Compiling Programming Languages

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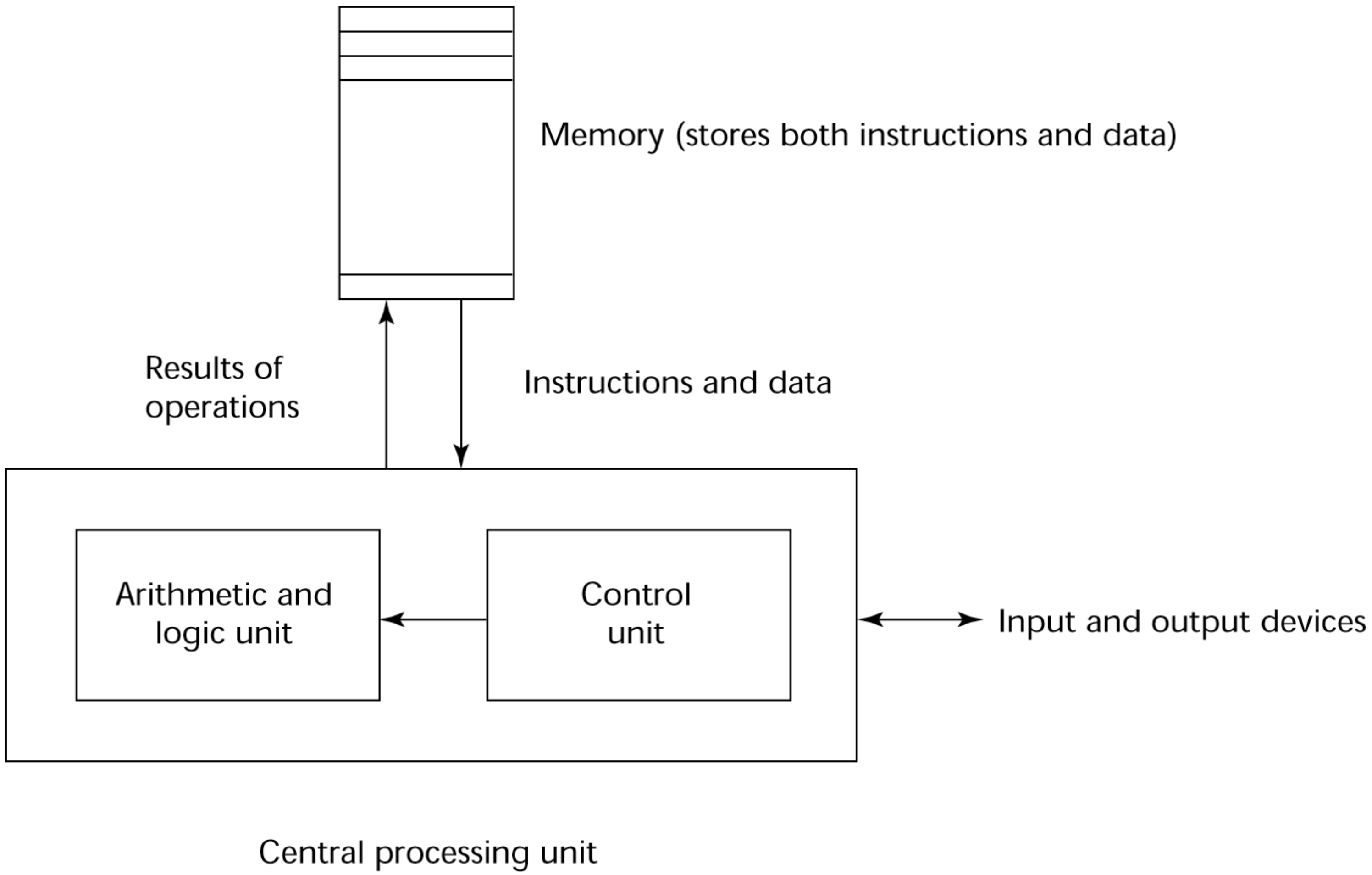
Introduction

- All software running on all computers is written in some programming language.
- To be executed by a computer, a program must be translated into the machine language of that computer.
- A *compiler* is the software system that does this translation.

The von Neumann Architecture



Sebesta. Robert W., Concepts of Programming Languages, 8th ed., Addison Wesley Longman, 2008.

Execution of Machine Code by Hardware Interpreter

- Fetch-execute-cycle

```
initialize the program counter
repeat forever
  fetch the instruction pointed by the counter
  increment the counter
  decode the instruction
  execute the instruction
end repeat
```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Evolution of Programming Languages

Machine Language – 0's and 1's

Assembly Language – mnemonic form of Machine Language

First Generation Languages – higher-level data and control constructions corresponding to Machine Language data and control (e.g. FORTRAN)

Second Generation Languages – higher-level data and control constructions, not always corresponding to, but still modeled after Machine Language data and control (e.g. ALGOL 60, COBOL)

Third Generation Languages – introduction of more abstract forms of data, including user-defined data types (e.g. Pascal, C)

Object-Based Languages – support for objects and abstract data types (e.g. Ada)

Object-Oriented Languages – support for classes of objects organized as a class hierarchy (e.g. Smalltalk, C++, Java)

. . .

