CS412/413

Introduction to
Compilers and Translators

Lecture 1: Overview
22 Jan 05

Outline

- Course Organization
  - General course information
  - Homework & project information
- Introduction to Compilers
  - What are compilers?
  - Why do we need compilers?
  - General compiler structure

General Information

When Where	MWF 10:10 - 11:00AM TH 205
Instructor Teaching Assistant	Tim Teitelbaum (none)
Course staff email	cs412-l@cs.cornell.edu
Web page	courses.cs.cornell.edu/cs412
Newsgroup	cornell.class.412

Important

- CS 413 is required !
- Large implementation project
- Substantial amount of theory

Textbooks

- Optional texts
  - Compilers -- Principles, Techniques and Tools (Dragon Book), by Aho, Sethi and Ullman (1986)
  - Modern Compiler Implementation in Java, by Andrew Appel (2002)
  - Engineering a Compiler, by Linda Torczon and Keith Cooper (2003)
- They will be on reserve in Engineering Library

Work Distribution

- Theory:
  - Homeworks = 20%
    - 4 homeworks: 5% each
  - Exams = 35%
    - 2 prelims: 17% and 18%; no final exam
    - Prelims on: March 8, April 28 (evening)
- Practice:
  - Programming Assignments = 45%
    - 6 assignments: 5/9/9/9/9
    - Project demo

Homeworks

- 4 homework assignments
  - Three assignments in first half of course
  - One homework in second half
- Not done in groups
  - do your own work

Project

- Implementation:
  - Designed language = a subset of Java
  - Generated code = assembly x86
  - Implementation language = Java
- 5 programming assignments
- Groups of 3-4 students
  - Usually same grade for all
  - Group information due Friday
  - We will respect consistent preferences

Assignments

- Due at beginning of class
  - Homeworks: paper turn in (at beginning of class)
  - Project files: electronic turn in (day before class)
  - Assignments managed with CMS
- Late homeworks, programming assignments increasingly penalized
  - Penalty linearly increasing : 10% per day
  - 1 day: 10%, 2 days: 20%, 3 days: 30%, etc.

Why Take This Course?

- CS412/413 is an elective course
- Reason #1: understand compilers/languages
  - Understand the code structure
  - Understand the language semantics
  - Understand the relation between source code and generated machine code
  - Become a better programmer

Why Take This Course? (ctd.)

- Reason #2: nice balance of theory and practice:
  - Theory:
    - Lots of mathematical models: regular expressions, automata, grammars, graphs, lattices
    - Lots of algorithms that use these models
  - Practice:
    - Apply theoretical notions to build a real compiler
    - Better understand why “theory and practice are the same in theory; in practice they are different”

Why Take This Course? (ctd.)

- Reason #3: Programming experience
  - Write a large program that manipulates complex data structures
  - Learn how to be a better programmer in groups
  - Learn more about Java and Intel x86 architecture and assembly language

Why Take This Course? (ctd.)

- Reason #4: Technical background for emerging field of software assurance
  - Software assurance will be major priority of coming decade
  - Bug-finding and security-violation finding tools build on compiler techniques

What Are Compilers?

- Compilers = translate information from one representation to another
- Usually information = program
- So compilers=translators, but typically:
  - Compilers refer to the translation from high-level source code to low-level code (e.g. object code)
  - Translators refer to the transformation at the same level of abstraction

Examples

- Typical compilers: gcc, javac
- Non-typical compilers:
  - latex (document compiler) :
    - Transforms a LaTeX document into DVI printing commands
    - Input information = document (not program)
  - C-to-Hardware compiler:
    - Generates hardware circuits for C programs
    - Output is lower-level than typical compilers
- Translators:
  - f2c : Fortran-to-C translator (both high-level)
  - latex2html : LaTeX-to-HTML (both documents)
  - dvi2ps: DVI-to-PostScript (both low-level)

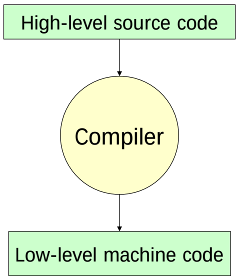
In This Class

- We will study typical compilation: from programs written in high-level languages to low-level object code and machine code
- Most of the principles and techniques in this course apply to non-typical compilers and translators

Why Do We Need Compilers?

