cooper & Torczon*