Natural Languages – humans communicate directly with the machine (e.g. English)

Implementation Methods

- Compilation
  - Programs are translated into machine language, which is then executed by the hardware interpreter
- Pure Interpretation
  - Programs are interpreted by another program known as a software interpreter
- Hybrid Implementation Systems
  - A compromise between compilers and pure interpreters

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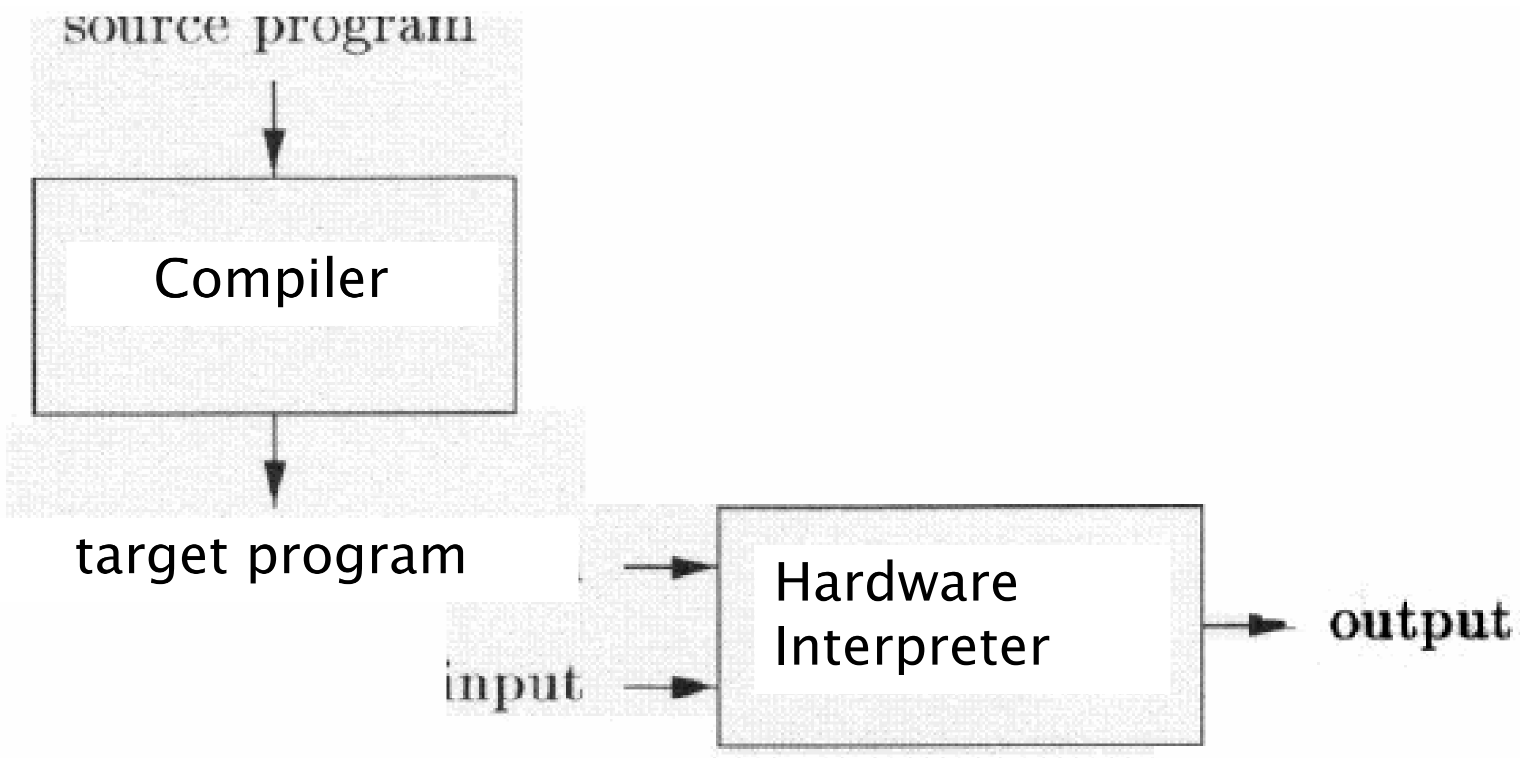
Compilation



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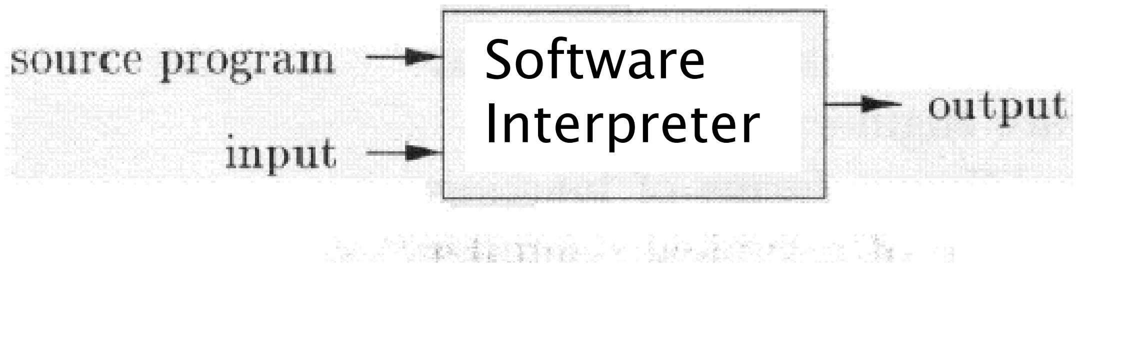

