Compilerconstructie

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`http://www.liacs.nl/home/rvvliet/coco/`

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Symbol Table / Lexical Analysis

2.7 Symbol Table

- Symbol table holds information about *source-program constructs* (e.g., identifiers)
  - string
  - additional information (type, position in storage)

- Symbol table is globally accessible (to all phases of compiler)

- Information is collected incrementally by analysis phases, and used by synthesis phases

- Implementation by Hashtable, with methods
  - *put (String, Symbol)*
  - *get (String)*

Symbol Table Per Scope

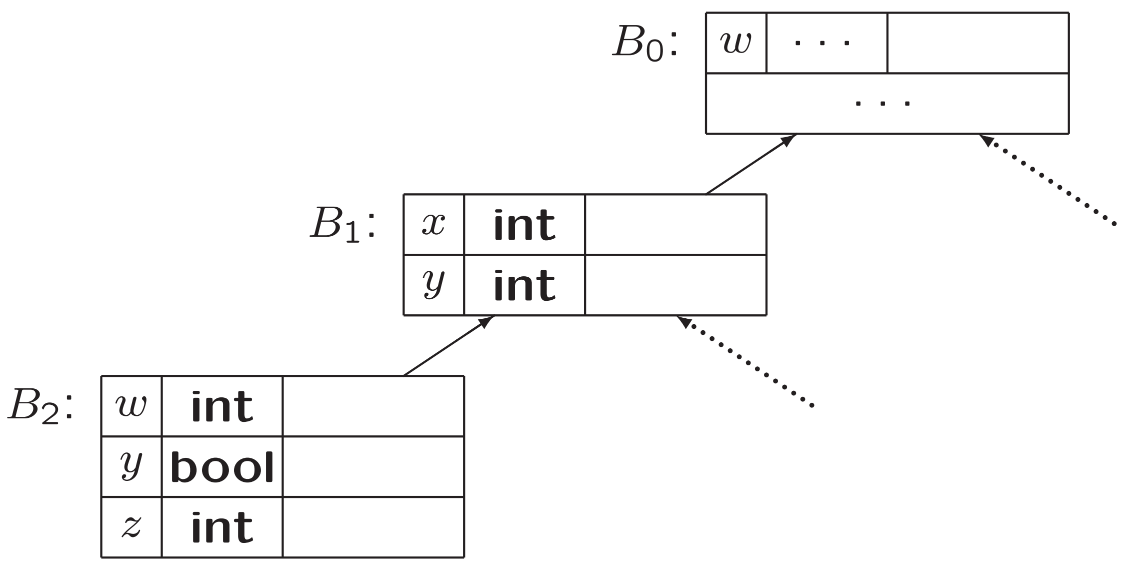
The same identifier may be declared more than once

```
{ int x; int y;
  { int w; bool y; int z;
    ... w ...; ... x ...; ... y ...; ... z ...;
  }
  ... w ...; ... x ...; ... y ...;
}
```

Symbol Table Per Scope

The same identifier may be declared more than once

```
1)  { int x1; int y1;
2)    { int w2; bool y2; int z2;
3)      ... w2 ...; ... x1 ...; ... y2 ...; ... z2 ...;
4)    }
5)    ... w0 ...; ... x1 ...; ... y1 ...;
6)  }
```



Implementation Symbol Table

(in Java)

```
public class Env
{ private Hashtable table;
  protected Env prev;

  public Env (Env p)
  { table = new Hashtable();
    prev = p;
  }

  public void put (String s, Symbol sym)
  { table.put (s, sym);
  }

  public Symbol get (String s);
  { for (Env e=this; e!=null; e=e.prev)
    { Symbol found = (Symbol)(e.table.get(s));
      if (found != null)
        return found;
    }
    return null;
  }
}
```

Translation Scheme (Example)

(from college 1)

$$
\begin{array}{rcl}
\mathit{expr} & \rightarrow & \mathit{expr}_1 + \mathit{term}\ \{\text{print('+')}\} \\
\mathit{expr} & \rightarrow & \mathit{expr}_1 - \mathit{term}\ \{\text{print('−')}\} \\
\mathit{expr} & \rightarrow & \mathit{term} \\
\mathit{term} & \rightarrow & 0\ \{\text{print('0')}\} \\
\mathit{term} & \rightarrow & 1\ \{\text{print('1')}\} \\
\ldots & & \ldots \\
\mathit{term} & \rightarrow & 9\ \{\text{print('9')}\}
\end{array}
$$

