CSE 309 (Compilers)

Lexical Analysis

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January 2025

Version: 1.1, Last modified: April 13, 2025

The Role of the Lexical Analyzer

- As the first phase of a compiler, the main task of the lexical analyzer is to,
  - read the input characters of the source program,
  - group them into lexemes,
  - and produce as output a sequence of tokens for each lexeme in the source program.

- The stream of tokens is sent to the parser for syntax analysis.
- It is common for the lexical analyzer to interact with the symbol table as well.

The Role of the Lexical Analyzer — *continued*

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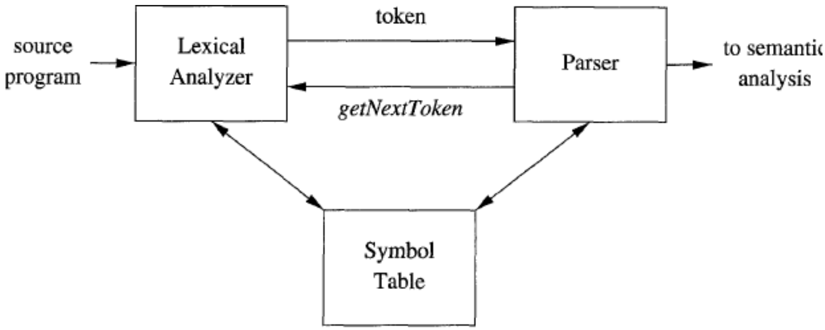
- It is common for the lexical analyzer to interact with the symbol table as well.

The Role of the Lexical Analyzer — *continued*

- When the lexical analyzer discovers a lexeme constituting an identifier, it needs to enter that lexeme into the symbol table.
- In some cases, information regarding the kind of identifier may be read from the symbol table by the lexical analyzer to assist it in determining the proper token it must pass to the parser.

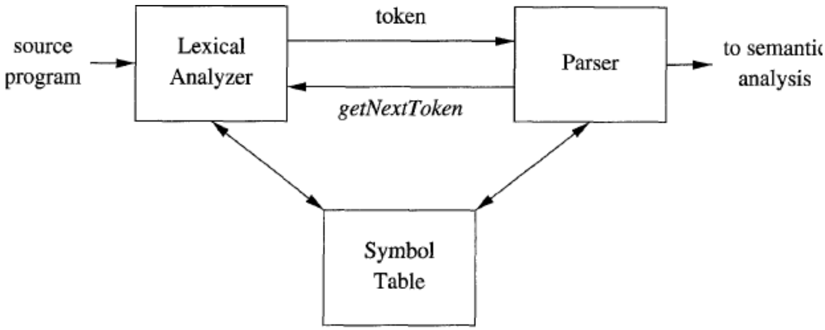
The Role of the Lexical Analyzer — *continued*



Interactions between the lexical analyzer and the parser

- These interactions are suggested in figure.
- Commonly, the interaction is implemented by having the parser call the lexical analyzer.

The Role of the Lexical Analyzer — *continued*



Interactions between the lexical analyzer and the parser

- The call, suggested by the *getNextToken* command, causes the lexical analyzer to read characters from its input until it can identify the next lexeme and produce for it the next token, which it returns to the parser.

The Role of the Lexical Analyzer — *continued*

- The lexical analyzer is the part of the compiler that reads the source text.
- It may perform certain other tasks besides identification of lexemes.
- One such task is stripping out comments and whitespace (blank, newline, tab, and perhaps other characters that are used to separate tokens in the input).

The Role of the Lexical Analyzer — *continued*

- Another task is correlating error messages generated by the compiler with the source program.
- For instance, the lexical analyzer may keep track of the number of newline characters seen, so it can associate a line number with each error message.

The Role of the Lexical Analyzer — *continued*

- In some compilers, the lexical analyzer makes a copy of the source program with the error messages inserted at the appropriate positions.
- If the source program uses a macro-preprocessor, the expansion of macros may also be performed by the lexical analyzer.

The Role of the Lexical Analyzer — *continued*

- Sometimes, lexical analyzers are divided into a cascade of two processes:
  a) *Scanning* consists of the simple processes that do not require tokenization of the input, such as deletion of comments and compaction of consecutive whitespace characters into one.
  b) *Lexical analysis proper* is the more complex portion, where the scanner produces the sequence of tokens as output.

The Role of the Lexical Analyzer — *continued*

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  a) *Scanning* consists of the simple processes that do not require tokenization of the input, such as deletion of comments and compaction of consecutive whitespace characters into one.
  b) *Lexical analysis proper* is the more complex portion, where the scanner produces the sequence of tokens as output.

Lexical Analysis Versus Parsing

- There are a number of reasons why the analysis portion of a compiler is normally separated into lexical analysis and parsing (syntax analysis) phases.

Lexical Analysis Versus Parsing — *continued*

1. Simplicity of design is the most important consideration.
   - The separation of lexical and syntactic analysis often allows us to simplify at least one of these tasks.
   - For example, a parser that had to deal with comments and whitespace as syntactic units would be considerably more complex than one that can assume comments and whitespace have already been removed by the lexical analyzer.
   - If we are designing a new language, separating lexical and syntactic concerns can lead to a cleaner overall language design.

Lexical Analysis Versus Parsing — *continued*

2. Compiler efficiency is improved.
   - A separate lexical analyzer allows us to apply specialized techniques that serve only the lexical task, not the job of parsing.
   - In addition, specialized buffering techniques for reading input characters can speed up the compiler significantly.

Lexical Analysis Versus Parsing — *continued*

3. Compiler portability is enhanced.
   - Input-device-specific peculiarities can be restricted to the lexical analyzer.

Tokens, Patterns, and Lexemes

- When discussing lexical analysis, we use three related but distinct terms:

A token is a pair consisting of a token name and an optional attribute value.

- The token name is an abstract symbol representing a kind of lexical unit, e.g., a particular keyword, or a sequence of input characters denoting an identifier.
- The token names are the input symbols that the parser processes.
- We shall generally write the name of a token in boldface.
- We will often refer to a token by its token name.

Tokens, Patterns, and Lexemes

- When discussing lexical analysis, we use three related but distinct terms:

A pattern
: is a description of the form that the lexemes of a token may take.
    - In the case of a keyword as a token, the pattern is just the sequence of characters that form the keyword.
    - For identifiers and some other tokens, the pattern is a more complex structure that is matched by many strings.

Tokens, Patterns, and Lexemes

- When discussing lexical analysis, we use three related but distinct terms:

A lexeme
: is a sequence of characters in the source program that matches the pattern for a token and is identified by the lexical analyzer as an instance of that token.

TOKEN	INFORMAL DESCRIPTION	SAMPLE LEXEMES
if	characters `i`, `f`	`if`
else	characters `e`, `l`, `s`, `e`	`else`
comparison	`<` or `>` or `<=` or `>=` or `==` or `!=`	`<=`, `!=`
id	letter followed by letters and digits	`pi`, `score`, `D2`
number	any numeric constant	`3.14159`, `0`, `6.02e23`
literal	anything but `"`, surrounded by `"`'s	`"core dumped"`

Examples of tokens

- Figure gives some typical tokens, their informally described patterns, and some sample lexemes.

TOKEN	INFORMAL DESCRIPTION	SAMPLE LEXEMES
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Examples of tokens

- To see how these concepts are used in practice, in the C statement `printf("Total = %d\n", score);` both `printf` and `score` are lexemes matching the pattern for token **id**, and `"Total = %d\n"` a lexeme matching **literal**.

Tokens, Patterns, and Lexemes — *continued*

In many programming languages, the following classes cover most or all of the tokens:

1. One token for each keyword.
   - The pattern for a keyword is the same as the keyword itself.
2. Tokens for the operators, either individually or in classes such as the token `comparison` mentioned.
3. One token representing all identifiers.
4. One or more tokens representing constants, such as numbers and literal strings.
5. Tokens for each punctuation symbol, such as left and right parentheses, comma, and semicolon.

Attributes for Tokens

- When more than one lexeme can match a pattern, the lexical analyzer must provide the subsequent compiler phases additional information about the particular lexeme that matched.
- For example, the pattern for token **number** matches both 0 and 1, but it is extremely important for the code generator to know which lexeme was found in the source program.

Attributes for Tokens — *continued*

- Thus, in many cases the lexical analyzer returns to the parser not only a token name, but an attribute value that describes the lexeme represented by the token.
- The token name influences parsing decisions, while the attribute value influences translation of tokens after the parse.

Attributes for Tokens — *continued*

- We shall assume that tokens have at most one associated attribute, although this attribute may have a structure that combines several pieces of information.
- The most important example is the token **id**, where we need to associate with the token a great deal of information.

Attributes for Tokens — *continued*

- Normally, information about an identifier e.g.,
    - its lexeme,
    - its type,
    - and the location at which it is first found (in case an error message about that identifier must be issued)

  — is kept in the symbol table.
- Thus, the appropriate attribute value for an identifier is a pointer to the symbol-table entry for that identifier.

Example

- The token names and associated attribute values for the Fortran statement

  `E = M * C ** 2`

  are written below as a sequence of pairs.