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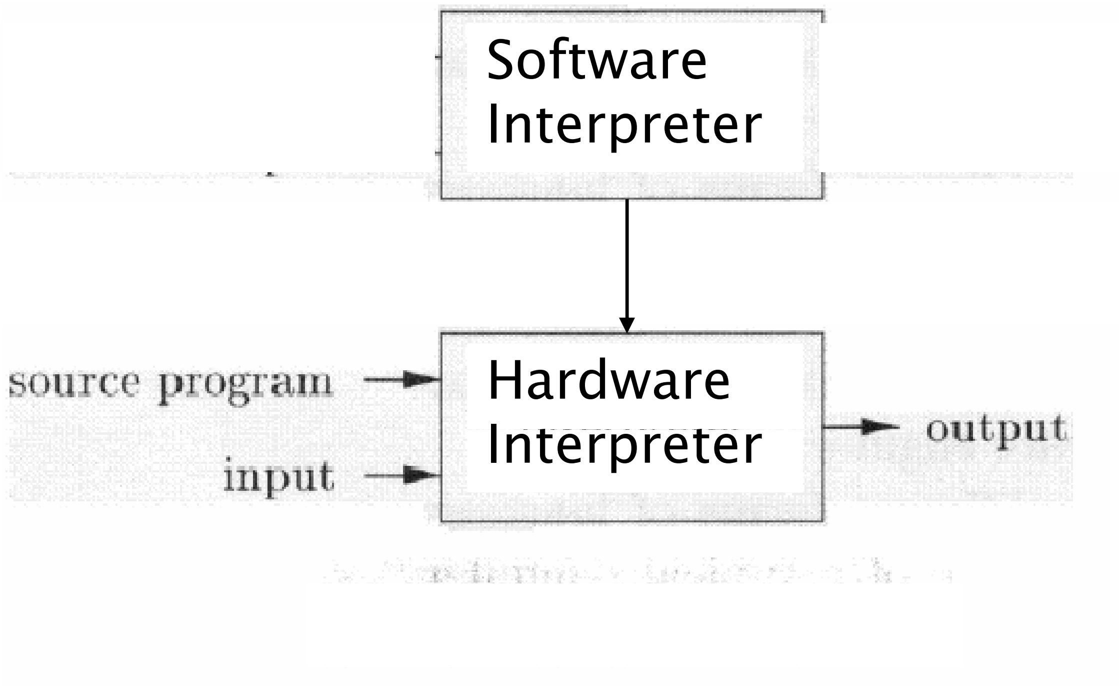

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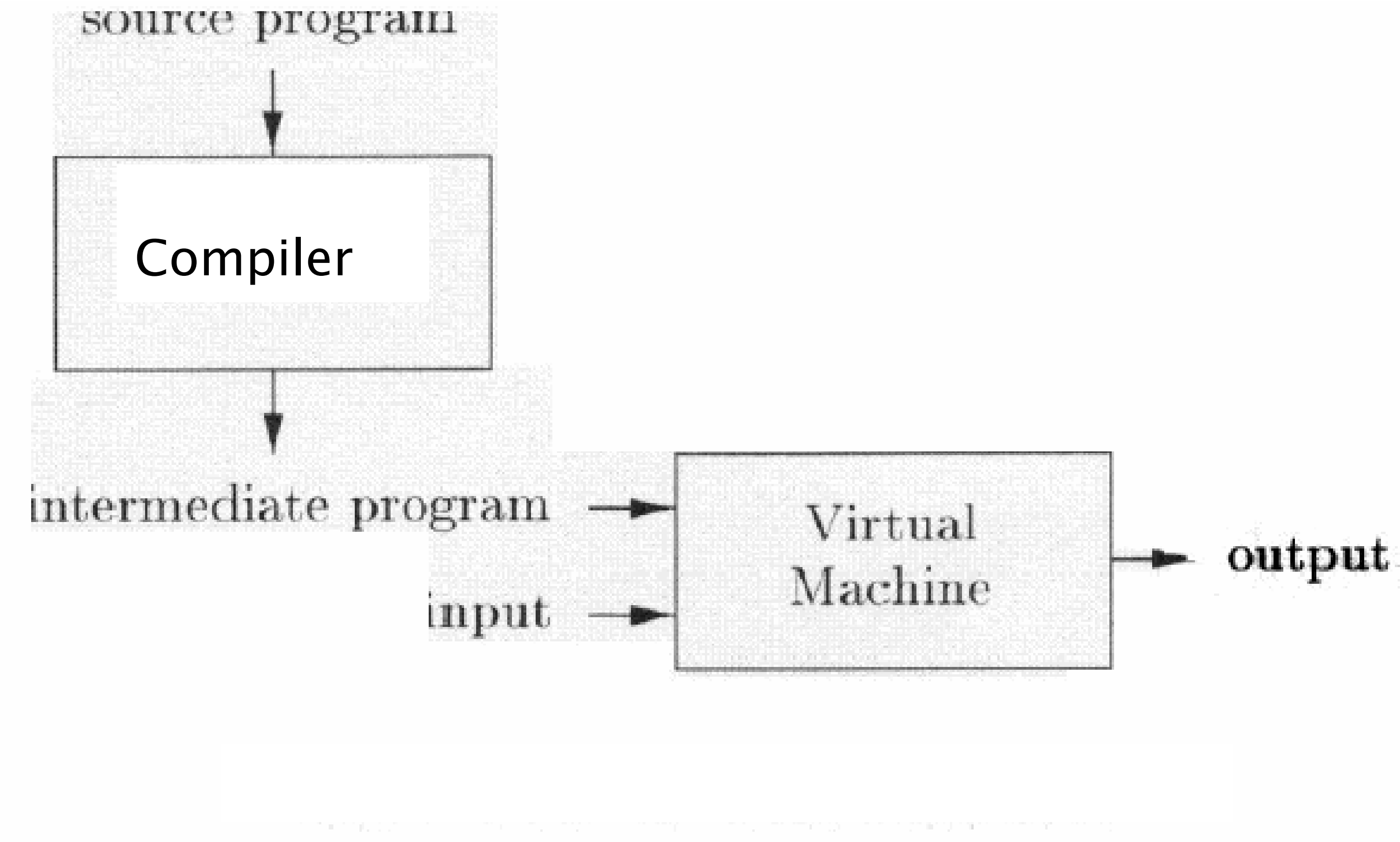
Hybrid Implementation