Example: parse tree for $9 - 5 + 2$

Implementation requires postorder traversal

CFG for Program with Blocks

$$
\begin{array}{lcl}
\textit{program} & \rightarrow & \textit{block} \\
\textit{block} & \rightarrow & '\{' \textit{decls stmts } '\}' \\
\textit{decls} & \rightarrow & \textit{decls decl} \\
 & | & \epsilon \\
\textit{decl} & \rightarrow & \textbf{type id}; \\
\textit{stmts} & \rightarrow & \textit{stmts stmt} \\
 & | & \epsilon \\
\textit{stmt} & \rightarrow & \textit{block} \\
 & | & \textit{factor};
\end{array}
$$

The Use of Symbol Tables

program	$\rightarrow$		$\{$ *top* $=$ **null**; $\}$
		block	
block	$\rightarrow$	$'\{'$	$\{$ *saved* $=$ *top*; *top* $=$ **new** *Env*(*top*); $\}$
		decls stmts $'\}'$	$\{$ *top* $=$ *saved*; $\}$
decls	$\rightarrow$	*decls decl*	
	$\mid$	ϵ	
decl	$\rightarrow$	**type id**;	$\{$ s $=$ **new** *Symbol*; s.*type* $=$ **type**.*lexeme*; *top*.*put*(**id**.*lexeme*, s); $\}$

In book (edition 2) extended for real translation

2.6 Lexical Analyser

Reads and converts the input into a stream of tokens to be analysed by the parser

Lexeme: Sequence of input characters comprising single token

Typical tasks of the lexical analyser

- Remove white space and comments
- Encode constants as tokens:
  $$31 + 28 + 59 \rightarrow \langle \textbf{num}, 31 \rangle \; \langle + \rangle \; \langle \textbf{num}, 28 \rangle \; \langle + \rangle \; \langle \textbf{num}, 59 \rangle$$
- Recognize keywords
- Recognize identifiers:
  $$\texttt{count} = \texttt{count} + \texttt{increment}; \quad \rightarrow$$
  $$\langle \textbf{id}, "\texttt{count}" \rangle \; \langle = \rangle \; \langle \textbf{id}, "\texttt{count}" \rangle \; \langle + \rangle \; \langle \textbf{id}, "\texttt{increment}" \rangle \; \langle ; \rangle$$

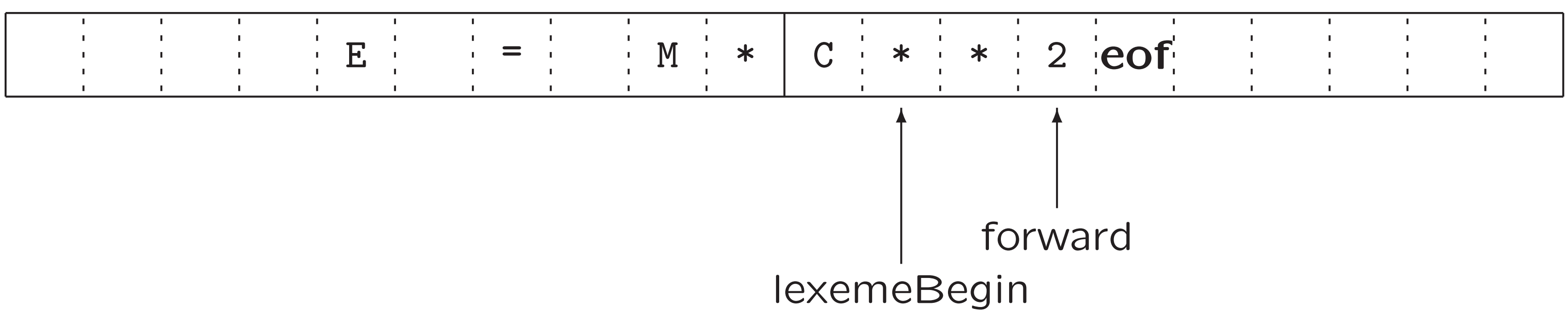
Lexical analyser may need to read ahead (with input buffer)