  $<$**id**, pointer to symbol-table entry for `E`$>$
  $<$**assign-op**$>$
  $<$**id**, pointer to symbol-table entry for `M`$>$
  $<$**mult-op**$>$
  $<$**id**, pointer to symbol-table entry for `C`$>$
  $<$**exp-op**$>$
  $<$**number**, integer value 2$>$

Example — *continued*

- In certain pairs, especially operators, punctuation, and keywords, there is no need for an attribute value.
- In this example, the token **number** has been given an integer-valued attribute.
- In practice, a typical compiler would instead store a character string representing the constant and use as an attribute value for **number** as pointer to that string.

Lexical Errors

- It is hard for a lexical analyzer to tell, without the aid of other components, that there is a source-code error.
- For instance, if the string `fi` is encountered for the first time in a C program in the context:
  `fi ( a == f(x)) dots`
  a lexical analyzer cannot tell whether `fi` is a misspelling of the keyword `if` or an undeclared function identifier.
- Since `fi` is a valid lexeme for the token **id**, the lexical analyzer must return the token **id** to the parser and let some other phase of the compiler — probably the parser in this case — handle an error due to transposition of the letters.

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Lexical Errors — *continued*

- Suppose a situation does arise in which the lexical analyzer is unable to proceed because none of the patterns for tokens matches a prefix of the remaining input.
- Perhaps the simplest recovery strategy is “panic mode” recovery.
- We delete successive characters from the remaining input until the lexical analyzer can find a well-formed token.
- This recovery technique may occasionally confuse the parser, but in an interactive computing environment it may be quite adequate.

Lexical Errors — *continued*

Other possible error-recovery actions are:

1. deleting an extraneous character,
2. inserting a missing character,
3. replacing an incorrect character by a correct character,
4. transposing two adjacent characters.

Lexical Errors — *continued*

lexerror1.cpp

```
#include <iostream>
int main()
{
  `int i, j, k;
  return 0;
}
```

Response from gcc

```
lexerror1.cpp:4: error: stray ` in program
```

Lexical Errors — *continued*

lexerror2.cpp

```
int main()
{
  int 5test;

  return 0;
}
```

Response from gcc

```
lexerror2.cpp:3:7: error: invalid suffix
"test" on integer constant
```

Lexical Errors — *continued*

- Transformations like these may be tried in an attempt to repair the input.
- The simplest such strategy is to see whether a prefix of the remaining input can be transformed into a valid lexeme by a single transformation.
- This strategy makes sense, since in practice most lexical errors involve a single character.

Lexical Errors — *continued*

- A more general correction strategy is to find the smallest number of transformations needed to convert the source program into one that consists only of valid lexemes.
- But this approach is considered too expensive in practice to be worth the effort.

Input Buffering

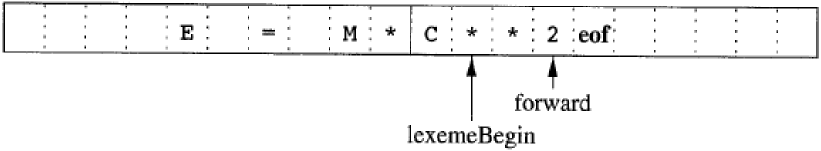
- Let us examine some ways that the simple but important task of reading the source program can be speeded.
- This task is made difficult by the fact that we often have to look one or more characters beyond the next lexeme before we can be sure we have the right lexeme.
- There are many situations where we need to look at least one additional character ahead.

Input Buffering — *continued*

- For instance, we cannot be sure we've seen the end of an identifier until we see a character that is not a letter or digit, and therefore is not part of the lexeme for id.
- In C, single-character operators like $-$, $=$, or $<$ could also be the beginning of a two-character operator like $->$, $==$, or $<=$.
- Thus, we shall introduce a two-buffer scheme that handles large lookaheads safely.
- We then consider an improvement involving "sentinels" that saves time checking for the ends of buffers.

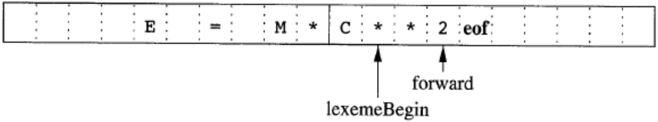
Buffer Pairs

- The amount of time taken is high to process characters of a large source program.
- Specialized buffering techniques have been developed to reduce the amount of overhead required to process a single input character.
- An important scheme involves two buffers that are alternately reloaded, as suggested in figure.



Using a pair of input buffers

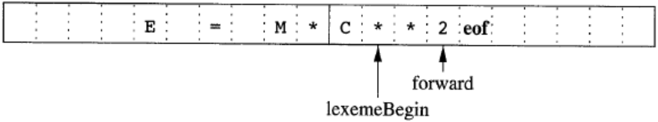
Buffer Pairs — *continued*



Using a pair of input buffers

- Each buffer is of the same size N.
- N is usually the size of a disk block, e.g., 4096 bytes.
- Using one system read command we can read N characters into a buffer, rather than using one system call per character.

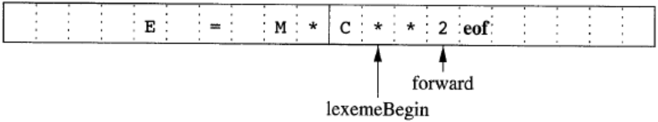
Buffer Pairs — *continued*



Using a pair of input buffers

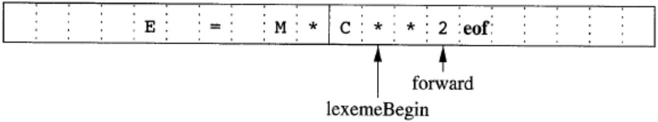
- If fewer than N characters remain in the input file, then a special character, represented by **eof**, marks the end of the source file.
- This **eof** is different from any possible character of the source program.

Buffer Pairs — *continued*



Using a pair of input buffers

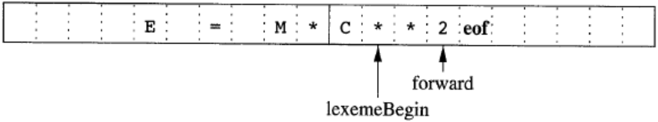
- Two pointers to the input are maintained:
  1. Pointer `lexemeBegin`, marks the beginning of the current lexeme, whose extent we are attempting to determine.
  2. Pointer `forward` scans ahead until a pattern match is found.



Using a pair of input buffers

- Once the next lexeme is determined, `forward` is set to the character at its right end.
- Then, after the lexeme is recorded as an attribute value of a token returned to the parser, `lexemeBegin` is set to the character immediately after the lexeme just found.
- In figure, we see `forward` has passed the end of the next lexeme, `**` (the Fortran exponentiation operator), and must be retracted one position to its left.

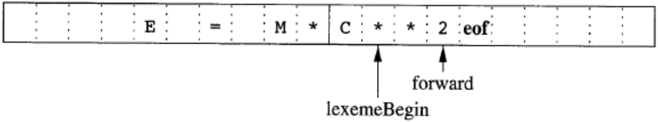
Buffer Pairs — *continued*



Using a pair of input buffers

- Advancing `forward` requires that we first test whether we have reached the end of one of the buffers.
- If so, we must reload the other buffer from the input.
- And move `forward` to the beginning of the newly loaded buffer.

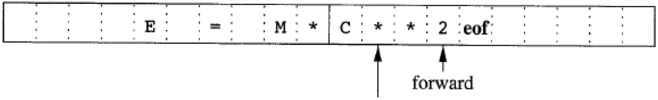
Buffer Pairs — *continued*



Using a pair of input buffers

- As long as we never need to look so far ahead of the actual lexeme that the sum of the lexeme's length plus the distance we look ahead is greater than N, we shall never overwrite the lexeme in its buffer before determining it.

Sentinels



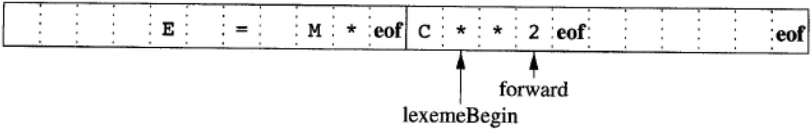
Using a pair of input buffers

- If we use the previous scheme as described, we must check, each time we advance forward, that we have not moved off one of the buffers.
- If we do, then we must also reload the other buffer.
- Thus, for each character read, we make two tests:
  - one for the end of the buffer.
  - And one to determine what character is read (the latter may be a multiway branch).

Sentinels — *continued*

- We can combine the buffer-end test with the test for the current character if we extend each buffer to hold a sentinel character at the end.
- The sentinel is a special character that cannot be part of the source program, and a natural choice is the character **eof**.

Sentinels — *continued*



Sentinels at the end of each buffer

- Figure shows the same arrangement as previous, but with the sentinels added.
- Note that **eof** retains its use as a marker for the end of the entire input.
- Any **eof** that appears other than at the end of a buffer means that the input is at an end.

```
switch ( *forward++ ) {
    case eof:
        if (forward is at end of first buffer ) {
            reload second buffer;
            forward = beginning of second buffer;
        }
        else if (forward is at end of second buffer ) {
            reload first buffer;
            forward = beginning of first buffer;
        }
        else /* eof within a buffer marks the end of input */
            terminate lexical analysis;
        break;
    Cases for the other characters
}
```

Lookahead code with sentinels

- Figure summarizes the algorithm for advancing forward.
- Notice how the first test, which can be part of a multiway branch based on the character pointed to by forward, is the only test we make, except in the case where we actually are at the end of a buffer or the end of the input.

