Informatik II
Languages, Compilers, and Theory

Lecture 1:
Introduction and Overview

Introduction

- Eight lectures covering:
  - Basic programming language concepts
  - Organization of compilers for modern programming languages
  - Introduction to the theory of formal languages and automata
- Text:
  - *Programming Language Pragmatics* by Michael L. Smith

Abstractions…

- Eliminate detail unnecessary for solving a particular problem
  - Complexity is hidden
- Often build upon one another
  - Allow us to solve increasingly complex problems
- Modern software's complexity is without precedent
  - Abstractions are absolutely necessary to manage this complexity

Abstraction	**Abstracts**
Digital logic	Transistors
Computer architecture	Digital logic
Assembly language	Machine language
Operating systems	Resource allocation (time, storage, etc.)
Computer communications	Physical networks, protocols

Languages as abstraction

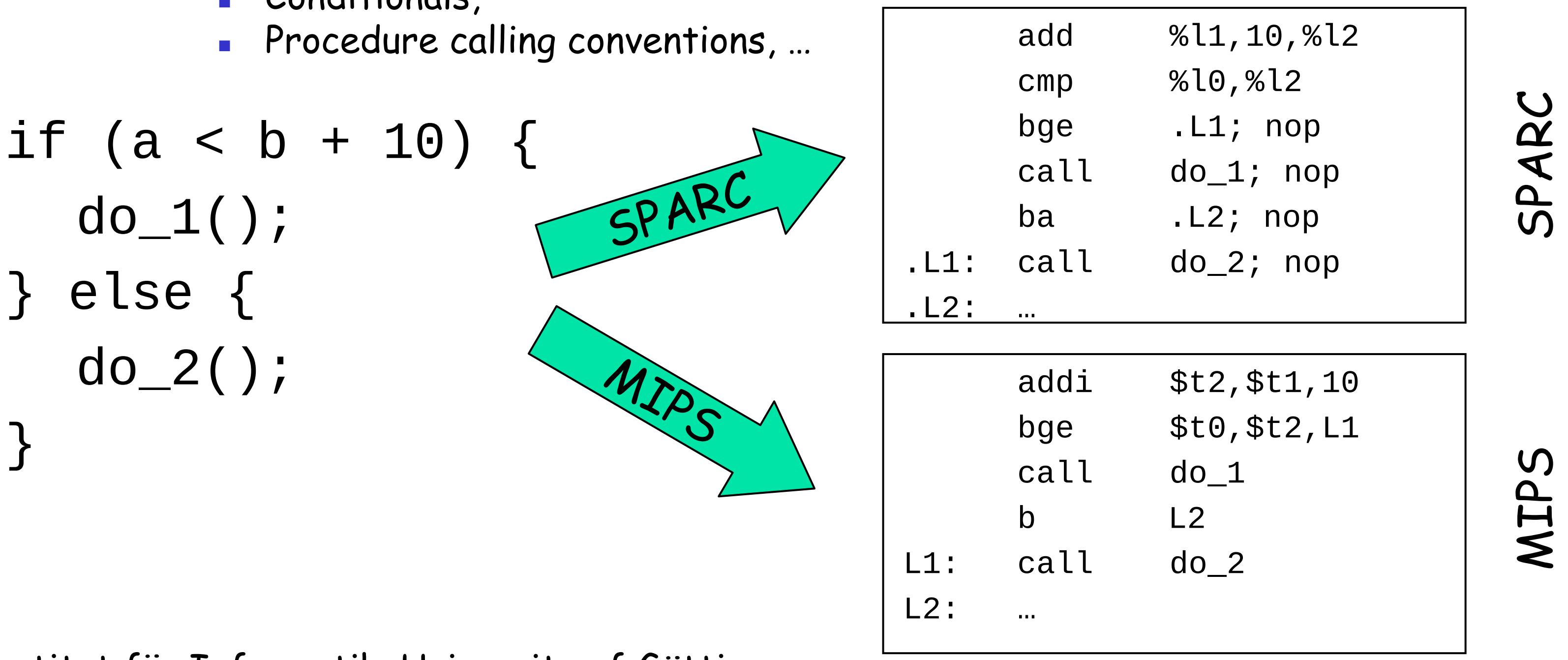
- Human languages are a tool for abstracting thought
  - "When I am warm I turn on the fan"
    - Communicates a simple intention, whereas the cognitive and neurological conditions from which the intention arose are most likely too complex for anyone to understand
    - Meaning of this statement is left to the understanding of the individual who utters it and the individuals who hear it
- Programming languages are a tool for abstracting computation
  - `if (temperature() > 30.0) { turn_on_fan(); }`
    - Involves a complex, but concrete sequence of actions:
      - read the thermostat; convert the reading to an IEEE floating point value on the centigrade scale; compare the value to 30.0; if greater then send a command to a PCI card which sends a signal to a relay which then turns on the fan
    - Meaning of this statement is fixed by the formal semantics of the programming language and by the implementations of the functions temperature() and turn_on_fan()

How do programming languages abstract computation?