3.2 Input Buffering

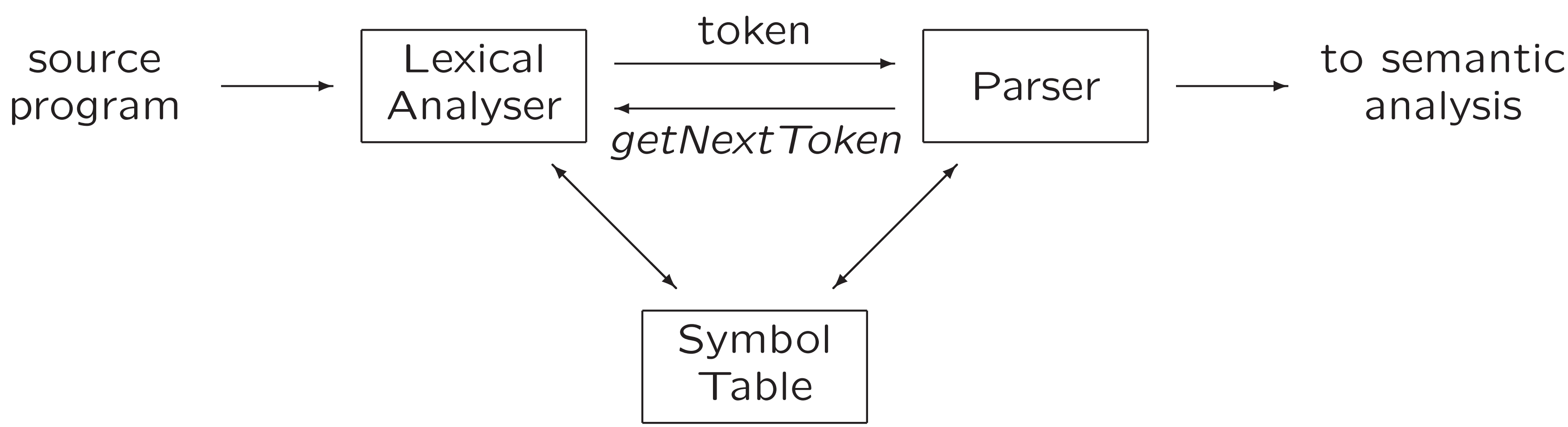
Use two buffers of size N for input

- Saves time
- Allows for looking ahead one or more characters, e.g., for
  - identifiers: `ifoundit`
  - relational operators: `<=`

Take longest prefix of input that matches any pattern



3.1 Lexical Analyser - Parser Interaction



Lexical Analyser

Reasons why it is a separate phase of a compiler

- Simplifies the design of the compiler
- Provides efficient implementation
  - Systematic techniques to implement lexical analysers (by hand or automatically)
- Improves portability
  - Non-standard symbols and alternate character encodings can be more easily translated (only relevant for lexical analyser)

Tokens, Patterns and Lexemes

- Token: pair of token name and optional attribute value, e.g., $\langle \textbf{id}, 1\rangle, \langle \textbf{num}, 31\rangle, \langle \textbf{assign\_op}\rangle$
- Lexeme: specific sequence of characters that makes up token, e.g., `count`, `31`, `=`
- Pattern: description of form that lexemes of a token may take

Examples of Tokens

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`
literal	anything but `"`, surrounded by `"`'s	`"core dumped"`

Attributes for Tokens

`E = M * C ** 2`

↓

Lexical Analyser

↓

⟨**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⟩

↓

Parser

Lexical Errors

- Hard to detect by lexical analyser alone, e.g.,

```
fi ( a == f(x) ) ...
```

- What if none of the patterns matches?
  - 'Panic mode' recovery: delete characters until you find well-formed token
  - * Delete one character from remaining input
    * Insert missing character into remaining input
    * Replace character by another character
    * Transpose two adjacent characters

Implementing a Lexical Analyser

- By hand,
  using transition diagram to specify lexemes

- With a lexical-analyser generator (`Lex`),
  using regular expressions to specify lexemes:

  Regular expressions $\rightarrow$
      (non-deterministic) finite automaton $\rightarrow$
      determininistic finite automaton
  Input to 'driver'

3.3 Specification of Tokens

Regular expressions to specify patterns for tokens

Terminology (from FI1)

- An alphabet Σ is a finite set of symbols (characters), e.g., $\{0, 1\}$, ASCII, Unicode