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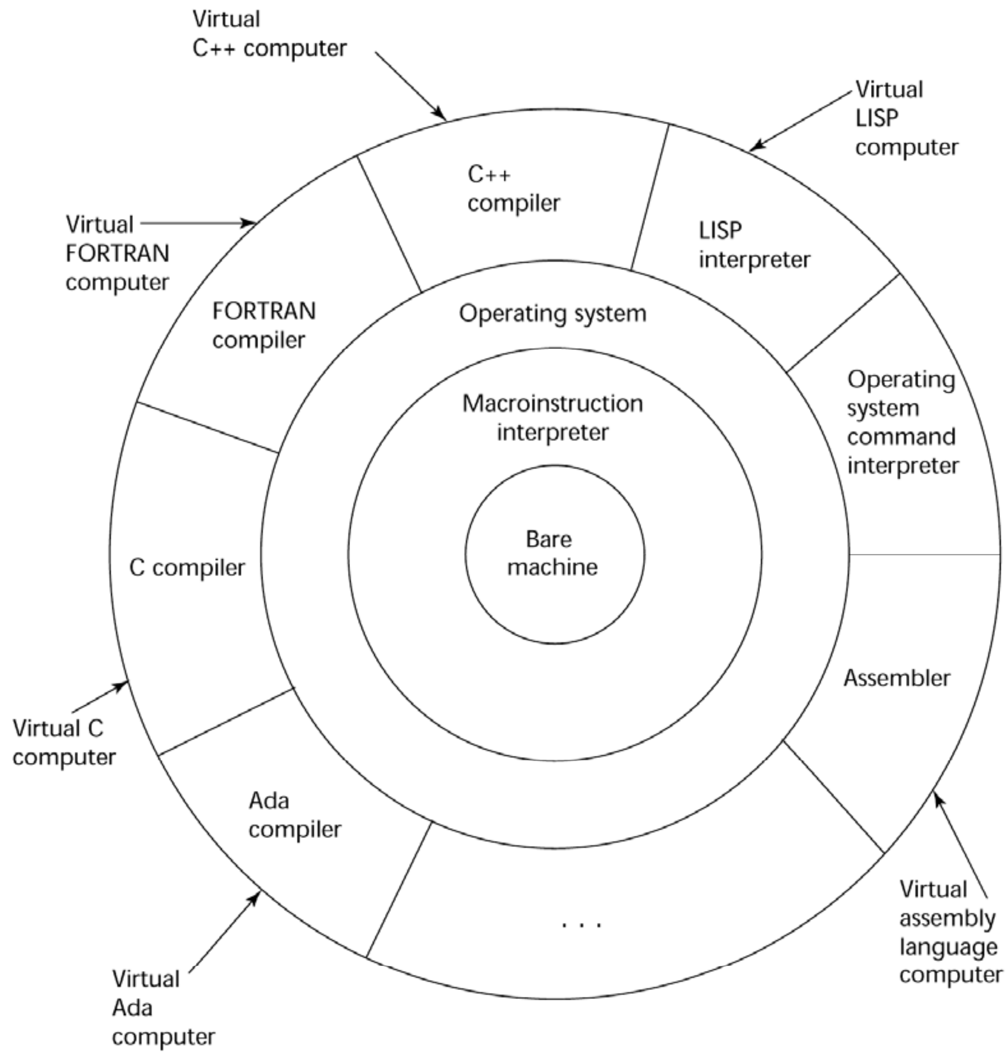
Layered View of Computer

The operating system and language implementation are layered over the machine interface of the underlying computer. Each language runs on its own *virtual machine*.



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Compilation

- Translate high-level program (source language) into machine code (machine language)
- Slow translation, fast execution
- Compilation process has several phases:
  - lexical analysis: converts characters in the source program into lexical units
  - syntax analysis: transforms lexical units into *parse trees* which represent the syntactic structure of program
  - semantics analysis: generate intermediate code
  - code generation: machine code is generated

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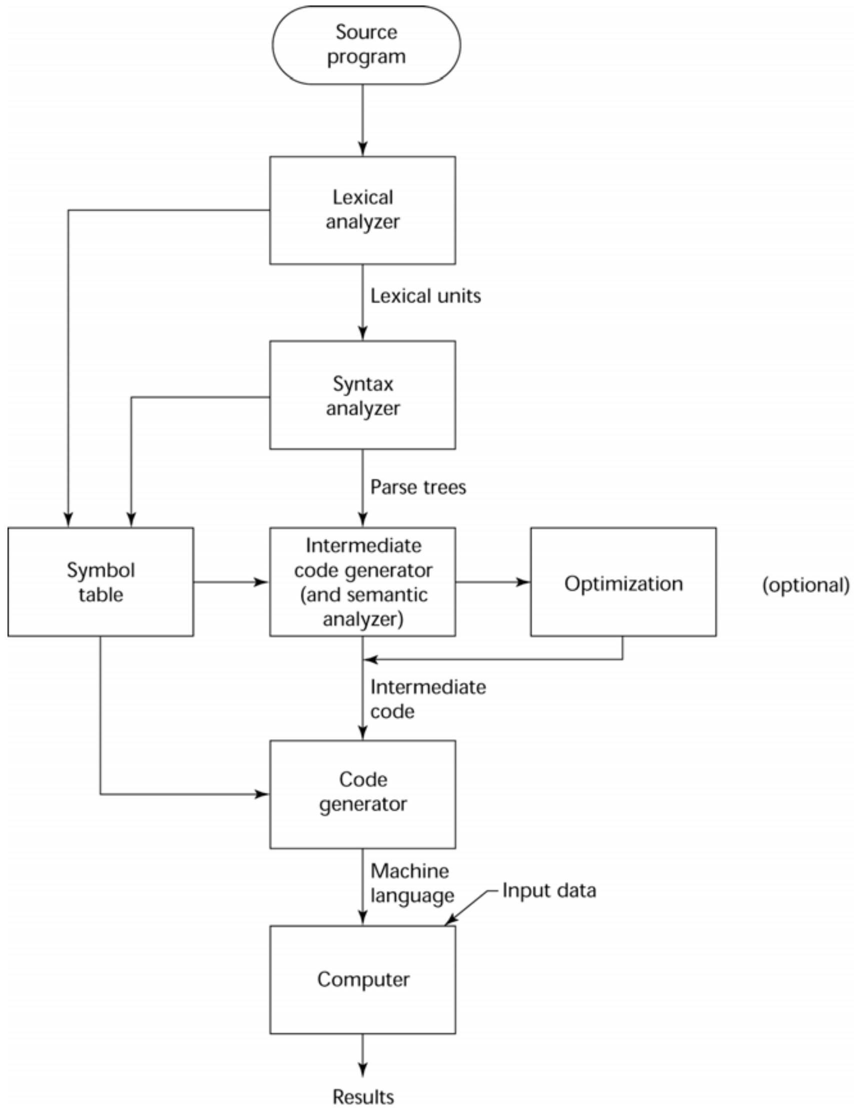
The Compilation Process



