Overview of Compilers and Interpreters

- Common compiler and interpreter configurations
- Virtual machines
- Integrated programming environments
- Compiler phases
  - Lexical analysis
  - Syntax analysis
  - Semantic analysis
  - Code generation

Note: These slides cover Chapter 1 of the textbook

Compiling and Interpreting Programming Languages

- The *compiler* versus *interpreter* implementation is often fuzzy
  - One can view an interpreter as a *virtual machine*
  - A *processor* (CPU) is an implementation in hardware of a virtual machine for *machine code*
- Some languages cannot be purely compiled into machine code when the language allows a program to rewrite its own code, requiring the interpreter or virtual machine to invoke the compiler
- In general, compilers try to be as smart as possible to fix decisions that can be taken at compile time to avoid to generate code that makes a decision at run time
- Compilation leads to better performance in general
  - Allocation of variables without variable lookup at run time
  - Aggressive code optimization to exploit hardware features
- Interpretation leads to better diagnostics of a programming problem
  - Procedures can be invoked from command line by a user
  - Variable values can be inspected and modified by a user

Compilation and Interpretation

- *Compilation (conceptual):*

Source Program ® [Compiler] ® Target Program

Input ® [Target Program] ® Output

- *Interpretation (conceptual):*

Source Program ®
Input ® [Interpreter] ® Output

Pure Compilation and Linking

- Adopted by the typical Fortran implementation
- Library routines are separately linked (merged) with the object code of the program

Source Program ® [Compiler] ® Incomplete Object Code

Incomplete Object Code ®
Library Routines ® [Linker] ® Object Code

Compilation, Assembly, and Linking

- Adopted by most compilers
- Facilitates debugging of the compiler

Source Program ® [Compiler] ® Assembly

Assembly ® [Assembler] ® Incomplete Object Code

Incomplete Object Code ®
Library Routines ® [Linker] ® Object Code

Mixed Compilation and Interpretation

- Adopted by Pascal, Java, functional and logic languages, and most scripting languages
- Pascal compilers generate *P-code* that can be interpreted or compiled into object code
- Java compilers generate *byte code* that is interpreted by the Java virtual machine (or translated into machine code by a just-in-time (JIT) compiler)
- Functional and logic languages are compiled, but also allow dynamically created code to be compiled at run time for which the virtual machine invokes the compiler

Source Program ® [Translator] ® Intermediate Program

Intermediate Program ®
Input ® [Virtual Machine] ® Output

Preprocessing

- Compilers for C and C++ adopt a preprocessor

Source Program ® [Preprocessor] ® Modified Source Program

Modified Source Program ® [Compiler] ® Assembly

- Early C++ compilers generated intermediate C code

Source Program ® [Preprocessor] ® Modified Source Program

Modified Source Program ® [C++ Compiler] ® C Code

C Code ® [C Compiler] ® Assembly

Integrated Programming Environments

- Programming tools (editors, compilers, interpreters, debuggers) function together in concert
- Trace facilities to monitor execution of the program
- Upon run time error in compiled code the editor is invoked with cursor at source line
- Fundamental to Smalltalk-80
- Java Studio, Visual C++, VisualStudio

Overview of Compilation

- Compilation of a program proceeds through a series of *phases*, where subsequent phases use information found in an earlier phase or uses a form of the program produced by an earlier phase
- Each phase may consist of a number of *passes* over the program representation

Character Stream

–

[Scanner]

Token Stream

↓

Parser

↓

Parse Tree

↓

Semantic Analysis and Intermediate Code Generation

↓

Abstract Syntax Tree or Other Intermediate Form

↓

Machine-Independent Code Improvement

↓

Modified Intermediate Form

↓

Target Code Generation

↓

Assembly or Object Code

↓

Machine-Specific Code Improvement

↓

Modified Assembly or Object Code

Front end (analysis)

Back end (synthesis)

Lexical Analysis

- Lexical analysis breaks up a program (e.g. in Pascal)

```
program gcd (input, output);
var i, j : integer;
begin
  read (i, j);
  while i <> j do
    if i > j then i := i - j else j := j - i;
  writeln (i)
end.
```

into a stream of *tokens*

```
program  gcd  (   input  ,  output  )     ;
var      i    ,   j      :  integer ;     begin
read     (    i   ,      j  )       ;     while
i        <>   j   do     if i       >     j
then     i    :=  i      -  j       else  j
:=       j    -   i      ;  writeln (     i
)        end  .
```