- 1) Provide a notation for the expression of algorithms that:
  - Is (mostly) independent of the machine on which the algorithm will execute
  - Provides high-level features that focus the programmer's attention more on the algorithm and less on:
    - How the algorithm will be implemented in a machine language
    - Implementing auxiliary algorithms, e.g., hash tables
  - Allows the programmer to build her own abstractions (subroutines, modules, libraries, classes, etc.) thus allowing the continuation of the "complexity management by layering" principle

How do programming languages abstract computation?

- 2) Hide low-level details of the target architecture
  - Assembly language instruction names, register names, argument ordering, …
  - Mapping of language elements to assembly language
    - Arithmetic expressions,
    - Conditionals,
    - Procedure calling conventions, …



```
if (a < b + 10) {
   do_1();
} else {
   do_2();
}
```

SPARC

```
        add     %l1,10,%l2
        cmp     %l0,%l2
        bge     .L1; nop
        call    do_1; nop
        ba      .L2; nop
.L1:    call    do_2; nop
.L2:    …
```

MIPS

```
        addi    $t2,$t1,10
        bge     $t0,$t2,L1
        call    do_1
        b       L2
L1:     call    do_2
L2:     …
```

How do programming languages abstract computation?

- 3) Provide primitives, subroutines, and run-time support for common programming chores

Examples

- Reading and writing files
- Character string handling (comparison, substring detection, etc.)
- Dynamic memory allocation (new, malloc, etc.)
- Reclamation of unused memory (garbage collection)
- Sorting

How do programming languages abstract computation?

- 4) Provide features that encourage or enforce a particular style of algorithm or software development

Structured programming

- Subroutines
- Nested variable scopes
- Loops
- Restricted forms of the "goto" statement

Object Oriented Programming

- Classes
- Inheritance
- Polymorphism

Categories of programming languages

- All languages fall into one of the following two categories:
  - *Imperative languages* require programmers to describe, step-by-step, how an algorithm should do its work
    - Real world analogy » A recipe is a type of imperative program that tells a cook how to prepare a dish
  - *Declarative languages* allow programmers to describe what an algorithm should do without having to specify exactly how it should do it
    - Real world analogy » The recent Pfand law is a declarative program that tells retailers that they must institute a recycling program for the einweg Flasche and Dosen that they sell, without telling them exactly how to do it

Imperative Languages

- The von Neumann languages
  - Include Fortran, Pascal, Basic, C
  - Are a reflection of the von Neumann computer architectures on which their programs run
  - Execute statements which alter the program's state (variables/memory)
    - Sometimes called computing by side effects
  - Example: summing the first n integers in C
    - `for(sum=0,i=1;i<=n;i++) { sum += i; }`

Imperative Languages

- The object oriented languages
  - Include Smalltalk, Eiffel, C++, Java
  - Are similar to the von Neumann languages with the addition of objects
  - Objects:
    - Contain their own internal state (member variables) and functions which operate on that state (methods)
    - Computation is organized as interactions between objects (one object calling another's methods)
  - Most object oriented languages provide facilities based on objects that encourage object oriented programming
    - Encapsulation, inheritance, and polymorphism
    - We'll talk about these more in a future lecture

Declarative Languages

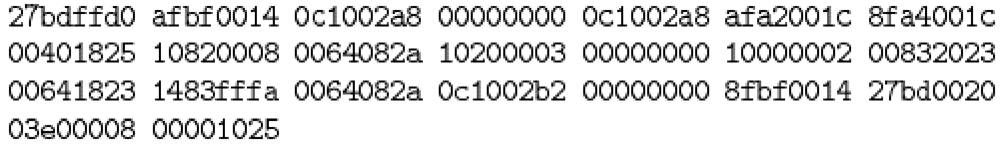
- The functional languages
  - Include Lisp/Scheme, ML, Haskell
  - Are a reflection of Church's theory of recursive functions (lambda calculus)
  - Computation carried out as functions return values based on the (possibly recursive) evaluation of other functions
    - Mechanism known as reduction
  - No side effects!
    - Permits equational reasoning, easier formal proofs of program correctness, etc.
  - Example: summing the first n integers in SML
    - `fun sum (n) = if n <= 1 then n else n + sum(n-1)`