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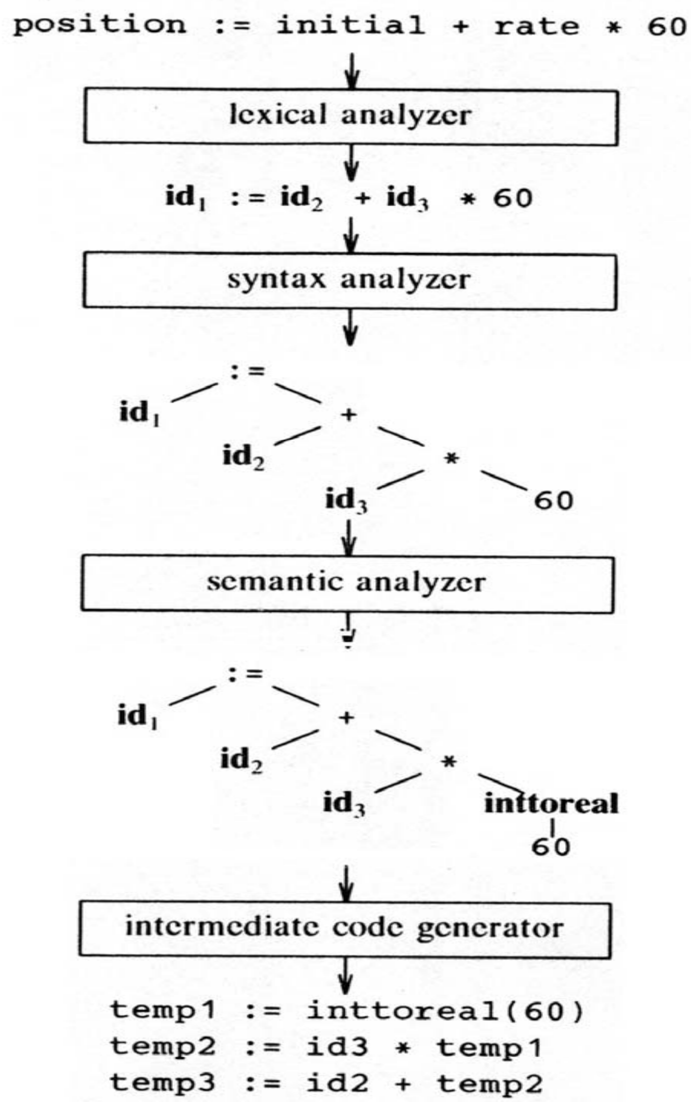
Front-End of a Compiler



id1 := temp3

SYMBOL TABLE

1	position	...
2	initial	...
3	rate	...
4		

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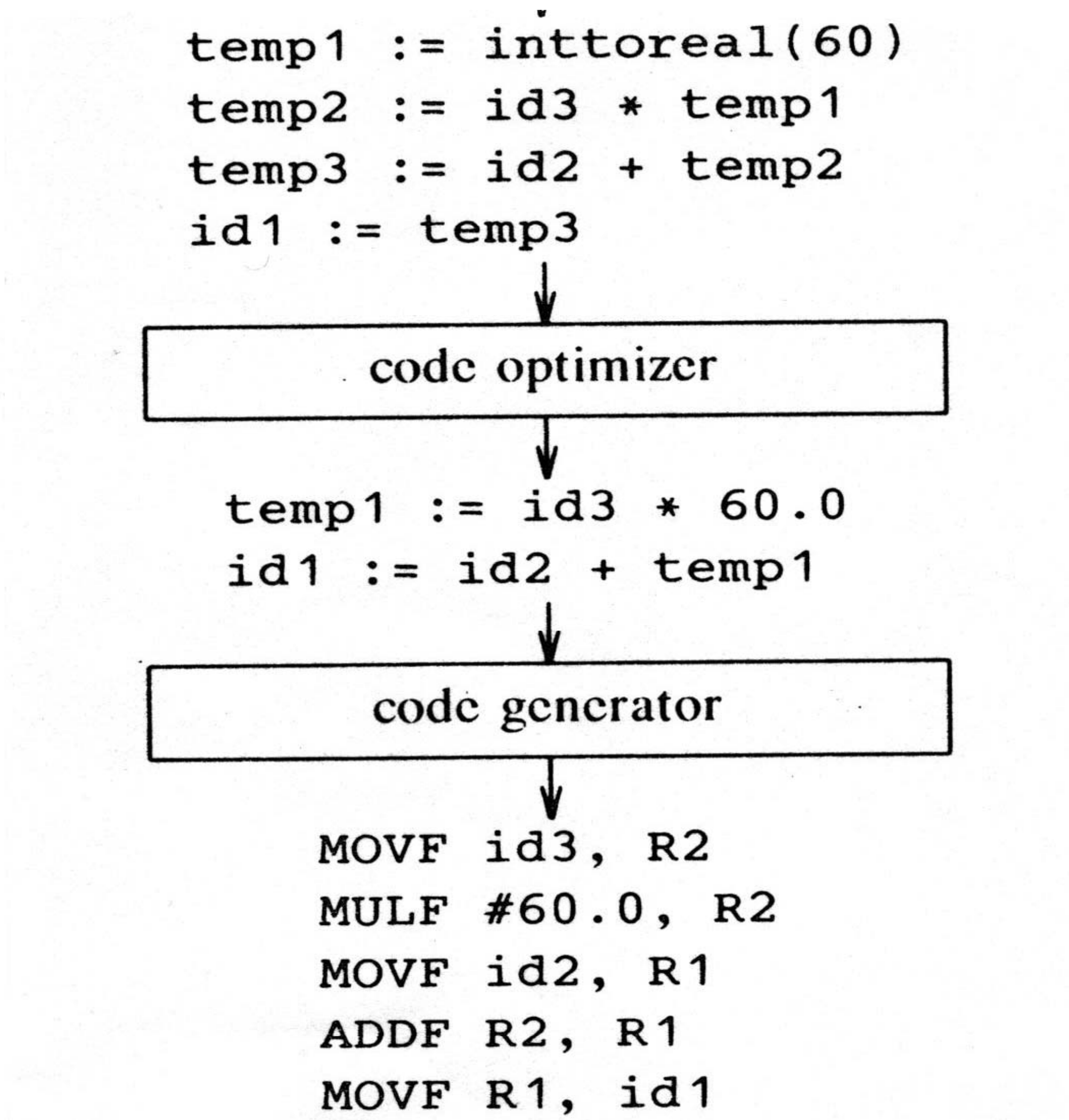
Back-End of a Compiler