Recognition of Tokens

- We can express patterns using regular expressions.

Recognition of Tokens

- Our discussion will make use of the following running example.

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \epsilon \\
expr & \rightarrow & term \textbf{ relop } term \\
 & | & term \\
term & \rightarrow & \textbf{id} \\
 & | & \textbf{number}
\end{array}
$$

A grammar for branching statements

Example

- The grammar fragment describes a simple form of branching statements and conditional expressions.
- This syntax is similar to that of the language Pascal, in that **then** appears explicitly after conditions.

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \epsilon \\
expr & \rightarrow & term \textbf{ relop } term \\
 & | & term \\
term & \rightarrow & \textbf{id} \\
 & | & \textbf{number}
\end{array}
$$

A grammar for branching statements

Example

- For **relop**, we use the comparison operators of languages like Pascal or SQL, where $=$ is "equals" and $<>$ is "not equals," because it presents an interesting structure of lexemes.

$$
\begin{array}{lcl}
stmt & \rightarrow & \textbf{if } expr \textbf{ then } stmt \\
 & | & \textbf{if } expr \textbf{ then } stmt \textbf{ else } stmt \\
 & | & \epsilon \\
expr & \rightarrow & term \textbf{ relop } term \\
 & | & term \\
term & \rightarrow & \textbf{id} \\
 & | & \textbf{number}
\end{array}
$$

A grammar for branching statements

Example

- The terminals of the grammar, which are **if**, **then**, **else**, **relop**, **id**, and **number**, are the names of tokens as far as the lexical analyzer is concerned.

$$
\begin{array}{lcl}
\mathit{stmt} & \rightarrow & \textbf{if}\ \mathit{expr}\ \textbf{then}\ \mathit{stmt} \\
 & | & \textbf{if}\ \mathit{expr}\ \textbf{then}\ \mathit{stmt}\ \textbf{else}\ \mathit{stmt} \\
 & | & \epsilon \\
\mathit{expr} & \rightarrow & \mathit{term}\ \textbf{relop}\ \mathit{term} \\
 & | & \mathit{term} \\
\mathit{term} & \rightarrow & \textbf{id} \\
 & | & \textbf{number}
\end{array}
$$

A grammar for branching statements

Example — *continued*

$$
\begin{array}{rcl}
digit & \to & [\texttt{0-9}] \\
digits & \to & digit^{+} \\
number & \to & digits\ (\texttt{.}\ digits)?\ (\ \texttt{E}\ [\texttt{+-}]?\ digits\ )? \\
letter & \to & [\texttt{A-Za-z}] \\
id & \to & letter\ (\ letter \mid digit\ )^{*} \\
if & \to & \texttt{if} \\
then & \to & \texttt{then} \\
else & \to & \texttt{else} \\
relop & \to & \texttt{<} \mid \texttt{>} \mid \texttt{<=} \mid \texttt{>=} \mid \texttt{=} \mid \texttt{<>}
\end{array}
$$

Patterns for tokens of Example

- The patterns for these tokens are described using regular definitions.

$$
\begin{array}{rcl}
\mathit{digit} & \rightarrow & \texttt{[0-9]} \\
\mathit{digits} & \rightarrow & \mathit{digit}^{+} \\
\mathit{number} & \rightarrow & \mathit{digits}\ (\texttt{.}\ \mathit{digits})?\ (\ \texttt{E}\ \texttt{[+-]}?\ \mathit{digits}\ )? \\
\mathit{letter} & \rightarrow & \texttt{[A-Za-z]} \\
\mathit{id} & \rightarrow & \mathit{letter}\ (\ \mathit{letter} \mid \mathit{digit}\ )^{*} \\
\mathit{if} & \rightarrow & \texttt{if} \\
\mathit{then} & \rightarrow & \texttt{then} \\
\mathit{else} & \rightarrow & \texttt{else} \\
\mathit{relop} & \rightarrow & \texttt{<} \mid \texttt{>} \mid \texttt{<=} \mid \texttt{>=} \mid \texttt{=} \mid \texttt{<>}
\end{array}
$$

Patterns for tokens of Example

- For this language, the lexical analyzer will recognize the keywords **if**, **then**, and **else**, as well as lexemes that match the patterns for *relop*, *id*, and *number*.

Example — *continued*

digit	$\rightarrow$	`[0-9]`
digits	$\rightarrow$	$digit^+$
number	$\rightarrow$	*digits* (`.` *digits*)? (`E` `[+-]`? *digits*)?
letter	$\rightarrow$	`[A-Za-z]`
id	$\rightarrow$	*letter* (*letter* | *digit*)*
if	$\rightarrow$	`if`
then	$\rightarrow$	`then`
else	$\rightarrow$	`else`
relop	$\rightarrow$	`<` | `>` | `<=` | `>=` | `=` | `<>`

Patterns for tokens of Example

- To simplify matters, we make the common assumption that keywords are also *reserved words*.
- They are not identifiers, even though their lexemes match the pattern for identifiers.

Example — *continued*

- In addition, we assign the lexical analyzer the job of stripping out white- space, by recognizing the “token” *ws* defined by:

$$ws \rightarrow (\textbf{blank} \mid \textbf{tab} \mid \textbf{newline})^{+}$$

- Here, **blank**, **tab**, and **newline** are abstract symbols that we use to express the ASCII characters of the same names.
- Token *ws* is different from the other tokens in that, when we recognize it, we do not return it to the parser.
- We rather restart the lexical analysis from the character that follows the whitespace.
- It is the following token that gets returned to the parser.

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
`if`	**if**	–
`then`	**then**	–
`else`	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
`<`	**relop**	`LT`
`<=`	**relop**	`LE`
`=`	**relop**	`EQ`
`<>`	**relop**	`NE`
`>`	**relop**	`GT`
`>=`	**relop**	`GE`

Tokens, their patterns, and attribute values

- Our goal for the lexical analyzer is summarized in figure.

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
if	**if**	–
then	**then**	–
else	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
<	**relop**	LT
<=	**relop**	LE
=	**relop**	EQ
<>	**relop**	NE
>	**relop**	GT
>=	**relop**	GE

Tokens, their patterns, and attribute values

- That table shows, for each lexeme or family of lexemes, which token name is returned to the parser and what attribute value is returned.

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
`if`	**if**	–
`then`	**then**	–
`else`	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
`<`	**relop**	`LT`
`<=`	**relop**	`LE`
`=`	**relop**	`EQ`
`<>`	**relop**	`NE`
`>`	**relop**	`GT`
`>=`	**relop**	`GE`

Tokens, their patterns, and attribute values

- Note that for the six relational operators, symbolic constants `LT`, `LE`, and so on are used as the attribute value, in order to indicate which instance of the token relop we have found.

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
`if`	**if**	–
`then`	**then**	–
`else`	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
`<`	**relop**	`LT`
`<=`	**relop**	`LE`
`=`	**relop**	`EQ`
`<>`	**relop**	`NE`
`>`	**relop**	`GT`
`>=`	**relop**	`GE`

Tokens, their patterns, and attribute values

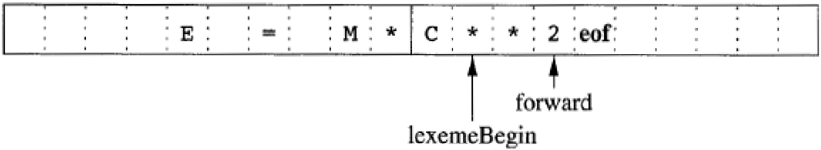
- The particular operator found will influence the code that is output from the compiler.

Transition Diagrams

- As an intermediate step in the construction of a lexical analyzer, we first convert patterns into stylized flowcharts, called “transition diagrams.”
- In this section, we perform the conversion from regular-expression patterns to transition diagrams by hand.
- Later we shall see that there is a mechanical way to construct these diagrams from collections of regular expressions.

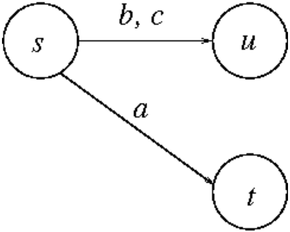
Transition Diagrams — *continued*

- Transition diagrams have a collection of nodes or circles, called states.
- Each state represents a condition that could occur during the process of scanning the input looking for a lexeme that matches one of several patterns.
- We may think of a state as summarizing all we need to know about what characters we have seen between the `lexemeBegin` pointer and the `forward` pointer.



Transition Diagrams — *continued*

- Edges are directed from one state of the transition diagram to another.
- Each edge is labeled by a symbol or set of symbols.
- If we are in some state s, and the next input symbol is a, we look for an edge out of state s labeled by a (and perhaps by other symbols, as well).
- If we find such an edge, we advance the forward pointer and enter the state of the transition diagram to which that edge leads.



- We shall assume that all our transition diagrams are deterministic, meaning that there is never more than one edge out of a given state with a given symbol among its labels.
- Later we shall relax the condition of determinism, making life much easier for the designer of a lexical analyzer, although trickier for the implementer.