- It is difficult to write, debug, maintain, and understand programs written in assembly language
- Tremendous increase in productivity when first compilers appeared (≅ 55 years ago)
- There are still few cases when it is better to manually write assembly code
  - E.g. to access low-level resources of the machine (device drivers)
  - These code fragments are very small; the compiler handles the rest of the code in the application

Overall Compiler Structure



Source Code

- Optimized for human readability
  - Matches human notions of grammar
  - Uses named constructs such as variables and procedures

```
int expr(int n)
{
    int d;
    d = 4 * n * n * (n + 1) * (n + 1);
    return d;
}
```

Assembly and Machine Code

- Optimized for hardware
  - Consists of machine instructions; uses registers and unnamed memory locations
  - Much harder to understand by humans

```
        lda $30,-32($30)
        stq $26,0($30)
        stq $15,8($30)
        bis $30,$30,$15
        bis $16,$16,$1
        stl $1,16($15)
        lds $f1,16($15)
        sts $f1,24($15)
        ldl $5,24($15)
        bis $5,$5,$2
        s4addq $2,0,$3
        ldl $4,16($15)
        mull $4,$3,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        stl $2,20($15)
        ldl $0,20($15)
        br $31,$33
$33:
        bis $15,$15,$30
        ldq $26,0($30)
        ldq $15,8($30)
        addq $30,32,$30
        ret $31,($26),1
```

Translation Efficiency

- Goal: generate machine code that describes the same computation as the source code
- Is there a unique translation?
- Is there an algorithm for an "ideal translation"? (ideal = either fastest or smallest generated code)
- Compiler optimizations = find *better* translations!

Example: Output Assembly Code

Unoptimized Code

```
        lda $30,-32($30)
        stq $26,0($30)
        stq $15,8($30)
        bis $30,$30,$15
        bis $16,$16,$1
        stl $1,16($15)
        lds $f1,16($15)
        sts $f1,24($15)
        ldl $5,24($15)
        bis $5,$5,$2
        s4addq $2,0,$3
        ldl $4,16($15)
        mull $4,$3,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        ldl $3,16($15)
        addq $3,1,$4
        mull $2,$4,$2
        stl $2,20($15)
        ldl $0,20($15)
        br $31,$33
$33:
        bis $15,$15,$30
        ldq $26,0($30)
        ldq $15,8($30)
        addq $30,32,$30
        ret $31,($26),1
```

Optimized Code

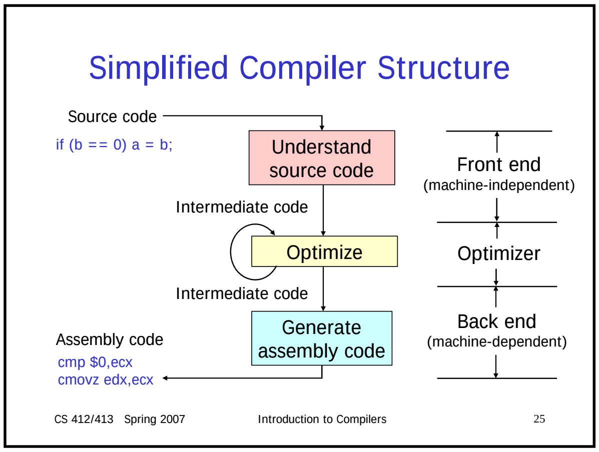
```
s4addq $16,0,$0

mull $16,$0,$0
addq $16,1,$16
mull $0,$16,$0
mull $0,$16,$0
ret $31,($26),1
```

Translation Correctness

- The generated code must execute precisely the same computation as in the source code
- Correctness is very important!
  - hard to debug programs with broken compiler…
  - implications for development cost, security
  - this course: techniques known to ensure correct translation

How To Translate?