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Additional Compilation Terminologies

- **Load module** (executable image): the user and system code together
- **Linking and loading**: the process of collecting system program and linking them to user program

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Pure Interpretation

- No translation
- Easier implementation of programs (run-time errors can easily and immediately be displayed)
- Slower execution (10 to 100 times slower than compiled programs)
- Often requires more space
- Now rare for traditional high-level languages
- Significant comeback with some Web scripting languages (e.g., JavaScript, PHP)

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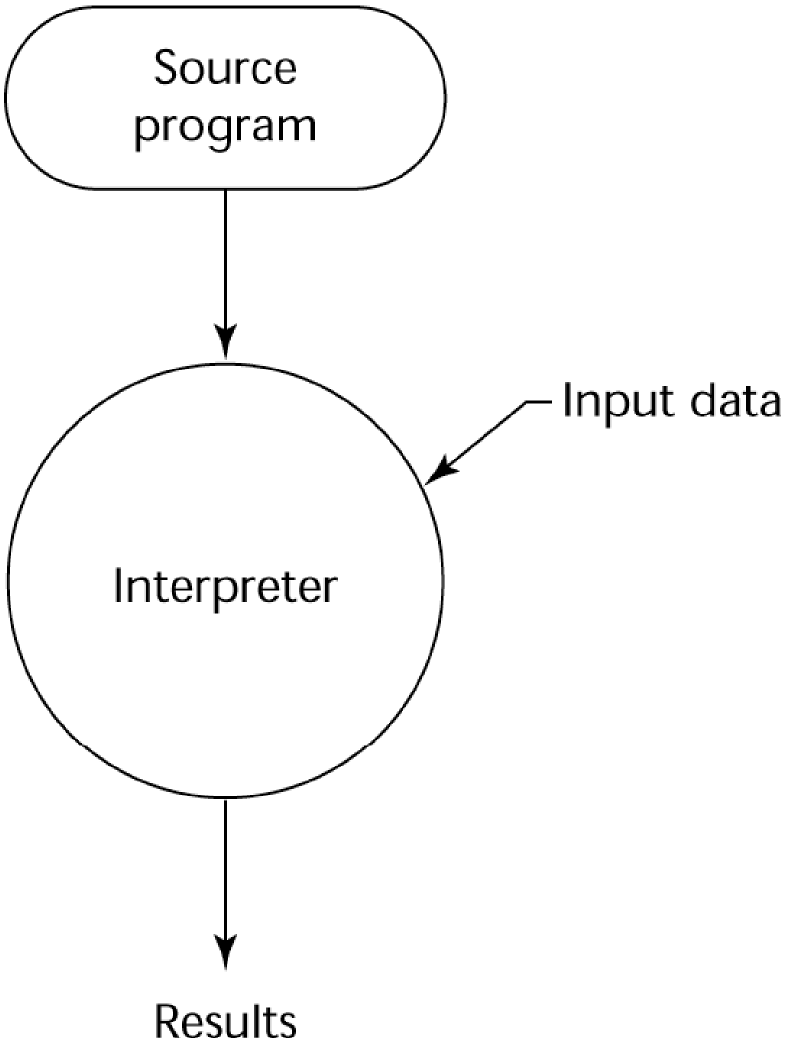
Pure Interpretation Process



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Hybrid Implementation Systems

- A compromise between compilers and pure interpreters
- A high-level language program is translated to an intermediate language that allows easy interpretation
- Faster than pure interpretation
- Examples
  - Perl programs are partially compiled to detect errors before interpretation
  - Initial implementations of Java were hybrid; the intermediate form, *byte code*, provides portability to any machine that has a byte code interpreter and a run-time system (together, these are called *Java Virtual Machine*)

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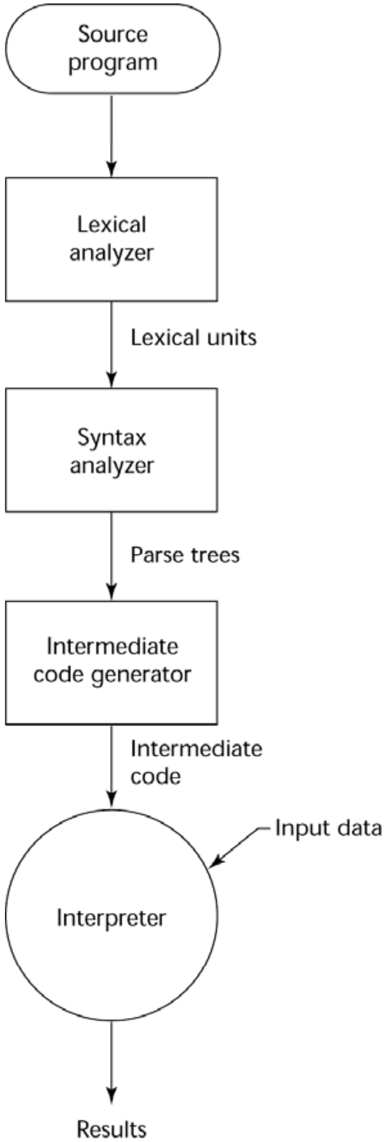
Hybrid Implementation Process