Transition Diagrams — *continued*

Some important conventions about transition diagrams are:

1. Certain states are said to be accepting, or final.

- These states indicate that a lexeme has been found, although the actual lexeme may not consist of all positions between the `lexemeBegin` and `forward` pointers.
- We always indicate an accepting state by a double circle.
- If there is an action to be taken — typically returning a token and an attribute value to the parser - we shall attach that action to the accepting state.

Transition Diagrams — *continued*

Some important conventions about transition diagrams are:

2. In addition, if it is necessary to retract the forward pointer one position (i.e., the lexeme does not include the symbol that got us to the accepting state), then we shall additionally place a $*$ near that accepting state.

- In our example, it is never necessary to retract forward by more than one position, but if it were, we could attach any number of $*$'s to the accepting state.

Transition Diagrams — *continued*

Some important conventions about transition diagrams are:

3. One state is designated the start state, or initial state it is indicated by an edge, labeled "start ," entering from nowhere.

- The transition diagram always begins in the start state before any input symbols have been read.

1. Certain states are said to be accepting, or final.
   - These states indicate that a lexeme has been found, although the actual lexeme may not consist of all positions between the `lexemeBegin` and `forward` pointers.
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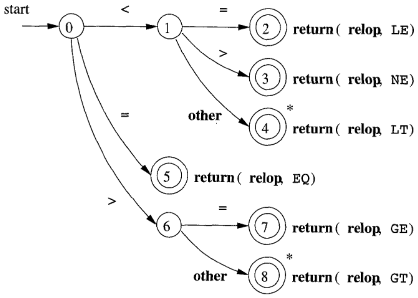
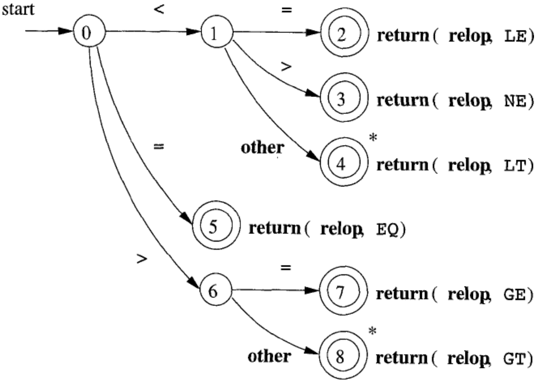


Transition diagram for **relop**

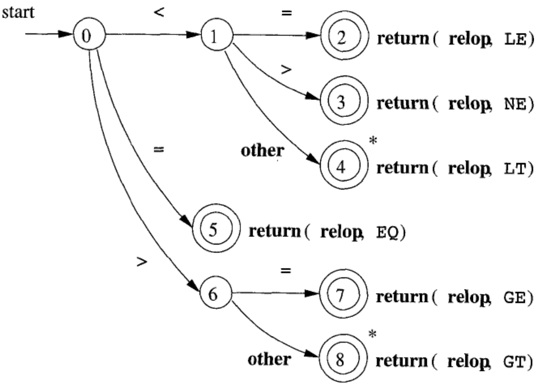
Example — *continued*

- We begin in state 0, the start state.
- If we see $<$ as the first input symbol, then among the lexemes that match the pattern for **relop** we can only be looking at $<$, $<>$, or $<=$.
- We therefore go to state 1, and look at the next character.

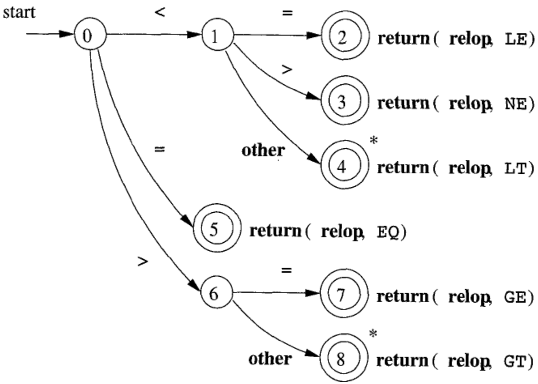


Example — *continued*

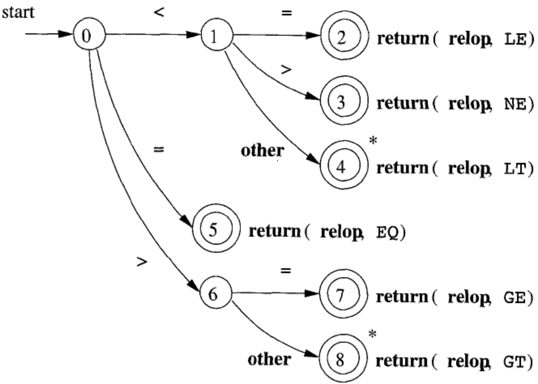
- If it is $=$, then we recognize lexeme $<=$, enter state 2, and return the token **relop** with attribute LE, the symbolic constant representing this particular comparison operator.
- If in state 1 the next character is $>$, then instead we have lexeme $<>$, and enter state 3 to return an indication that the not-equals operator has been found.



- On any other character, the lexeme is $<$, and we enter state 4 to return that information.
- Note, however, that state 4 has a $*$ to indicate that we must retract the input one position.

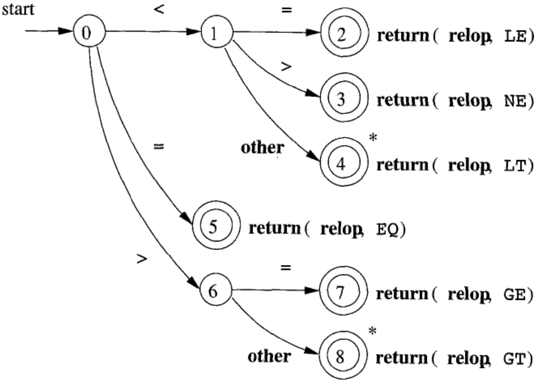


- On the other hand, if in state 0 the first character we see is $=$, then this one character must be the lexeme.
- We immediately return that fact from state 5.



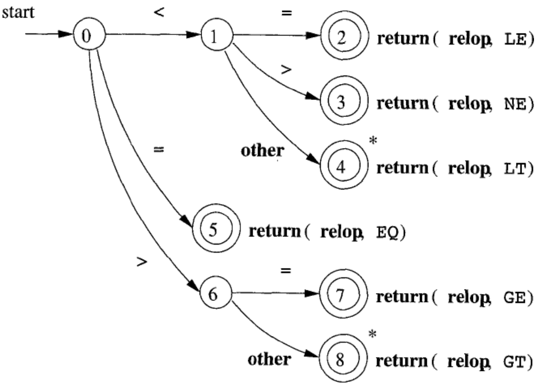
Example — *continued*

- The remaining possibility is that the first character is $>$.
- Then, we must enter state 6 and decide, on the basis of the next character, whether the lexeme is $>=$ (if we next see the $=$ sign), or just $>$ (on any other character).



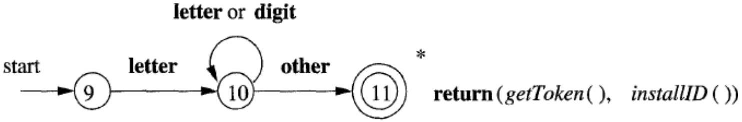
Example — *continued*

- Note that if, in state 0, we see any character besides $<$, $=$, or $>$, we can not possibly be seeing a **relop** lexeme, so this transition diagram will not be used.



Recognition of Reserved Words and Identifiers

- Recognizing keywords and identifiers presents a problem.
- Usually, keywords like `if` or `then` are reserved, so they are not identifiers even though they look like identifiers.
- Thus, we typically use a transition diagram like the following to search for identifier lexemes.



A transition diagram for **id**'s and keywords

- But, this diagram will also recognize the keywords `if`, `then`, and `else`.

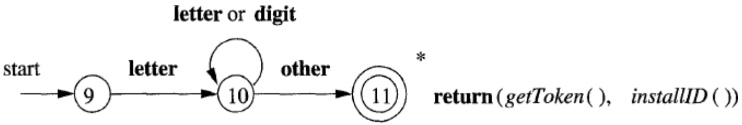
Recognition of Reserved Words and Identifiers — *continued*

- There are two ways that we can handle reserved words that look like identifiers.

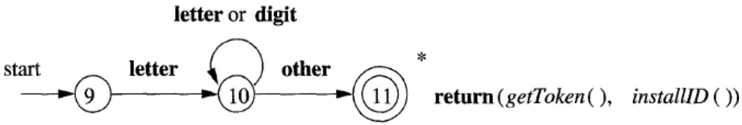
Recognition of Reserved Words and Identifiers — *continued*

1. Install the reserved words in the symbol table initially.

- A field of the symbol-table entry indicates that these strings are never ordinary identifiers, and tells which token they represent.
- This method is applicable below.



Recognition of Reserved Words and Identifiers — *continued*

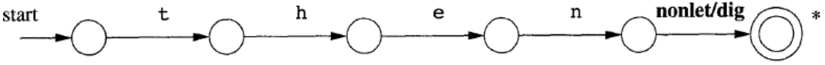


- When we find an identifier, a call to `installID` places it in the symbol table if it is not already there and returns a pointer to the symbol-table entry for the lexeme found.
- Of course, any identifier not in the symbol table during lexical analysis cannot be a reserved word, so its token is **id**.
- The function `getToken` examines the symbol table entry for the lexeme found, and returns whatever token name the symbol table says this lexeme represents - either **id** or one of the keyword tokens that was initially installed in the table.

