1.1 What is a Compiler?

I. Translator

Definition:

\[
\text{program in language } \xrightarrow{\text{translator}} \text{for language X} \xrightarrow{\text{program in language Y}}
\]

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 $\rightarrow$ 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
```

```plaintext
↓
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 \[\rightarrow\] for X 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

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>= assignment</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:

```%
"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

\[ \text{if } (x = 0) \ x = y + z \]

```
statement
  └── if-statement
      ├── if
      │   └── (condition)
      └── relation
          └── expression
              └── id
          └── relop
          └── expression
              └── constant
```

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. id := id op id
2. goto label
3. if condition goto label
Example:

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

1.3.4 Intermediate Code Generation

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

b. Examples

1) Rearrangement of Code

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

2) Redundancy Elimination

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

3) Strength Reduction

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

4) Frequency Reduction

\[
\begin{align*}
\text{for } & (i=1; i < n; i=i+1) \{ \\
x & = \text{sqrt}(26) \\
\} \\
\rightarrow & T1 = \text{sqrt}(26) \\
& \text{for } (i=1; i < n; i=i+1) \{ \\
& x = T1 \\
\}
\end{align*}
\]
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