

3. Compilers and Interpreters

Overview

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

Note: Study Chapter 1 Sections 1.4 to 1.6 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) can be viewed as an implementation in hardware of a virtual machine
- Some languages cannot be purely compiled into machine code
 - Some languages allow programs to rewrite/add code
- 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 ® **Interpreter** ® Output

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 ® **Linker** ® 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 ® **Linker** ® 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 ® **Virtual Machine** ® Output
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 (IDEs)

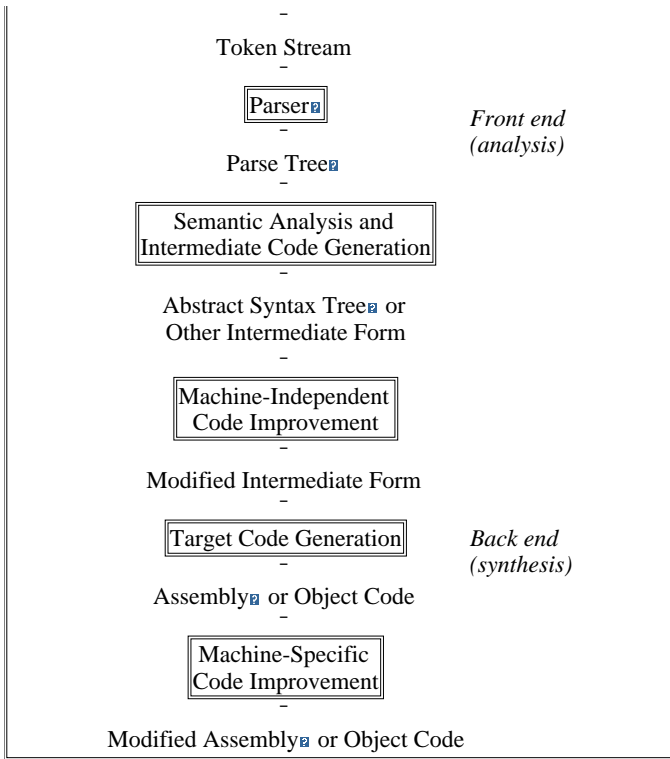
- Programming tools (editors, compilers/interpreters, debuggers, preprocessors, assemblers, linkers) function together in concert
- Editors can help formatting and cross referencing
- Trace facilities to monitor execution of the program
- Upon run time error in compiled code the editor is invoked with cursor at source line
- Fundamental to Smalltalk-80
- Java Studio, VisualStudio, Borland

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



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
:= j - i ; writeln ( i
) end .

```

- This is also known as *scanning* performed by a *scanner*
- A *lexical error* is produced when an unrecognized character is encountered

Note: Download a scanner application in Java

Context-Free Grammars

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

```

<statement> -> <loop-statement>
<statement> -> <if-statement>
<loop-statement> -> for (<expression>; <expression>; <expression>
<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
- A *syntax error* is produced by a compiler when the parse tree cannot be constructed for a program (fragment)
- Example (incomplete) Pascal grammar:

```

<Program> -> program <id> ( <id> <More_ids> ) ; <Block> .
<Block> -> <Variables> begin <Stmnt> <More_Stmnts> 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
<Stmnt> -> <id> := <Exp>
| read ( <id> <More_ids> )
| writeln ( <Exp> <More_Exps> )
| if <Exp> then <Stmnt> else <Stmnt>
| while <Exp> do <Stmnt>
| begin <Stmnt> <More_Stmnts> 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

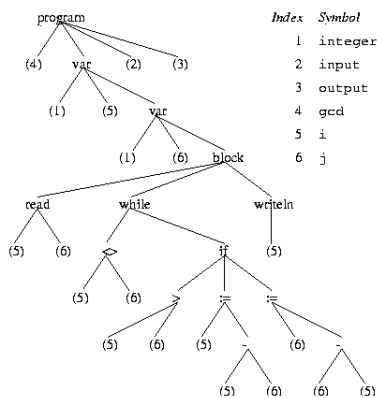
- Semantic analysis is applied by a compiler to discover the *meaning* of a program by analyzing its parse tree or abstract syntax tree (see later)
- *Static semantic checks* are performed at compile time
 - Type checking
 - Every variable is declared before used
 - Identifiers are used in appropriate 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:



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

Exercise 1: Name two languages in which a program can rewrite new pieces of itself. Hint: which languages are said to be suitable for symbolic and logic processing?

Exercise 2: Which IDEs do you regularly use? If not, explain the tools you use for programming projects.

Exercise 3: Describe the six tools that are commonly used with a compiler within an IDE.

Exercise 4: Using your favorite compiled programming language, give an example of

- a lexical error detected by the scanner
- a syntax error detected by the parser
- a static semantic error detected by semantic analysis
- a dynamic semantic error detected at runtime by the code generated by the compiler