Recognition of Reserved Words and Identifiers — *continued*

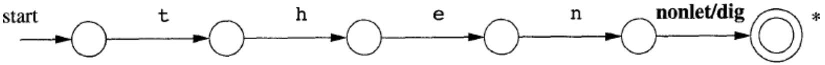
2. Create separate transition diagrams for each keyword.

- An example for the keyword `then` is shown in figure.



Hypothetical transition diagram for the keyword **then**

Recognition of Reserved Words and Identifiers — *continued*



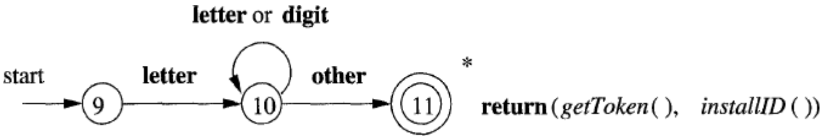
- Note that such a transition diagram consists of states representing the situation after each successive letter of the keyword is seen, followed by a test for a “nonletter-or-digit,” i.e., any character that cannot be the continuation of an identifier.
- It is necessary to check that the identifier has ended, or else we would return token then in situations where the correct token was **id**, with a lexeme like `thenextvalue` that has `then` as a proper prefix.

Recognition of Reserved Words and Identifiers — *continued*

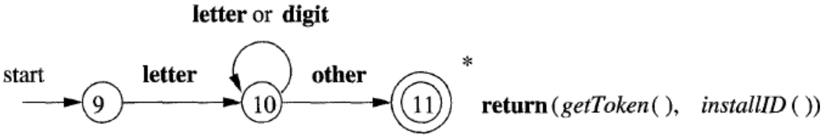
- If we adopt this approach, then we must prioritize the tokens so that the reserved-word tokens are recognized in preference to **id**, when the lexeme matches both patterns.

Completion of the Running Example

- The transition diagram for **id**'s in the figure below has a simple structure.

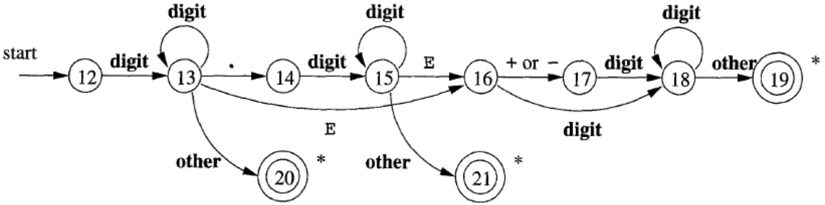


Completion of the Running Example — *continued*

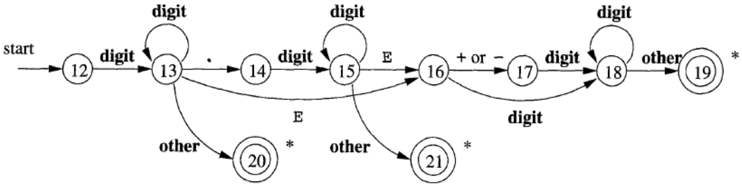


- Starting in state 9, it checks that the lexeme begins with a letter and goes to state 10 if so.
- We stay in state 10 as long as the input contains letters and digits.
- When we first encounter anything but a letter or digit, we go to state 11 and accept the lexeme found.
- Since the last character is not part of the identifier, we must retract the input one position.
- We enter what we have found in the symbol table and determine whether we have a keyword or a true identifier.

- The transition diagram for token **number** is shown in figure.



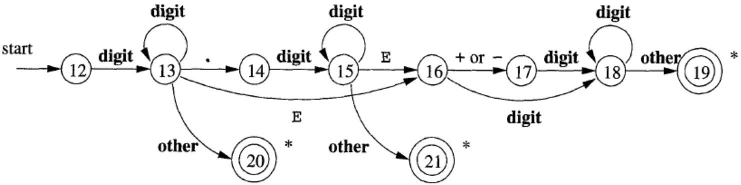
A transition diagram for unsigned numbers



123

- Beginning in state 12, if we see a digit, we go to state 13.
- In that state, we can read any number of additional digits.
- However, if we see anything but a digit or a dot, we have seen a number in the form of an integer.
- That case is handled by entering state 20, where we return token number and a pointer to a table of constants where the found lexeme is entered.

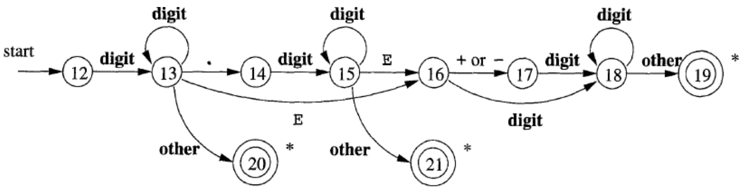
Completion of the Running Example — *continued*



123

- These mechanics are not shown on the diagram but are analogous to the way we handled identifiers.

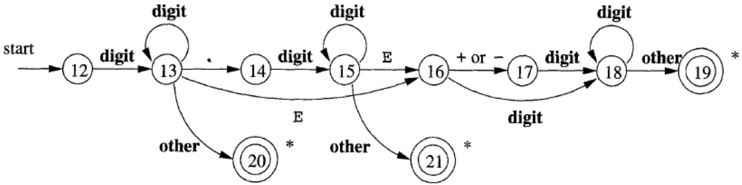
Completion of the Running Example — *continued*



123.456

- If we instead see a dot in state 13, then we have an "optional fraction."
- State 14 is entered, and we look for one or more additional digits; state 15 is used for that purpose.

Completion of the Running Example — *continued*

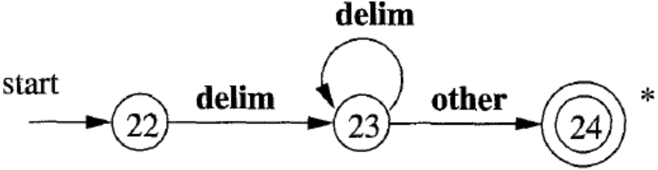


123.456E789   123.456E+789   123.456E-789

- If we see an E, then we have an "optional exponent," whose recognition is the job of states 16 through 19.
- Should we, in state 15, instead see anything but E or a digit, then we have come to the end of the fraction, there is no exponent, and we return the lexeme found, via state 21.

Completion of the Running Example — *continued*

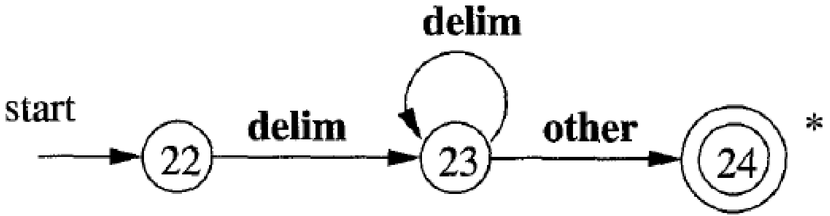
- Transition diagram for whitespace is shown.



A transition diagram for whitespace

- In that diagram, we look for one or more "whitespace" characters, represented by **delim** in that diagram.
- Typically these characters would be blank, tab, newline, and perhaps other characters that are not considered by the language design to be part of any token.

Completion of the Running Example — *continued*



- Note that in state 24, we have found a block of consecutive whitespace characters, followed by a nonwhitespace character.
- We retract the input to begin at the nonwhitespace, but we do not return to the parser.
- Rather, we must restart the process of lexical analysis after the whitespace.

Architecture of a Transition-Diagram-Based Lexical Analyzer

- There are several ways that a collection of transition diagrams can be used to build a lexical analyzer.
- Regardless of the overall strategy, each state is represented by a piece of code.
- We may imagine a variable `state` holding the number of the current state for a transition diagram.
- A switch based on the value of `state` takes us to code for each of the possible states, where we find the action of that state.
- Often, the code for a state is itself a switch statement or multiway branch that determines the next state by reading and examining the next input character.