- A string s is a finite sequence of symbols from Σ
  - $|s|$ denotes the length of string s, e.g., $|\text{banana}| = 6$
  - ϵ denotes an empty string: $|\epsilon| = 0$

- A language is a set of strings over some fixed alphabet Σ

String operations

- Concatenation of strings x and y is denoted as xy
  e.g., if $x = \texttt{dog}$ and $y = \texttt{house}$ then $xy = \texttt{doghouse}$
  $s\epsilon = \epsilon s = s$

- Exponentiation
  - Define

$$\begin{aligned} s^0 &= \epsilon \\ s^i &= s^{i-1}s \quad \text{if } i > 0 \end{aligned}$$

  - Then

$$\begin{aligned} s^1 &= s \\ s^2 &= ss \\ s^3 &= sss \end{aligned}$$

Language Operations

- Union $L \cup D = \{s \mid s \in L \text{ or } s \in D\}$
- Concatenation $LD = \{xy \mid x \in L \text{ and } y \in D\}$
- Exponentiation $L^0 = \{\epsilon\}; \quad L^i = L^{i-1}L \quad \text{if } i > 0$
- Kleene closure $L^* = \cup_{i=0,\ldots,\infty} L^i$
  (zero or more concatenation)
- Positive closure $L^+ = \cup_{i=1,\ldots,\infty} L^i$
  (one or more concatenation)

Language Operations (Example)

Let alphabets $L = \{\mathtt{A}, \mathtt{B}, \ldots, \mathtt{Z}, \mathtt{a}, \mathtt{b}, \ldots, \mathtt{z}\}$ and $D = \{0, 1, \ldots, 9\}$

- $L \cup D$ is set of letters and digits
- LD is set of strings consisting of a letter followed by a digit
- L^4 is set of all four-letter strings
- L^* is set of all finite strings of letters, including ϵ
- $L(L \cup D)^*$ is set of all strings of letters and digits beginning with a letter ('identifiers')
- D^+ is set of all strings of one or more digits ('nonnegative integers')

Regular Expressions (Example)

In C, an identifier is a letter followed by zero or more letters or digits (underscore is considered letter):

$$\mathit{letter\_}\ (\mathit{letter\_}\ \mid \mathit{digit}\ )^*$$

Regular Expressions (Definition)

- Each regular expression r denotes a language $L(r)$

- Defining rules:
  - ϵ is regular expression, and $L(\epsilon) = \{\epsilon\}$
  - if $a \in \Sigma$, then **a** is regular expression, and $L(\mathbf{a}) = \{a\}$.
  - if r and s are regular expressions, then
    * $(r) \mid (s)$ is regular expression denoting $L(r) \cup L(s)$
    * $(r)(s)$ is regular expression denoting $L(r)L(s)$
    * $(r)^*$ is regular expression denoting $(L(r))^*$
    * (r) is regular expression denoting $L(r)$

Regular Expressions (Example)

- Remove unnecessary parentheses by assuming precedence relation between $*$, concatenation, and $|$, e.g.,
  $(\mathbf{a}) \mid ((\mathbf{b})^*(\mathbf{c}))$ is equivalent to $\mathbf{a} \mid \mathbf{b}^*\mathbf{c}$

- Let $\Sigma = \{a, b\}$. Then the regular expression:
  - $\mathbf{a} \mid \mathbf{b}$ denotes the set $\{a, b\}$
  - $(\mathbf{a} \mid \mathbf{b})(\mathbf{a} \mid \mathbf{b})$ denotes the set $\{aa, ab, ba, bb\}$
  - $\mathbf{a}^*$ denotes the set $\{\epsilon, a, aa, aaa, \ldots\}$
  - $(\mathbf{a} \mid \mathbf{b})^*$ denotes the sets of all strings over $\{a, b\}$
  - $\mathbf{a} \mid \mathbf{a}^*\mathbf{b}$ denotes the string a and all strings consisting of zero or more a's followed by one b

- If r and s denote the same language L, then $r = s$, e.g., $(\mathbf{a} \mid \mathbf{b}) = (\mathbf{b} \mid \mathbf{a})$

Regular Definitions

- A regular definition is a sequence of definitions of the form:

$$\begin{array}{rcl} d_1 & \rightarrow & r_1 \\ d_2 & \rightarrow & r_2 \\ & \cdots & \\ d_n & \rightarrow & r_n \end{array}$$

  where r_i is a regular expression over $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$

- Obtain regular expression over Σ by . . .