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Just-in-Time Implementation Systems

- Initially translate programs to an intermediate language
- Then compile the intermediate language of the subprograms into machine code when they are called
- Machine code version is kept for subsequent calls
- JIT systems are widely used for Java programs
- .NET languages are implemented with a JIT system
  - All such languages are translated to a Common Intermediate Language (CIL) whose virtual machine is called the Common Language Run-Time (CLR)

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Execution of a Java Applet

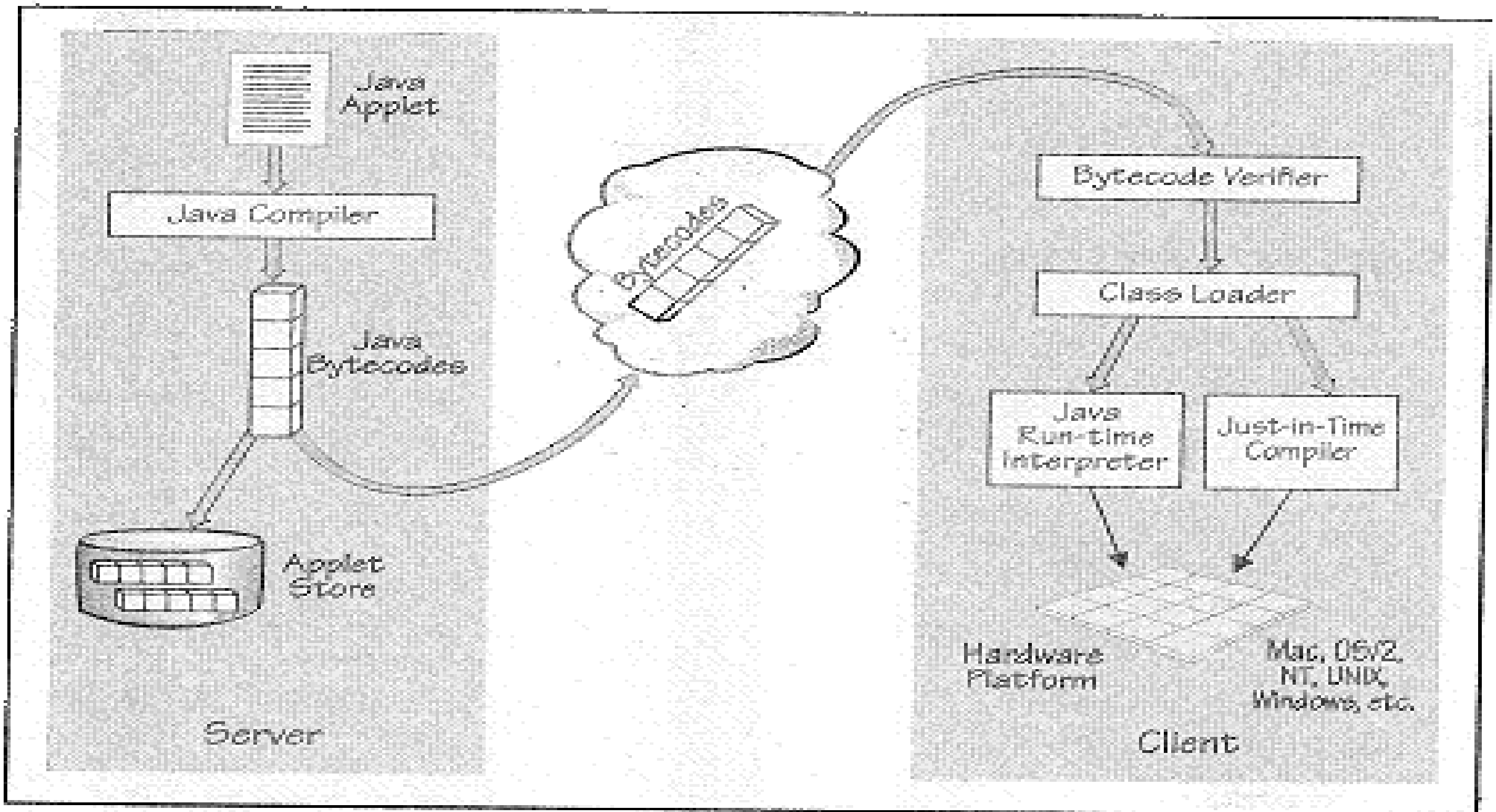

Figure 2-3. The Bytecode Cycle: From Production to Execution.

Orfali, R. and Harkey, D., Client/Server Programming with Java and CORBA, 1st ed., Wiley, 1997.