Example

- In figure we see a sketch of `getRelop()`, a C++ function whose job is to simulate the transition diagram for **relop**.

```
TOKEN getRelop()
{
    TOKEN retToken = new(RELOP);
    while(1) { /* repeat character processing until a return
                  or failure occurs */
        switch(state) {
            case 0: c = nextChar();
                    if ( c == '<' ) state = 1;
                    else if ( c == '=' ) state = 5;
                    else if ( c == '>' ) state = 6;
                    else fail(); /* lexeme is not a relop */
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

Example

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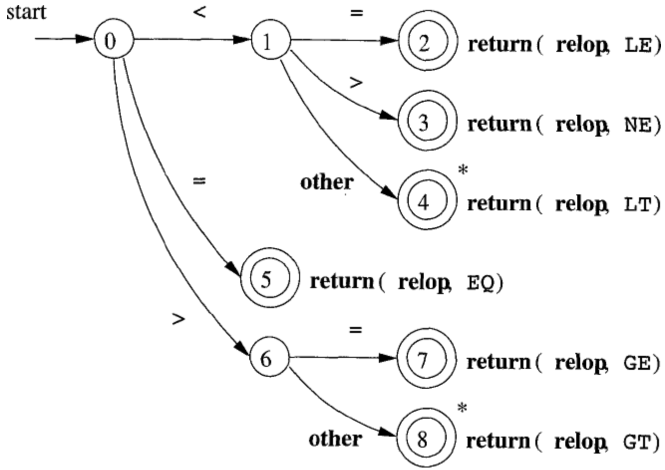

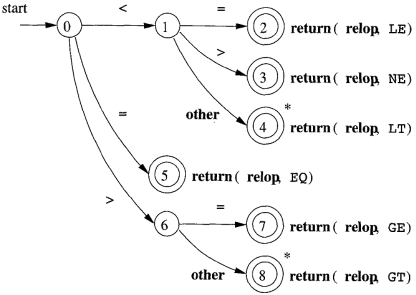


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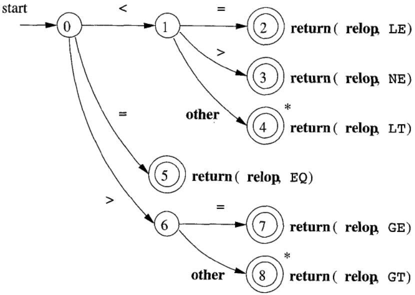
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- Function `getRelop()` returns an object of type `TOKEN`, that is, a pair consisting of the token name **relop** and an attribute value (the code for one of the six comparison operators in this case).
- `getRelop()` first creates a new object `retToken` and initializes its first component to RELOP, the symbolic code for token **relop**.

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                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```
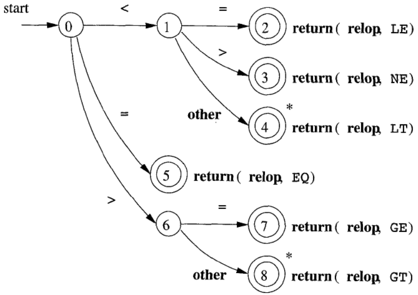

- We see the typical behavior of a state in case 0, the case where the current state is 0.
- A function `nextchar()` obtains the next character from the input and assigns it to local variable `c`.

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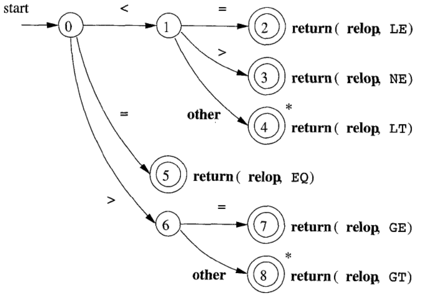
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- We then check `c` for the three characters we expect to find, making the state transition dictated by the transition diagram in each case.
- For example, if the next input character is $=$, we go to state 5.

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                    break;
            case 1: ...
            ...
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                    retToken.attribute = GT;
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}
```
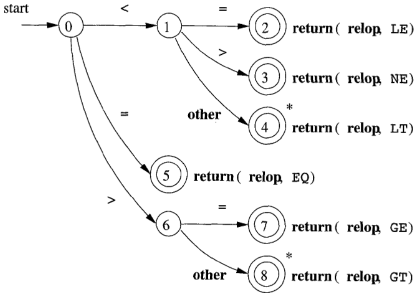

- If the next input character is not one that can begin a comparison operator, then a function `fail()` is called.
- What `fail()` does depends on the global error recovery strategy of the lexical analyzer.

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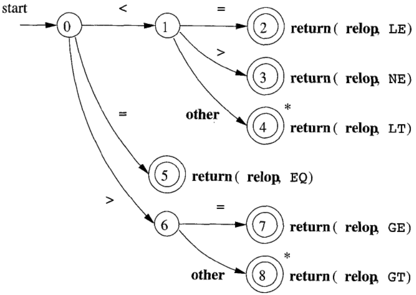
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- It should reset the forward pointer to `lexemeBegin`, in order to allow another transition diagram to be applied to the true beginning of the unprocessed input.
- It might then change the value of `state` to be the start state for another transition diagram, which will search for another token.

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            ...
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                    retToken.attribute = GT;
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```
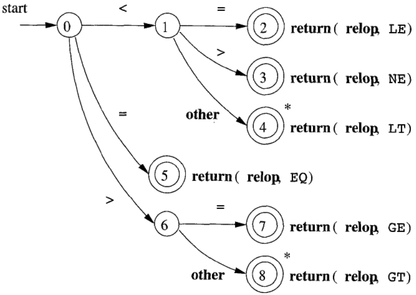

- Alternatively, if there is no other transition diagram that remains unused, `fail()` could initiate an error-correction phase that will try to repair the input and find a lexeme.

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            ...
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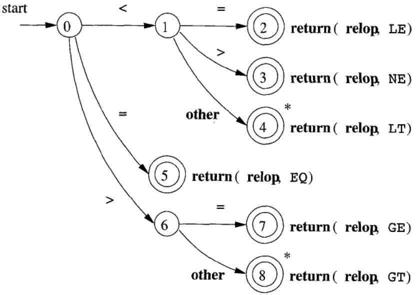
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- We also show the action for state 8.
- Because state 8 bears a $*$, we must retract the input pointer one position (i.e., put `c` back on the input stream).
- That task is accomplished by the function `retract()`.

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                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- Since state 8 represents the recognition of lexeme $>=$, we set the second component of the returned object, which we suppose is named `attribute`, to `GT`, the code for this operator.

Architecture of a . . . Lexical Analyzer — *continued*

- To place the simulation of one transition diagram in perspective, let us consider the ways code could fit into the entire lexical analyzer.

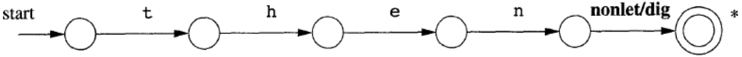
```
TOKEN getRelop()
{
    TOKEN retToken = new(RELOP);
    while(1) { /* repeat character processing until a return
                  or failure occurs */
        switch(state) {
            case 0: c = nextChar();
                    if ( c == '<' ) state = 1;
                    else if ( c == '=' ) state = 5;
                    else if ( c == '>' ) state = 6;
                    else fail(); /* lexeme is not a relop */
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

1. We could arrange for the transition diagrams for each token to be tried sequentially.

- Then, the function `fail()` resets the pointer forward and starts the next transition diagram, each time it is called.