- Translation is a complex process
  - source language and generated code are very different
- Need to structure the translation
  - Define intermediate steps
  - At each step use a specific program representation
  - More machine-specific, less language-specific as translation proceeds



Simplified Compiler Structure

Source code

if (b == 0) a = b;

Understand source code

Intermediate code

Optimize

Intermediate code

Generate assembly code

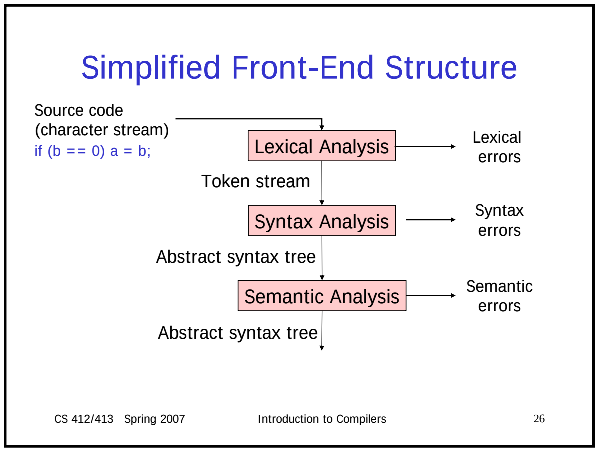
Assembly code

cmp $0,ecx
cmovz edx,ecx

Front end
(machine-independent)

Optimizer

Back end
(machine-dependent)



Simplified Front-End Structure

Source code
(character stream)
if (b == 0) a = b;

Lexical Analysis → Lexical errors

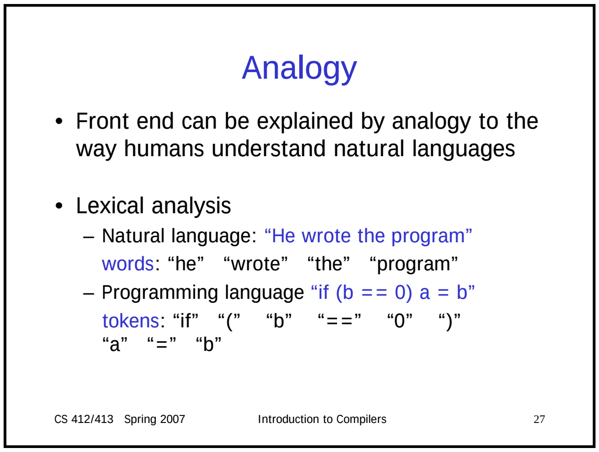
Token stream

Syntax Analysis → Syntax errors

Abstract syntax tree

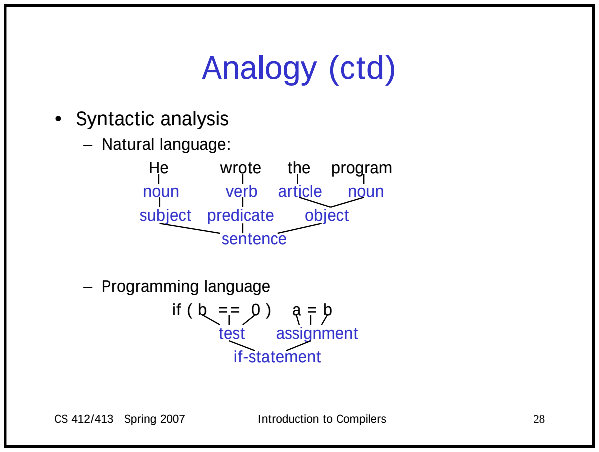
Semantic Analysis → Semantic errors

Abstract syntax tree



Analogy

- Front end can be explained by analogy to the way humans understand natural languages
- Lexical analysis
  - Natural language: “He wrote the program”
    words: “he” “wrote” “the” “program”
  - Programming language “if (b == 0) a = b”
    tokens: “if” “(” “b” “==” “0” “)” “a” “=” “b”