Preprocessors

- Preprocessor macros (instructions) are commonly used to specify that code from another file is to be included
- A preprocessor processes a program immediately before the program is compiled to expand embedded preprocessor macros
- A well-known example: C preprocessor
  - expands `#include`, `#define`, and similar macros

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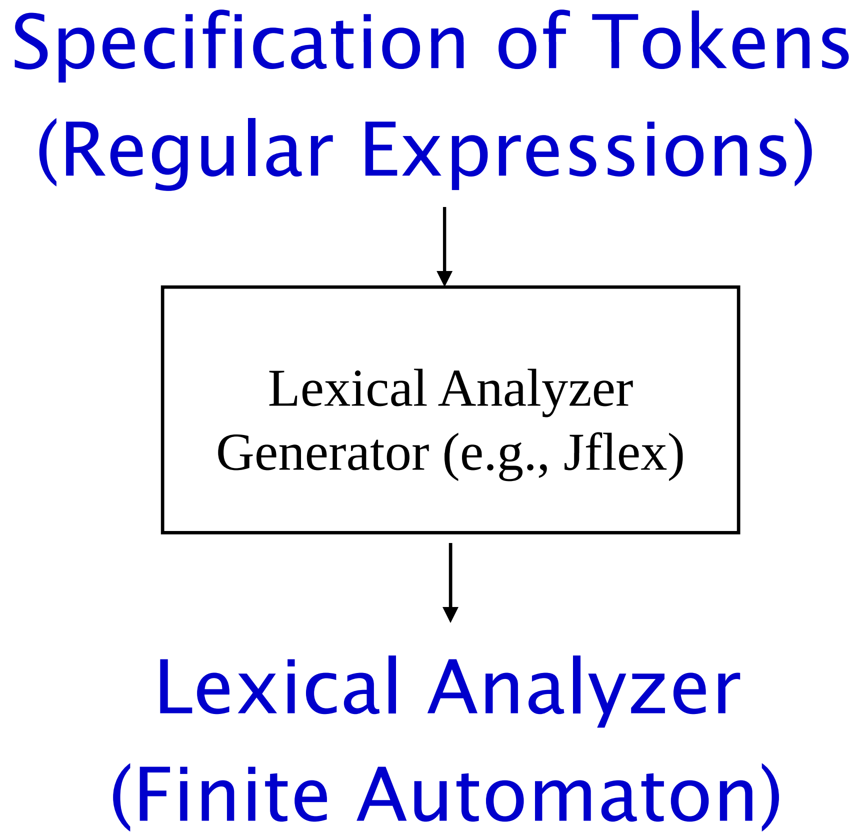
Compiler Construction Tools

- Scanner generators – produce lexical analyzers from regular expression descriptions of tokens
- Parser generators – produce syntax analyzers from grammars
- Syntax-directed translation engines – produce collections of routines for walking a parse tree and generating intermediate code

Scanner Generation



JFlex Example

```
Identifier = [:letter:] [:letter: | :digit:]*
Integer    = [:digit:] [:digit:]*
%%
[ \t\n]  { echo (); }
";"      { echo (); return new Token (Token.SEMICOLON); }
"."      { echo ();  return new Token (Token.PERIOD); }
"<"      { echo (); return new Token (Token.RELOP, Token.LT); }
">"      { echo (); return new Token (Token.RELOP, Token.GT); }
"="      { echo (); return new Token (Token.RELOP, Token.EQ); }
"+"      { echo (); return new Token (Token.ADDOP, Token.PLUS); }
"*"      { echo (); return new Token (Token.MULTOP, Token.TIMES); }
if       { echo (); return new Token (Token.IF); }
while    { echo (); return new Token (Token.WHILE); }
{Integer}         { echo ();
                    return new Token (Token.INTEGER, yytext ()); }
{Identifier}      { echo ();
                    return new Token (Token.ID, yytext ()); }
```

Parser Generation

Specification of Syntax
(Context-Free Grammar)

↓

Parser Generator
(e.g., CUP)

↓

Syntax Analyzer
(Pushdown Automaton)

CUP Example

```
program ::= block PERIOD ;

block ::= constDecl varDecl procDecl statement ;

constDecl ::= CONST constAssignmentList SEMICOLON | ;

constAssignmentList ::= ID EQ INTEGER | constAssignmentList
    COMMA ID EQ INTEGER ;

varDecl ::= VAR identList SEMICOLON | ;

identList ::= ID | identList COMMA ID ;

procDecl ::= procDecl PROC ID SEMICOLON block SEMICOLON | ;

statement ::= ID ASSIGN expression | BEGIN statementList END |
    IF condition THEN statement | WHILE condition DO statement | ;
```

Syntax-Directed Translation Engines

Specification of Semantics

(Attributed Context-Free Grammar)

↓

Attribute Grammar
Evaluator (e.g., LISA)

↓

Semantic Analyzer and

Intermediate Code Generator

Attribute Grammar Example

<term> ::= <factor>

<factor> . env ← <term> . env
<term> . tree ← <factor> . tree
<term> . type ← <factor> . type

| <term>[1] <multiplying-operator> <factor>

<term>[1] . env ← <term> . env
<factor> . env ← <term> . env
<term> . tree ←
tree (<multiplying-operator> . lexeme,
<term>[1] . tree, <factor> . tree)
<term> . type ←
compatible (<term>[1] . type, <factor> . type)

<multiplying-operator> ::= * | /

Applications of Compiler Technology

- Implementation of High-Level Programming Languages
- Optimizations for Computer Architectures (e.g. parallelism, memory hierarchies)
- Design of New Computer Architectures (e.g. RISC, embedded systems)
- Program Translations (e.g. binary translation, hardware synthesis, database query interpreters)
- Software Productivity Tools (e.g. type/bounds checking, memory management)

A Grand Challenge for Computing Research

- A *verifying compiler* uses automated mathematical and logical reasoning to check the correctness of the programs that it compiles.
- The criterion of correctness is specified by types, assertions, and other redundant annotations that are associated with the code of the program.
- C. A. R. Hoare, The Verifying Compiler: A Grand Challenge for Computing Research, Journal of the ACM 50, 1 (January 2003), pp. 63 – 69.

Further Information

Primary References:

- Aho, Alfred V., Lam, Monica, Sethi, Ravi, and Ullman, Jeffrey D., *Compilers: Principles, Techniques, and Tools*, 2nd ed., Addison Wesley Longman, 2007.
- Sebesta. Robert W., *Concepts of Programming Languages*, 8th ed., Addison Wesley Longman, 2008.

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