Declarative Languages

- The logic languages
  - Include Prolog, SQL, and Microsoft Excel
  - Are a reflection of the theory of propositional logic
  - Computation is an attempt to find values which satisfy a set of logical relationships
    - Mechanism most commonly used to find these values is known as resolution and unification
  - Example: summing the first n integers in Prolog
    - `sum(1,1).`
    - `sum(N,S) :- N1 is N-1, sum(N1,S1), S is S1+N.`

A historical perspective: Machine languages

- First machines programmed directly in machine language or machine code
- Tedious, but machine time more expensive than programmer time



```
27bdffd0 afbf0014 0c1002a8 00000000 0c1002a8 afa2001c 8fa4001c
00401825 10820008 0064082a 10200003 00000000 10000002 00832023
00641823 1483fffa 0064082a 0c1002b2 00000000 8fbf0014 27bd0020
03e00008 00001025
```

MIPS machine code for a program that computes the GCD of two integers

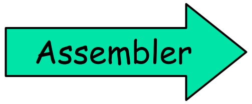
A historical perspective: Assembly languages

- Programs became more complex
  - Too difficult, time-consuming, and expensive to write them in machine code
- Assembly languages developed
  - Human readable
  - Originally provided a one-to-one correspondence between machine language instructions and assembly language instructions
  - Eventually "macro" facilities were added to further speed software development by providing a primitive form of code-reuse
  - The assembler was the program which translated an assembly language program into machine code which the machine could run

```
    addiu   sp,sp,-32
    sw      ra,20(sp)
    jal     getint
    nop
    jal     getint
    sw      v0,28(sp)
    lw      a0,28(sp)
    move    v1,v0
    beq     a0,v0,D
    slt     at,v1,a0
A:  beq     at,zero,B
    nop
```

```

    b       C
    subu    a0,a0,v1
B:  subu    v1,v1,a0
C:  bne     a0,v1,A
    slt     at,v1,a0
D:  jal     putint
    nop
    lw      ra,20(sp)
    addiu   sp,sp,32
    jr      ra
    move    v0,zero
```

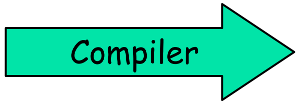

Assembler

```
27bdffd0 afbf0014 0c1002a8 00000000 0c1002a8 afa2001c 8fa4001c
00401825 10820008 0064082a 10200003 00000000 10000002 00832023
00641823 1483fffa 0064082a 0c1002b2 00000000 8fbf0014 27bd0020
03e00008 00001025
```

A historical perspective: High-level languages

- Programs became even more complex
  - Too difficult, time-consuming, and expensive to write in assembly language
  - Too difficult to move from one machine to another with a different assembly language
- High-level languages developed
  - Mid 1950's Fortran was designed and implemented
    - Allowed numerical computations to be expressed in a form similar to mathematical formulae
  - The compiler was the program which translated a high-level program into an assembly language or machine language program
    - Originally, good programmers could write faster assembly language programs than the compiler
  - Other high-level languages followed Fortran in the late 50's and early 60's
    - Lisp: first functional language, based on recursive function theory
    - Algol: first block-structured language

```
int gcd (int i, int j) {
  while (i != j) {
    if (i > j)
      i = i - j;
    else
      j = j - i;
  }
  printf(“%d\n”,i);
}
```



```
     addiu   sp,sp,-32
     sw      ra,20(sp)
     jal     getint
     nop
     jal     getint
     sw      v0,28(sp)
     lw      a0,28(sp)
     move    v1,v0
     beq     a0,v0,D
     slt     at,v1,a0
A:   beq     at,zero,B
     nop
```

```
     b       C
     subu    a0,a0,v1
B:   subu    v1,v1,a0
C:   bne     a0,v1,A
     slt     at,v1,a0
D:   jal     putint
     nop
     lw      ra,20(sp)
     addiu   sp,sp,32
     jr      ra
     move    v0,zero
```

Running high-level language programs

- Compilation
  - Program is translated into assembly language or directly into machine language
  - Compiled programs can be made to run relatively fast
  - Fortran, C, C++, …
- Interpretation
  - Program is read by another program and executed one source language element at a time
  - Slower than compiled programs
  - Interpreters are (usually) easier to implement than compilers, are more flexible, and can provide excellent debugging and diagnostic support
  - Java, Python, Perl,…

Designing a Compiler

- Compilers are well-studied, but very complex programs
- Complexity is managed by dividing the compilers work into independent stages or phases
- Typically a phase analyzes a representation of a program, and translates that representation into another that is more appropriate for the next phase
- Design of these intermediate program representations are critical to the successful implementation of a compiler

The Compilation Process (Phases)

Scanner (lexical analysis)	Read program and convert character stream into tokens.
Parser (syntax analysis)	Read stream of tokens and generate a parse tree.
Semantic analysis	Traverse parse tree, checking non-syntactic rules.
Intermediate code generation	Traverse parse tree again, emitting intermediate code.
Optimization	Examine intermediate code, attempting to improve it.
Target code generation	Translate intermediate code to assembly / machine code.
Machine-level optimization	Examine machine code, attempting to improve it.