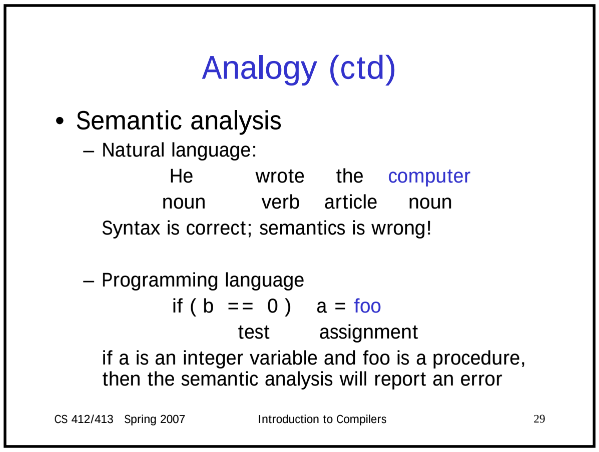
Analogy (ctd)

- Syntactic analysis
  - Natural language:

He wrote the program
noun verb article noun
subject predicate object
sentence

  - Programming language

if (b == 0) a = b
test assignment
if-statement



Analogy (ctd)

- Semantic analysis
  - Natural language:

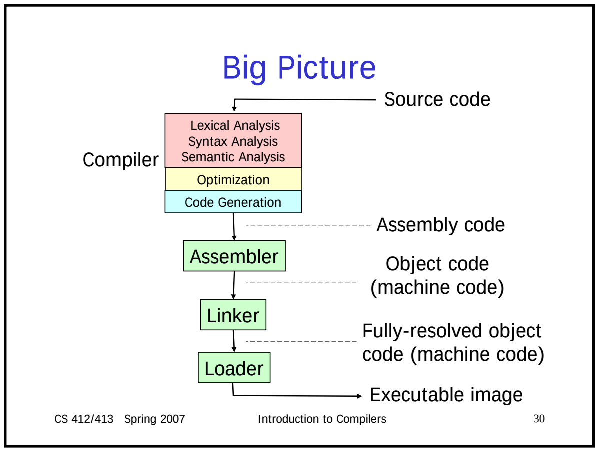
He wrote the computer
noun verb article noun

Syntax is correct; semantics is wrong!

  - Programming language

if (b == 0) a = foo
test assignment

if a is an integer variable and foo is a procedure, then the semantic analysis will report an error



Big Picture

Source code

Compiler: Lexical Analysis, Syntax Analysis, Semantic Analysis, Optimization, Code Generation

Assembly code

Assembler

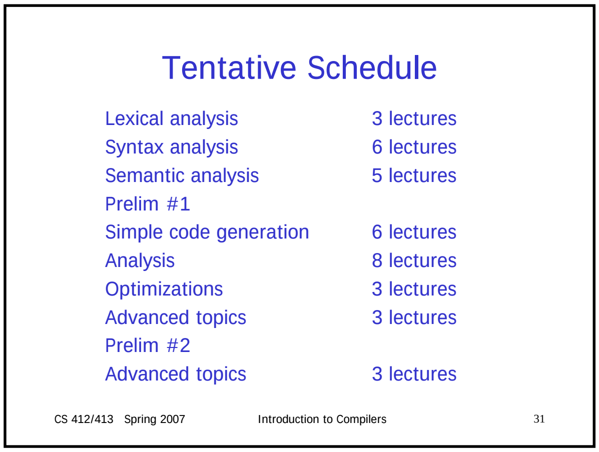
Object code
(machine code)

Linker

Fully-resolved object code (machine code)

Loader

Executable image



Tentative Schedule

Lexical analysis	3 lectures
Syntax analysis	6 lectures
Semantic analysis	5 lectures
Prelim #1	
Simple code generation	6 lectures
Analysis	8 lectures
Optimizations	3 lectures
Advanced topics	3 lectures
Prelim #2	
Advanced topics	3 lectures