- This is also known as *scanning* performed by a *scanner*

Note: a scanner in Java

Context-Free Grammars

- A *context-free grammar* defines the *syntax* of a programming lang
- The grammar defines *syntactic categories*
  - Statements
  - Expressions
  - Declarations
- Categories are subdivided into more detailed categories
  - Loop-statement
  - If-statement
  - Logical-expression
  - ...
- Most programming language manuals include language grammars

```
<statement> -> <loop-statement>
<statement> -> <if-statement>
<loop-statement> -> for (<expression>; <expression>; <expres
                       <statement>
<expression> -> <logical-expression>
...
```

Syntax Analysis

- Parsing organizes tokens into a hierarchy called a *parse tree*
- A grammar of a language with the token stream defines the structure of the parse tree
- Syntax analysis is applied by a compiler to check the syntax of a program by constructing a parse tree of the program
- Example (incomplete) Pascal grammar:

```
<Program> -> program <id> ( <id> <More_ids> ) ; <Block> .

<Block> -> <Variables> begin <Stmt> <More_Stmts> end

<More_ids> -> , <id> <More_ids>
           | e

<Variables> -> var <id> <More_ids> : <Type> ; <More_Variables>
            | e

<More_Variables> -> <id> <More_ids> : <Type> ; <More_Variables>
                 | e

<Stmt> -> <id> := <Exp>
       | read ( <id> <More_ids> )
       | writeln ( <Exp> <More_Exps> )
       | if <Exp> then <Stmt> else <Stmt>
       | while <Exp> do <Stmt>
       | begin <Stmt> <More_Stmts> end
```

Note: An interactive parser demo demonstrates the parsing of the `gcd` Pascal example program into a parse tree (see also textbook pp. 20-21)

Semantic Analysis

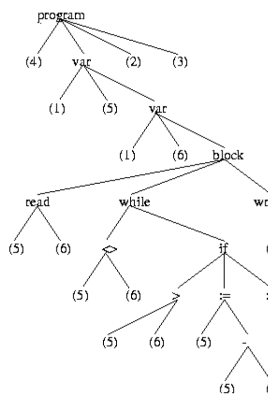
- Semantic analysis is applied by a compiler to discover the *meaning* of a program by analyzing its parse tree or abstract syntax tree (see later)
- *Static semantic checks* are performed at compile time
  - Type checking
  - Every variable is declared before used
  - Identifiers are used in appropriate contexts
  - Check subroutine call arguments
  - Check labels
- *Dynamic semantic checks* are performed at run time, and the compiler produces code that performs these checks
  - Array subscript values are within bounds
  - Arithmetic errors, e.g. division by zero
  - Pointers are not dereferenced unless pointing to valid object
  - A variable is used but hasn't been initialized
  - When a check fails at run time, an exception is raised

Strong Typing

- A language is strongly typed "if (type) errors are always detected"
- Such errors are listed on previous slide
- Errors are either detected at compile time or at run time
- Strong typing makes language safe and easier to use, but slower because of dynamic semantic checks
- Languages that are strongly typed are
  - Ada
  - Java
  - ML, Haskell
- Languages that are *not* strongly typed are
  - Fortran, Pascal, C
  - Lisp, C++
- In some languages, most (type) errors are detected late at run time which is detrimental to reliability (e.g. early Basic, Lisp, Prolog, some script languages)

Intermediate Code Generation

- A typical intermediate form of code produced by the semantic analyzer is an *abstract syntax tree* (AST)
- The AST is *annotated* with useful information such as pointers to the symbol table entry of identifiers
- Example AST for the `gcd` Pascal program:



Index	*Symbol*
1	`integer`
2	`input`
3	`output`
4	`gcd`
5	`i`
6	`j`

Target Code Generation and Optimization

- The AST with the annotated information is traversed by the compiler to generate a low-level intermediate form of code, close to assembly
- This *machine-independent* intermediate form is optimized
- From the machine-independent form assembly or object code is generated by the compiler
- This *machine-specific* code is optimized to exploit specific hardware features