Lexical analysis

- Program file is just a sequence of characters
- Wrong level of detail for syntax analysis
- Lexical analysis groups sequence of characters into tokens
- Tokens are the smallest "units of meaning" in the compilation process and are the foundation for parsing (syntax analysis)
- The compiler component that performs lexical analysis is called the scanner and is often automatically generated from a high-level specification
  - More on scanners in the next lecture...

Lexical analysis example

A GCD program in C

```
int gcd (int i, int j) {
  while (i != j) {
    if (i > j)
      i = i - j;
    else
      j = j - i;
  }
  printf(“%d\n”,i);
}
```

Tokens

```
int        gcd       (
int        i         ,
int        j         )
{          while     (
i          !=        j
)          {         if
(          i         >
j          )         i
=          i         -
j          ;         else
j          =         j
-          i         ;
}          printf    (
“%d\n”     ,         I
)          ;         }
```

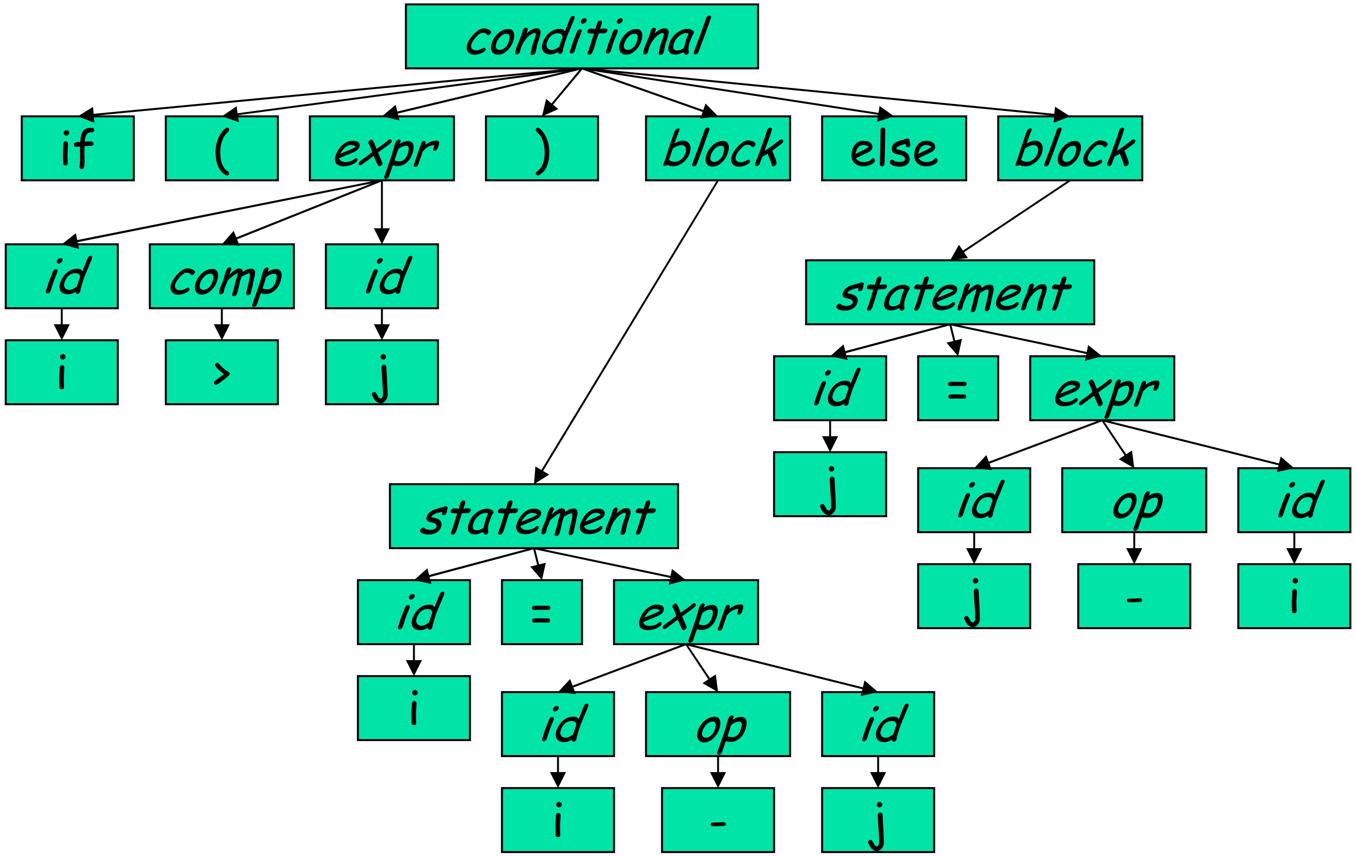
Syntactic analysis

- Lexical analysis generates a stream of tokens
- Wrong level of detail for semantic analysis and code generation
- Syntax analysis groups a string of tokens into parse trees guided by the context-free grammar that specifies the syntax of the language being compiled
  - conditional -> **if (** *expr* **)** *block* **else** *block*
- Parse trees represent the phrase structure of the program and are the foundation for semantic analysis and code generation
- The compiler component that performs syntax analysis is called the parser and is also often generated from a high-level specification
  - More on context-free grammars and parsing in upcoming lectures…

Syntax analysis example

Tokens

```
if      (       i
>       j       )
i       =       i
-       j       ;
else    j       =
j       -       i
;       }
```



Semantic analysis

- Determines the meaning of a program based on the a parse tree representation
- Enforces rules that are not governed by the program language syntax
  - Consistent use of types, e.g.,
    - int a; char s[10]; s = s + a; illegal!
  - Every identifier is declared before used
  - Subroutine calls provide the correct number and type of arguments
  - Etc.
- Updates the symbol table, notating among other things, the types of variables, their sizes, and the scope in which they were declared

Intermediate code generation

- Parse trees are the wrong level of detail for optimization and target code generation
- Intermediate code generation transforms the parse tree into a sequence of intermediate language statements which embody the semantics of the source program
- The intermediate language is just as powerful, but simpler than the high-level source language
  - E.g., the intermediate language may only have one type of looping construct (goto) whereas the source language may have several (for, while, do, etc.)