Regular Definitions

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$$\begin{array}{rcl} d_1 & \to & r_1 \\ d_2 & \to & r_2 \\ & \cdots & \\ d_n & \to & r_n \end{array}$$

  where r_i is a regular expression over $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$

- Obtain regular expression over Σ by successively substituting d_j $(j = 1, 2, \ldots, n-1)$ in $r_{j+1}, \ldots, r_n$ by (r_j)

Regular Definitions (Example)

- Identifiers in C

$$
\begin{aligned}
\textit{letter\_} &\rightarrow \texttt{A} \mid \texttt{B} \mid \ldots \mid \texttt{Z} \mid \texttt{a} \mid \texttt{b} \mid \ldots \mid \texttt{z} \mid \texttt{\_} \\
\textit{digit} &\rightarrow 0 \mid 1 \mid \ldots \mid 9 \\
\textit{id} &\rightarrow \textit{letter\_}(\textit{letter\_} \mid \textit{digit})^*
\end{aligned}
$$

- Recursion is not allowed

$$
\begin{aligned}
\textit{digit} &\rightarrow \textit{digit}(\textit{digit})^* & \text{not OK} \\
\textit{digits} &\rightarrow \textit{digit}(\textit{digit})^* & \text{OK}
\end{aligned}
$$

Notational Shorthands

- We often use the following shorthands:
  - one-or-more instance of: $r^+ = rr^*$
  - zero-or-one instance of: $r? = r \mid \epsilon$
  - character classes: $[\mathbf{abd}] = \mathbf{a} \mid \mathbf{b} \mid \mathbf{d}$

    $[\mathbf{a} - \mathbf{z}] = \mathbf{a} \mid \mathbf{b} \mid \ldots \mid \mathbf{z}$

- Example, unsigned numbers:

  5280, 0.01234, 6.336E4, 1.89E-4

$$\begin{array}{rcl} \textit{digit} & \rightarrow & [0 - 9] \\ \textit{digits} & \rightarrow & \textit{digit}^+ \\ \textit{number} & \rightarrow & \textit{digits}(.\textit{digits})?(E[+-]?\textit{digits})? \end{array}$$

3.4 Recognition of Tokens

Grammar for branching statements:

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

Terminals are **if**, **then**, **else**, **relop**, **id** and **number**.
These are the names of the tokens.

Regular Definitions for Tokens

Regular definitions describing patterns for these tokens

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

Regular definition for white space

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

Lexemes and Their Tokens

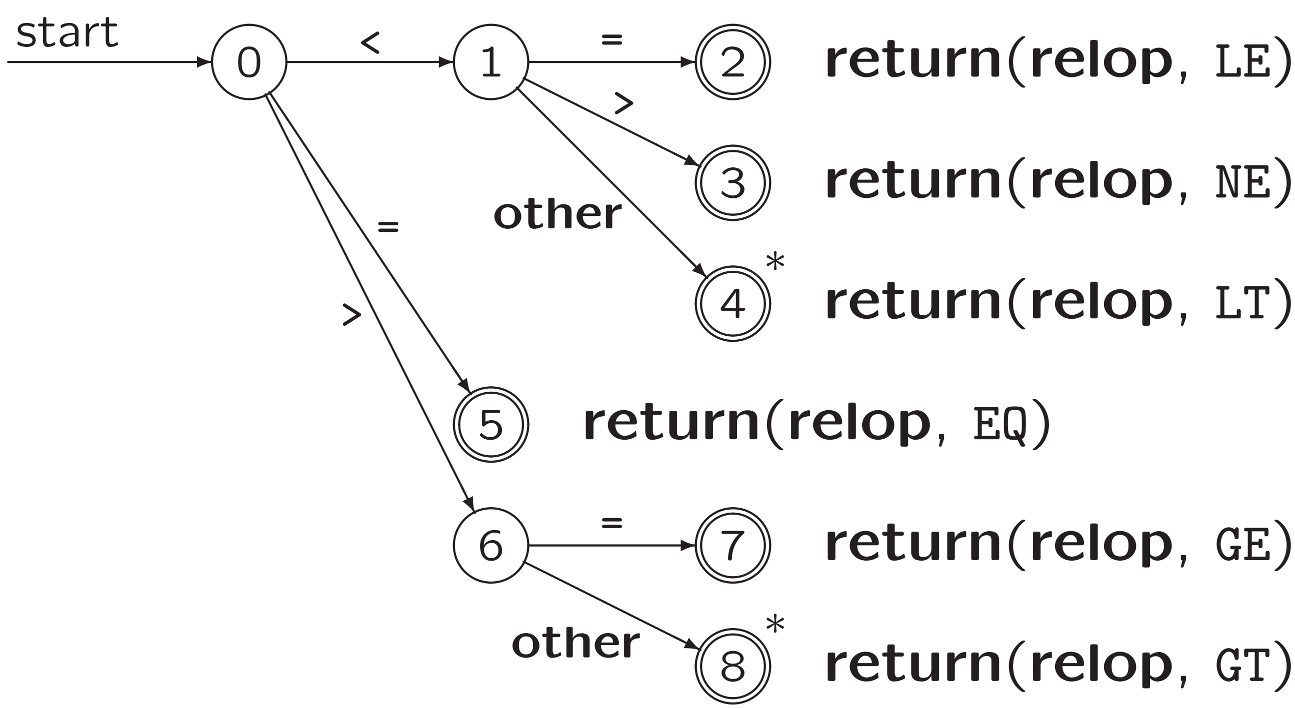
Goal:

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

Transition Diagrams

('Almost finite automata')

$$relop \rightarrow < \mid > \mid <= \mid >= \mid = \mid <>$$



Retract input one position, if necessary ($*$)

Transition Diagrams

Identifiers and keywords

$$id \rightarrow letter(letter \mid digit)^*$$

How to distinguish between identifiers and (reserved) keywords?

Transition Diagrams

How to distinguish between identifiers and (reserved) keywords?
Two possibilities:

- Install reserved words in symbol table initially
  Used in above diagram

- Separate transition diagram for each keyword
  Try these first, before the diagram for identifiers

From Diagram to Lexical Analyser

```
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);
    }
  }
}
```

Entire Lexical Analyser

Based on transition diagrams for different tokens
How?

Entire Lexical Analyser

Based on transition diagrams for different tokens
Three possibilities:

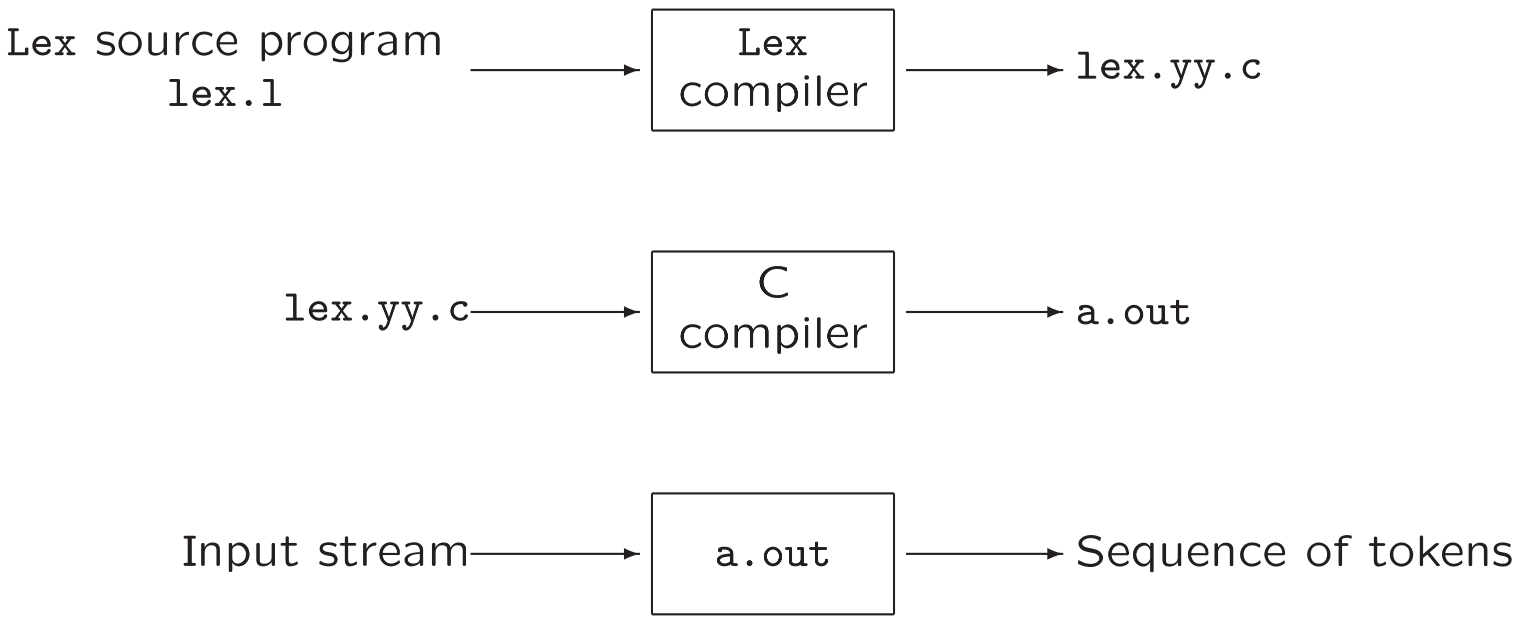
- Try transition diagrams sequentially (in right order)