```
TOKEN getRelop()
{
    TOKEN retToken = new(RELOP);
    while(1) { /* repeat character processing until a return
                  or failure occurs */
        switch(state) {
            case 0: c = nextChar();
                    if ( c == '<' ) state = 1;
                    else if ( c == '=' ) state = 5;
                    else if ( c == '>' ) state = 6;
                    else fail(); /* lexeme is not a relop */
                    break;
            case 1: ...
            ...
            case 8: retract();
                    retToken.attribute = GT;
                    return(retToken);
        }
    }
}
```

- This method allows us to use transition diagrams for the individual keywords.



- We have only to use these before we use the diagram for **id**, in order for the keywords to be reserved words.

Architecture of a . . . Lexical Analyzer — *continued*

2. We could run the various transition diagrams “in parallel,” feeding the next input character to all of them and allowing each one to make whatever transitions it required.

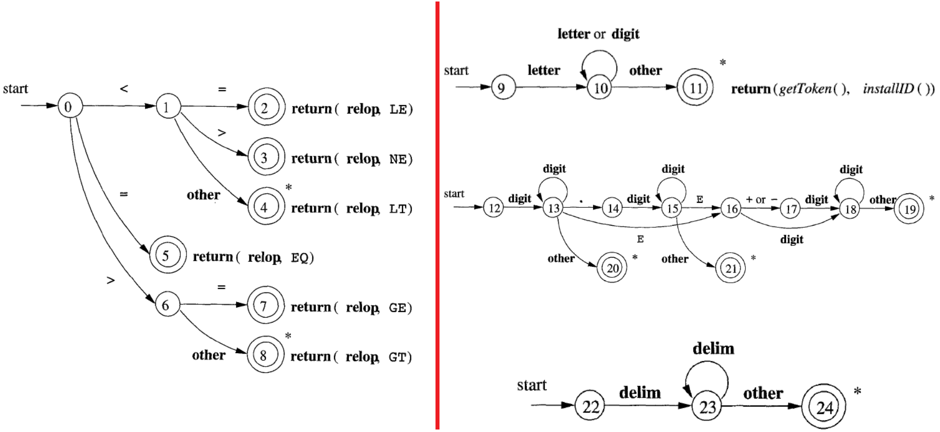
- If we use this strategy, we must be careful to resolve the case where one diagram finds a lexeme that matches its pattern, while one or more other diagrams are still able to process input.
- The normal strategy is to take the longest prefix of the input that matches any pattern.
- That rule allows us to prefer identifier `thenext` to keyword `then`, or the operator `->` to `-`, for example.

Architecture of a . . . Lexical Analyzer — *continued*

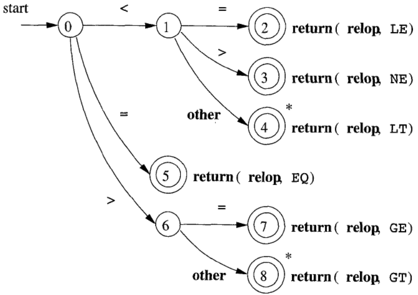
3. The preferred approach, is to combine all the transition diagrams into one.
   - We allow the transition diagram to read input until there is no possible next state.
   - And then take the longest lexeme that matched any pattern, as we discussed in item (2) above.

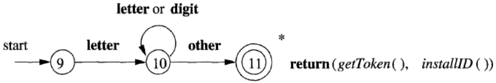
Architecture of a . . . Lexical Analyzer — *continued*

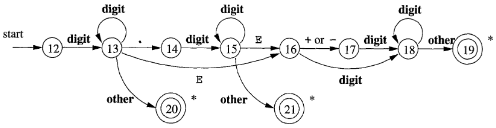
- In our running example, this combination is easy, because no two tokens can start with the same character.
- The first character immediately tells us which token we are looking for.

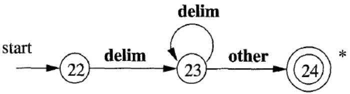


Architecture of a . . . Lexical Analyzer — *continued*









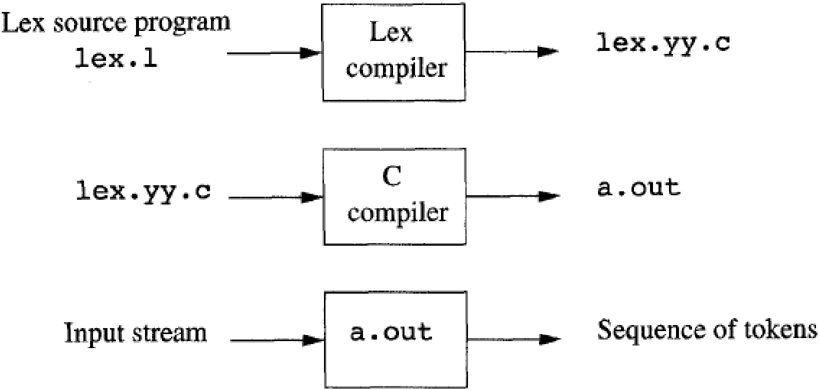
- Thus, we could simply combine states 0, 9, 12, and 22 into one start state, leaving other transitions intact.
- However, in general, the problem of combining transition diagrams for several tokens is more complex.

The Lexical- Analyzer Generator `Lex`

- We introduce a tool called `Lex`, or in a more recent implementation `Flex`.
- This allows one to specify a lexical analyzer by specifying regular expressions to describe patterns for tokens.
- The input notation for the `Lex` tool is referred to as the *Lex language* and the tool itself is the *Lex compiler*.
- Behind the scenes, the Lex compiler transforms the input patterns into a transition diagram and generates code, in a file called `lex.yy.c`, that simulates this transition diagram.

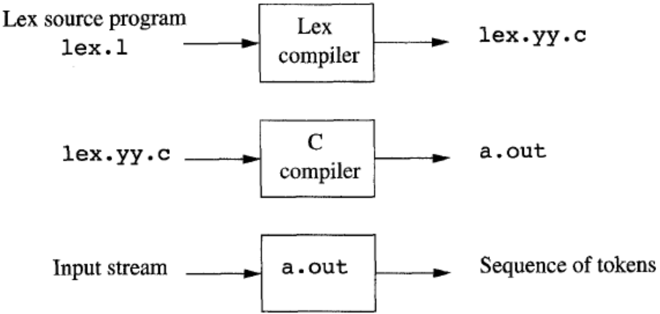
Use of Lex

- Figure suggests how Lex is used.



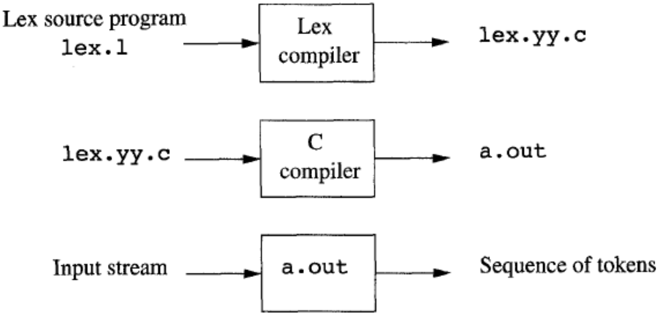
Creating a lexical analyzer with Lex

Use of Lex — *continued*



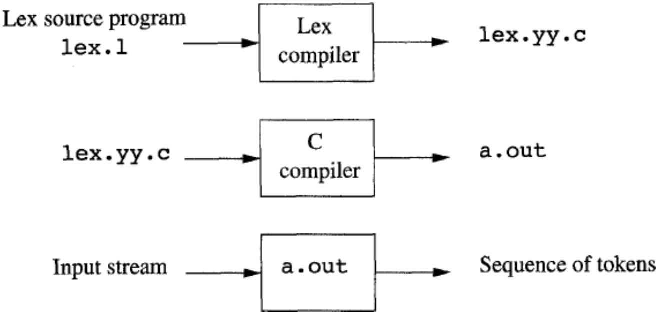
- An input file, which we call `lex.l`, is written in the Lex language and describes the lexical analyzer to be generated.
- The Lex compiler transforms `lex.l` to a C program, in a file that is always named `lex.yy.c`.

Use of Lex — *continued*



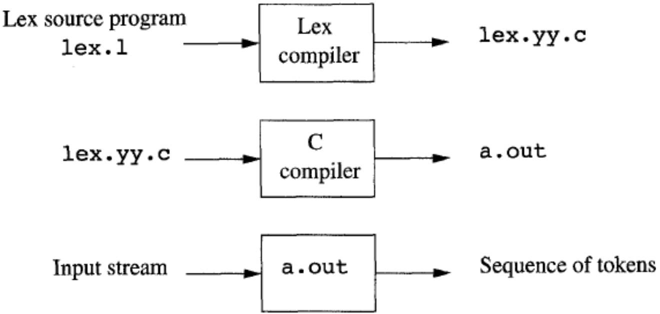
- The latter file is compiled by the C compiler into a file called `a.out`, as always.
- The C-compiler output is a working lexical analyzer that can take a stream of input characters and produce a stream of tokens.

Use of Lex — *continued*



- The normal use of the compiled C program, referred to as `a.out`, is as a subroutine of the parser.
- It is a C function that returns an integer, which is a code for one of the possible token names.

Use of Lex — *continued*



- The attribute value, whether it be another numeric code, a pointer to the symbol table, or nothing, is placed in a global variable `yylval` which is shared between the lexical analyzer and parser, thereby making it simple to return both the name and an attribute value of a token.

Structure of Lex Programs

- A Lex program has the following form:

```
declarations
%%
translation rules
%%
auxiliary functions
```

Structure of Lex Programs — *continued*

```
declarations
%%
translation rules
%%
auxiliary functions
```

- The declarations section includes
  - declarations of variables,
  - manifest constants (identifiers declared to stand for a constant, e.g., the name of a token),
  - and regular definitions.

Structure of Lex Programs — *continued*

```
declarations
%%
translation rules
%%
auxiliary functions
```

- The translation rules each have the form

  ```
  Pattern { Action }
  ```

- Each pattern is a regular expression, which may use the regular definitions of the declaration section.
- The actions are fragments of code, typically written in C, although many variants of Lex using other languages have been created.

Structure of Lex Programs — *continued*

```
declarations
%%
translation rules
%%
auxiliary functions
```

- The third section holds whatever additional functions are used in the actions.
- Alternatively, these functions can be compiled separately and loaded with the lexical analyzer.

Structure of Lex Programs — *continued*

- The lexical analyzer created by Lex behaves in concert with the parser as follows.
- When called by the parser, the lexical analyzer begins reading its remaining input, one character at a time, until it finds the longest prefix of the input that matches one of the patterns P_i.
- It then executes the associated action A_i.
- Typically, A_i will return to the parser.
- But if it does not (e.g., because P_i describes whitespace or comments), then the lexical analyzer proceeds to find additional lexemes, until one of the corresponding actions causes a return to the parser.
- The lexical analyzer returns a single value, the token name, to the parser, but uses the shared, integer variable `yylval` to pass additional information about the lexeme found, if needed.

Structure of Lex Programs — *continued*

- The lexical analyzer created by Lex behaves in concert with the parser as follows.
- When called by the parser, the lexical analyzer begins reading its remaining input, one character at a time, until it finds the longest prefix of the input that matches one of the patterns P_i.
- It then executes the associated action A_i.
- Typically, A_i will return to the parser.
- But if it does not (e.g., because P_i describes whitespace or comments), then the lexical analyzer proceeds to find additional lexemes, until one of the corresponding actions causes a return to the parser.
- The lexical analyzer returns a single value, the token name, to the parser, but uses the shared, integer variable `yylval` to pass additional information about the lexeme found, if needed.

Example

- Figure is a Lex program that recognizes the tokens of the definitions and returns the token found.

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT, GE,
    IF, THEN, ELSE, ID, NUMBER, RELOP */
%}

/* regular definitions */
delim     [ \t\n]
ws        {delim}+
letter    [A-Za-z]
digit     [0-9]
id        {letter}({letter}|{digit})*
number    {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%

{ws}      {/* no action and no return */}
if        {return(IF);}
then      {return(THEN);}
else      {return(ELSE);}
{id}      {yylval = (int) installID(); return(ID);}
{number}  {yylval = (int) installNum(); return(NUMBER);}
"<"       {yylval = LT; return(RELOP);}
"<="      {yylval = LE; return(RELOP);}
"="       {yylval = EQ; return(RELOP);}
"<>"      {yylval = NE; return(RELOP);}
">"       {yylval = GT; return(RELOP);}
">="      {yylval = GE; return(RELOP);}

%%

int installID() {/* function to install the lexeme, whose
                    first character is pointed to by yytext,
                    and whose length is yyleng, into the
                    symbol table and return a pointer
                    thereto */
}

int installNum() {/* similar to installID, but puts numer-
                     ical constants into a separate table */
}
```