- A simple intermediate language makes subsequent phases of the compiler easier to implement

Target code generation

- Ultimate goal of the compilation process is to generate a program which the computer can run
  - This is the job of the target code generator
- Step 1: traverse the symbol table, assigning variables to locations in memory
- Step 2: traverse the parse tree or intermediate language program, emitting loads and stores for variable references, along with arithmetic operations, comparisons, branches, and subroutine calls

Optimization

- Intermediate code and/or target code is typically not as efficient as it could be
  - Limitation allows code generators to focus on code generation, not on code improvement
- An optimizer can be called to improve the quality of intermediate and/or target code after each of these phases
- The compiler component which improves the quality of generated code is called the optimizer
- Optimizers are the most complicated part of the compiler
- Optimization algorithms are often very elaborate, require substantial amounts of memory and time to run, and produce only small improvement in program size and/or run-time performance
- Two important optimizations:
  - Register allocation – deciding which program variables can reside in registers at a particular point in the program's execution
  - Dead code elimination – removing functions, blocks, etc., which won't be executed by the program

So why study programming languages and compilers?

- According to Michael Scott:
  - Understand obscure language features
  - Choose among alternative ways to express things
  - Make good use of debuggers, assemblers, linkers, and related tools
  - Simulate useful features in languages that lack them
- According to me:
  - Compilers are large, complex programs: studying them helps you better understand "big software"
  - Lots of programs contain "little programming languages"
    - Unix shells, Microsoft Office applications, etc.
    - Its useful to know a bit about language design and implementation so that you can incorporate little languages into your own software

Roadmap of remaining lectures

- Next two lectures (Chapter 2 from text)
  - Lexical analysis
  - Syntactic analysis
  - Automata theory and automatic generation of scanners and parsers
- Final five lectures
  - Names, scopes and binding (Chapter 3)
  - Control flow (Chapter 6)
  - Subroutines and control abstraction (Chapter 8)
  - Building a runnable program (Chapter 9)
  - Object oriented programming (Chapter 10)

Programming language and compiler resources

- Website for our text
  - http://www.cs.rochester.edu/u/scott/pragmatics/
- Catalog of compiler construction tools
  - http://www.first.gmd.de/cogent/catalog/
- Conferences and journals
  - ACM Transactions on Programming Languages and Systems
  - ACM SIGPLAN Conference on Programming Language Design and Implementation
  - ACM SIGPLAN Conference on Programming Language Principles