1.1 What is a Compiler?

I. Translator

Definition:

\[
\begin{array}{ccc}
\text{program in} & \text{translator} & \text{program in} \\
\text{language} & \text{for} & \text{language} \\
X & X & Y \\
\end{array}
\]

Examples:

<table>
<thead>
<tr>
<th>Source Language</th>
<th>Object Language</th>
<th>Name</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Level</td>
<td>High Level</td>
<td>preprocessor</td>
<td>ratfor → /f77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>m4, cpp</td>
</tr>
<tr>
<td>Assembly</td>
<td>Machine</td>
<td>assembler</td>
<td>as</td>
</tr>
<tr>
<td>High Level</td>
<td>Machine</td>
<td>compiler</td>
<td>g++, javac</td>
</tr>
<tr>
<td>Any</td>
<td>executes</td>
<td>interpreter</td>
<td>BASIC (often)</td>
</tr>
<tr>
<td></td>
<td>immediately</td>
<td></td>
<td>c shell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>apl, lisp, java</td>
</tr>
</tbody>
</table>

- Preprocessor

```plaintext
for i=1 to n do
    (stmts)
end for

↓
i = 1
while (i<=n) do
    (stmts)
    i = i + 1
end while
```
II. Language Processing System

skeletal source program

\[
\downarrow
\]

preprocessor

\[
\downarrow
\]

source program

\[
\downarrow
\]

compiler

\[
\downarrow
\]

target (object) assembly program

\[
\downarrow
\]

assembler

\[
\downarrow
\]

relocatable machine code

\[
\downarrow
\]

loader/link-editor

\[
\downarrow
\]

absolute machine code

III. Compiler

program in high level \(\rightarrow\) compiler \(\rightarrow\) program in machine language X \(\rightarrow\) compiler for X \(\rightarrow\) language Y
1.2 STRUCTURE OF A COMPILER

General Overview

Source Code

↓

Lexical Analysis

↓
tokens

Syntax Analysis

↓
parse trees

Symbol Table Management

Intermediate Code Generation

↓
intermediate code

Error Handling

↓
intermediate code

Code Optimization

↓
intermediate code

Code Generation

↓
Object Program
1.3 PHASES OF COMPILATION

1.3.1 Lexical Analysis (Scanner)

a. Purpose: Read the same program character by character grouping them into atomic units called “tokens.”

b. Tokens:

- depend on language and compiler writer
- Examples:

  reserved words if, for
  operators +, -, <, =
  constants 0, 4.89
  punctuation (, ), [
  identifiers sb, ch

- treated as a pair: token.type and token.value
  - token type is a (mnemonic) integer
  - some tokens have no value

c. Example

if (x <= 0) x = y + z

when put through lexical analyzer produces:

<table>
<thead>
<tr>
<th>token</th>
<th>type</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>if</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>(</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>id</td>
<td>23</td>
<td>“x”</td>
</tr>
<tr>
<td>&lt;=</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>int constant</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>)</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>id</td>
<td>23</td>
<td>“x”</td>
</tr>
<tr>
<td>=</td>
<td>4</td>
<td>“=”</td>
</tr>
<tr>
<td>id</td>
<td>23</td>
<td>“y”</td>
</tr>
<tr>
<td>+</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>id</td>
<td>23</td>
<td>“z”</td>
</tr>
</tbody>
</table>
d. How does one build a lexical analyzer?

- from scratch
- lex

e. Preview of Lex

- idea: tokens described by regular expressions
- basic syntax:
  - regular expression, action
- basic semantics:
  - if match regular expression, then do action.
- Example:

```c%
"if" return(25);
"(" return(28);
[0-9]+ return(22);
```

f. Remarks

Besides returning token types and values, the lexical analyzer might

a) print error messages

b) insert identifiers in the symbol table

1.3.2 Syntax Analysis (Parsing)

a. Purpose: Accepts the sequence of tokens generated by the lexical analyzer, checks whether the program is syntactically correct, and generates a parse tree.

b. Syntax: formally described by a context free grammar.
c. Parse Tree

if \( x \leq 0 \) \( x = y + z \)

Figure 2 is the parse tree for this statement.

d. How does one build a parser?

- from scratch
- using a parser generator such as yacc

1.3.3 Intermediate Code Generator

a. Purpose: Traverse the parse tree, producing simple intermediate code.

b. Three-Address Code:

Instructions:

1. \( \text{id} := \text{id} \text{ op } \text{id} \)
2. \( \text{goto label} \)
3. \( \text{if condition goto label} \)
Example:

\[
\text{if } (x\leq 0) \quad x = x + z \\
\downarrow \\
\text{if } (x\leq 0) \quad \text{goto L1} \\
\quad \text{goto L2} \\
\text{L1: } \quad x := y + z \\
\text{L2: }
\]

1.3.4 Intermediate Code Generation

a. Purpose: Transform the intermediate code into “better” code.

b. Examples

1) Rearrangement of Code

\[
\text{if } (x\leq 0) \quad \text{goto L1} \quad \rightarrow \quad \text{if } (x>0) \quad \text{goto L2} \\
\quad \text{goto L2} \\
\text{L1: } \quad x = y + z \\
\text{L2: }
\]

2) Redundancy Elimination

\[
\begin{align*}
\text{a} &= w + x + y \\
&\quad \rightarrow \quad \text{T1} = x + y \\
\text{b} &= x + y + z \\
&\quad \rightarrow \quad \text{a} = w + \text{T1} \\
\text{b} &= \text{T1} + z
\end{align*}
\]

3) Strength Reduction

\[
\begin{align*}
\text{x}^2 \\
&\quad \rightarrow \quad \text{x} \times \text{x} \\
\text{expensive} &\rightarrow \quad \text{cheap} \\
\text{operator} &\rightarrow \quad \text{operator}
\end{align*}
\]

4) Frequency Reduction

\[
\begin{align*}
\text{for } (i=1; \ i<n; \ i=i+1) \ \{ \\
\quad \text{x} = \text{sqrt}(26) \\
\quad \} \\
\quad \text{T1} = \text{sqrt}(26) \\
\quad \text{for } (i=1; \ i<n; \ i=i+1) \ \{ \\
\quad \text{x} = \text{T1} \\
\quad \} \\
\end{align*}
\]
c. Remarks:

1) Main criteria for optimization is speed.

1.3.5 Code Generation

a. Purpose: Transform intermediate code to machine code (assembler)

b. Example: \[ a = b + c \]

\[
\begin{align*}
\text{mov} & \quad b, R1 \\
\text{add} & \quad c, R1 \\
\text{mov} & \quad R1, a
\end{align*}
\]

c. Remarks

1) completely machine dependent whereas other phases are not

2) “register allocation” is the most difficult task

- idea - use registers (fast access) to avoid memory use (slow access)
- problem - only a finite number of registers (during intermediate code phase, one assumes an infinite number)

1.4 Symbol Table

a. Purpose: record information about various objects in the source program

b. Examples

- procedure - no. and type of arguments
- simple variable - type
- array - type, size

c. Use - information is required during

- parsing
- code generation
1.5 Error Handler

a. Errors - all errors should be

- detected
- detected correctly
- detected as soon as possible
- reported at the appropriate place and in a helpful manner

b. Purpose

- report errors
- “error recovery” - proceed with processing

c. Note: Errors can occur in each phase

- misspelled token
- wrong syntax
- improper procedure call
- statements that cannot be reached