- Run transition diagrams in parallel
  Make sure to take longest prefix of input that matches any pattern

- Combine all transition diagrams into one

3.5 The Lexical-Analyser Generator Lex

Systematically translates regular definitions into C source code for efficient scanning



Structure of Lex Programs

- A `Lex` program has the following form

```
declarations
%%
translation rules
%%
user defined auxiliary functions
```

- Translation rules are of the form

  Pattern { Action }

  Patterns are `Lex` regular expressions

Operation of Lexical Analyser

The lexical analyser generated by `Lex`

- Activated by parser
- Reads input character by character
- Executes action A_i corresponding to pattern P_i
- Typically, A_i returns to the parser
- If not (e.g., in case of white space), proceed to find additional lexemes
- Lexical analyser returns single value: the token name
- Attribute value passed through global variable `yylval`

Regular Definitions for Tokens

Regular definitions describing patterns for these tokens

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

Regular definition for white space

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

Lexemes and Their Tokens

Goal:

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

The Lex Program (program.l)

```
/* declarations section */
%{
    /* definitions of constants */
#define LT 256
    /* etcetera for 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}+)?
```

The Lex Program (program.l)

```
%%
/* translation rules 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);}

%%
/* auxiliary functions section */
int installID() {...}
int installNum() {...}
```

Regular expressions in Lex

Operator characters: `\ " . ^ $ [ ] * + ? { } | /`

Expression	Matches	Example
c	non-operator character c	`a`
$\backslash c$	operator charater c literally	`\*`
$"s"$	string s literally	`"**"`
.	any character but newline	`a.*b`
^	beginning of a line	`^abc`
$	end of a line	`abc$`
$[s]$	any one of the characters in string s	`[abc]`
$[\hat{}s]$	any one character not in string s	`[^abc]`
$[c_1 - c_2]$	any one character between c_1 and c_2	`[a-z]`
$r*$	zero or more strings matching r	`a*`
$r+$	one or more strings matching r	`a+`
$r?$	zero or one string matching r	`a?`
$r\{m,n\}$	between m and n occurrences of r	`a{1,5}`
$r_1 r_2$	an r_1 followed by an r_2	`ab`
$r_1 \mid r_2$	an r_1 or an r_2	`a|b`
(r)	same as r	`(a|b)`
r_1/r_2	r_1 when followed by r_2	`abc/123`
$\{d\}$	regular expression defined by d	`{id}`

Lex Details

- installID()
  function to install the lexeme into the symbol table
  returns pointer to symbol table entry
  `yytext` – pointer to the first character of the lexeme
  `yyleng` – length of the lexeme

- installNum()
  similar to installID, but puts numerical constants into a separate table

Lex Details

- Example: input "\t\tif "
  - Longest initial prefix: "\t\t" = *ws*
    No action, so `yytext` points to 'i' and continue
  - Next lexeme is "if"
    Token **if** is returned, `yytext` points to 'i' and `yyleng`=2
- Ambiguity and longest pattern matching:
  - Patterns `if` and {id} match lexeme "if"
  - If input is "<=", then lexeme is "<="
- ```
  lex program.l
  gcc lex.yy.c -ll
  ./a.out < input
  ```
  ```

Compiler constructie

college 2
Symbol Table / Lexical Analysis

Chapters for reading: 2.6, 2.7, 3.1–3.5