Figure 3.23: Lex program for the tokens of Fig. 3.12

LEXEMES	TOKEN NAME	ATTRIBUTE VALUE
Any *ws*	–	–
if	**if**	–
then	**then**	–
else	**else**	–
Any *id*	**id**	Pointer to table entry
Any *number*	**number**	Pointer to table entry
<	**relop**	LT
<=	**relop**	LE
=	**relop**	EQ
<>	**relop**	NE
>	**relop**	GT
>=	**relop**	GE

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT, GE,
    IF, THEN, ELSE, ID, NUMBER, RELOP */
%}
```

- In the declarations section we see a pair of special brackets, `%{` and `%}`.
- Anything within these brackets is copied directly to the file `lex.yy.c`, and is not treated as a regular definition.
- It is common to place there the definitions of the manifest constants, using C `#define` statements to associate unique integer codes with each of the manifest constants.
- In our example, we have listed in a comment the names of the manifest constants, `LT`, `IF`, and so on, but have not shown them defined to be particular integer.

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT, GE,
    IF, THEN, ELSE, ID, NUMBER, RELOP */
%}
```

- In the declarations section we see a pair of special brackets, `%{` and `%}`.
- Anything within these brackets is copied directly to the file `lex.yy.c`, and is not treated as a regular definition.
- It is common to place there the definitions of the manifest constants, using C `#define` statements to associate unique integer codes with each of the manifest constants.
- In our example, we have listed in a comment the names of the manifest constants, `LT`, `IF`, and so on, but have not shown them defined to be particular integer.

Example — *continued*

```
/* regular definitions */
delim       [ \t\n]
ws          {delim}+
letter      [A-Za-z]
digit       [0-9]
id          {letter}({letter}|{digit})*
number      {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- Also in the declarations section is a sequence of regular definitions.
- These use the extended notation for regular expressions.

Example — *continued*

```
/* regular definitions */
delim       [ \t\n]
ws          {delim}+
letter      [A-Za-z]
digit       [0-9]
id          {letter}({letter}|{digit})*
number      {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- Regular definitions that are used in later definitions or in the patterns of the translation rules are surrounded by curly braces.
- Thus, for instance, *delim* is defined to be a shorthand for the character class consisting of the blank, the tab, and the newline.

Example — *continued*

```
/* regular definitions */
delim      [ \t\n]
ws         {delim}+
letter     [A-Za-z]
digit      [0-9]
id         {letter}({letter}|{digit})*
number     {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- The latter two are represented, as in all UNIX commands, by backslash followed by `t` or `n`, respectively.
- Then, `ws` is defined to be one or more delimiters, by the regular expression `{delim}`.

Example — *continued*

```
/* regular definitions */
delim       [ \t\n]
ws          {delim}+
letter      [A-Za-z]
digit       [0-9]
id          {letter}({letter}|{digit})*
number      {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- Notice that in the definition of *id* and *number*, parentheses are used as grouping metasymbols and do not stand for themselves.
- In contrast, `E` in the definition of *number* stands for itself.

Example — *continued*

```
/* regular definitions */
delim      [ \t\n]
ws         {delim}+
letter     [A-Za-z]
digit      [0-9]
id         {letter}({letter}|{digit})*
number     {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- If we wish to use one of the Lex metasymbols, such as any of the parentheses, `+`, `*`, or `?`, to stand for themselves, we may precede them with a backslash.

Example — *continued*

```
/* regular definitions */
delim      [ \t\n]
ws         {delim}+
letter     [A-Za-z]
digit      [0-9]
id         {letter}({letter}|{digit})*
number     {digit}+(\.{digit}+)?(E[+-]?{digit}+)?

%%
```

- For instance, we see `\.` in the definition of number, to represent the dot, since that character is a metasymbol representing “any character,” as usual in UNIX regular expressions.

```
int installID() {/* function to install the lexeme, whose
                     first character is pointed to by yytext,
                     and whose length is yyleng, into the
                     symbol table and return a pointer
                     thereto */
}

int installNum() {/* similar to installID, but puts numer-
                      ical constants into a separate table */
}
```

- In the auxiliary-function section, we see two such functions, `installID()` and `installNum()`.
- Like the portion of the declaration section that appears between `%{...%}` everything in the auxiliary section is copied directly to file `lex.yy.c`, but may be used in the actions.

```
{ws}       {/* no action and no return */}
if         {return(IF);}
then       {return(THEN);}
else       {return(ELSE);}
{id}       {yylval = (int) installID(); return(ID);}
{number}   {yylval = (int) installNum(); return(NUMBER);}
"<"        {yylval = LT; return(RELOP);}
"<="       {yylval = LE; return(RELOP);}
"="        {yylval = EQ; return(RELOP);}
"<>"       {yylval = NE; return(RELOP);}
">"        {yylval = GT; return(RELOP);}
">="       {yylval = GE; return(RELOP);}

%%
```

- Let us examine some of the patterns and rules in the middle section.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- First, `ws`, an identifier declared in the first section, has an associated empty action.
- If we find whitespace, we do not return to the parser, but look for another lexeme.

```
{ws}       {/* no action and no return */}
if         {return(IF);}
then       {return(THEN);}
else       {return(ELSE);}
{id}       {yylval = (int) installID(); return(ID);}
{number}   {yylval = (int) installNum(); return(NUMBER);}
"<"        {yylval = LT; return(RELOP);}
"<="       {yylval = LE; return(RELOP);}
"="        {yylval = EQ; return(RELOP);}
"<>"       {yylval = NE; return(RELOP);}
">"        {yylval = GT; return(RELOP);}
">="       {yylval = GE; return(RELOP);}

%%
```

- The second token has the simple regular expression pattern `if`.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- Should we see the two letters `if` on the input, and they are not followed by another letter or digit, then the lexical analyzer consumes these two letters from the input and returns the token name `IF`, that is, the integer for which the manifest constant `IF` stands.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- If we see letters or digits after `if` this would cause the lexical analyzer to find a longer prefix of the input matching the pattern for **id**.
- Keywords `then` and `else` are treated similarly.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- The fifth token has the pattern defined by **id**.
- Note that, although keywords like `if` match this pattern as well as an earlier pattern, Lex chooses whichever pattern is listed first in situations where the longest matching prefix matches two or more patterns.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- The action taken when id is matched is threefold.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

1. Function `installID()` is called to place the lexeme found in the symbol table.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

2. This function returns a pointer to the symbol table, which is placed in global variable `yylval`, where it can be used by the parser or a later component of the compiler.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- Note that `installID()` has available to it two variables that are set automatically by the lexical analyzer that Lex generates:

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

(a) `yytext` is a pointer to the beginning of the lexeme, analogous to `lexemeBegin`.

(b) `yyleng` is the length of the lexeme found.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

3. The token name `ID` is returned to the parser.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- The action taken when a lexeme matching the pattern number is similar, using the auxiliary function `installNum()`.

Conflict Resolution in `Lex`

- We have alluded to the two rules that `Lex` uses to decide on the proper lexeme to select, when several prefixes of the input match one or more patterns:
  1. Always prefer a longer prefix to a shorter prefix.
  2. If the longest possible prefix matches two or more patterns, prefer the pattern listed first in the Lex program.

Example

1. Always prefer a longer prefix to a shorter prefix.
2. If the longest possible prefix matches two or more patterns, prefer the pattern listed first in the Lex program.

- The first rule tells us to continue reading letters and digits to find the longest prefix of these characters to group as an identifier.
- It also tells us to treat $<=$ as a single lexeme, rather than selecting $<$ as one lexeme and $=$ as the next lexeme.
- The second rule makes keywords reserved, if we list the keywords before **id** in the program.

```
{ws}        {/* no action and no return */}
if          {return(IF);}
then        {return(THEN);}
else        {return(ELSE);}
{id}        {yylval = (int) installID(); return(ID);}
{number}    {yylval = (int) installNum(); return(NUMBER);}
"<"         {yylval = LT; return(RELOP);}
"<="        {yylval = LE; return(RELOP);}
"="         {yylval = EQ; return(RELOP);}
"<>"        {yylval = NE; return(RELOP);}
">"         {yylval = GT; return(RELOP);}
">="        {yylval = GE; return(RELOP);}

%%
```

- For instance, if `then` is determined to be the longest prefix of the input that matches any pattern, and the pattern `then` precedes **id**, then the token `THEN` is returned, rather than `ID`.

End of Slides