Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-15/
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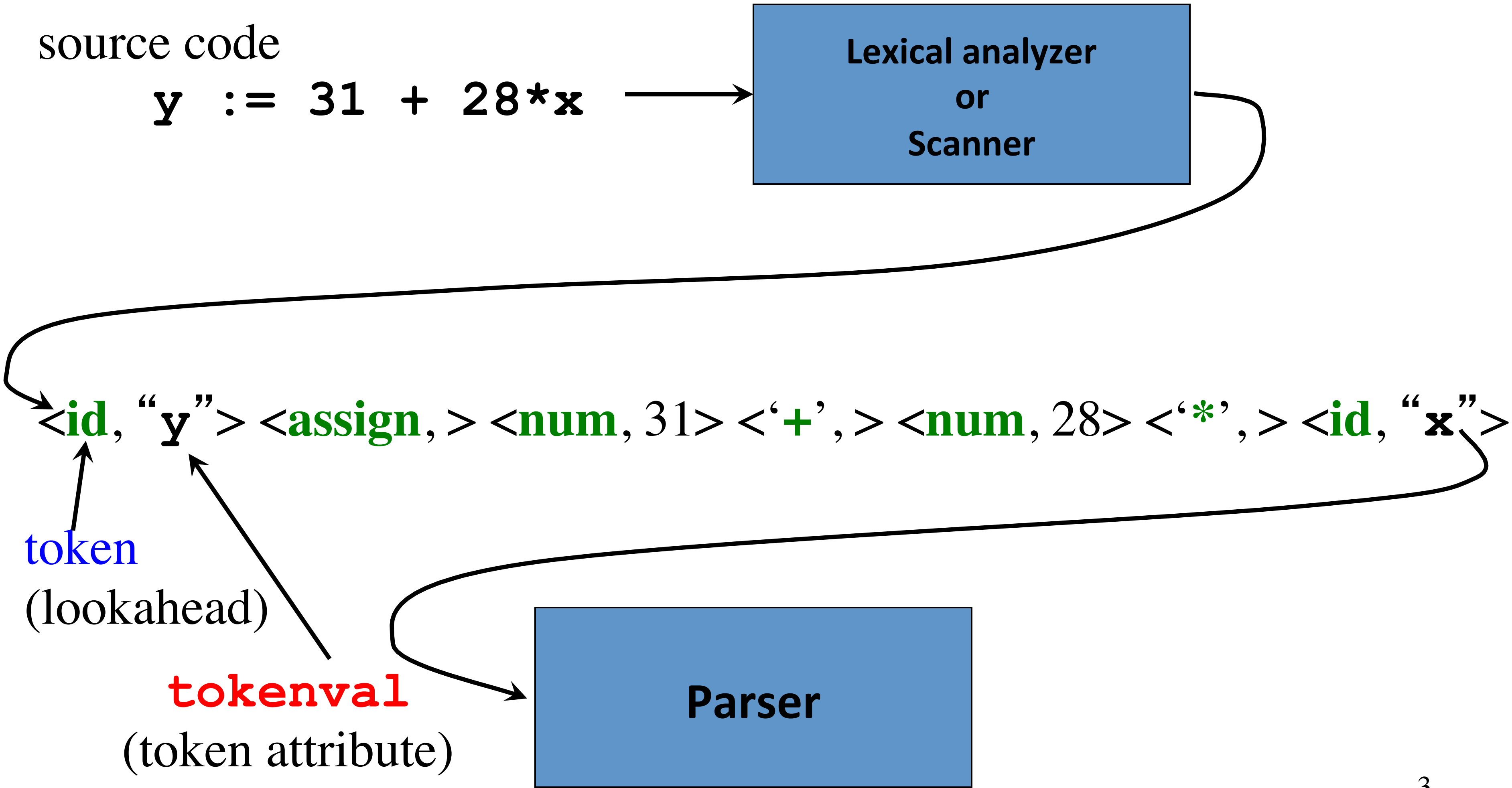
Lesson 5

- Lexical analysis: implementing a scanner

The Reason Why Lexical Analysis is a Separate Phase

- Simplifies the design of the compiler
  - LL(1) or LR(1) parsing with 1 token lookahead would not be possible (multiple characters/tokens to match)
- Provides efficient implementation
  - Systematic techniques to implement lexical analyzers by hand or automatically from specifications
  - Stream buffering methods to scan input
- Improves portability
  - Non-standard symbols and alternate character encodings can be normalized (e.g. UTF8, trigraphs)

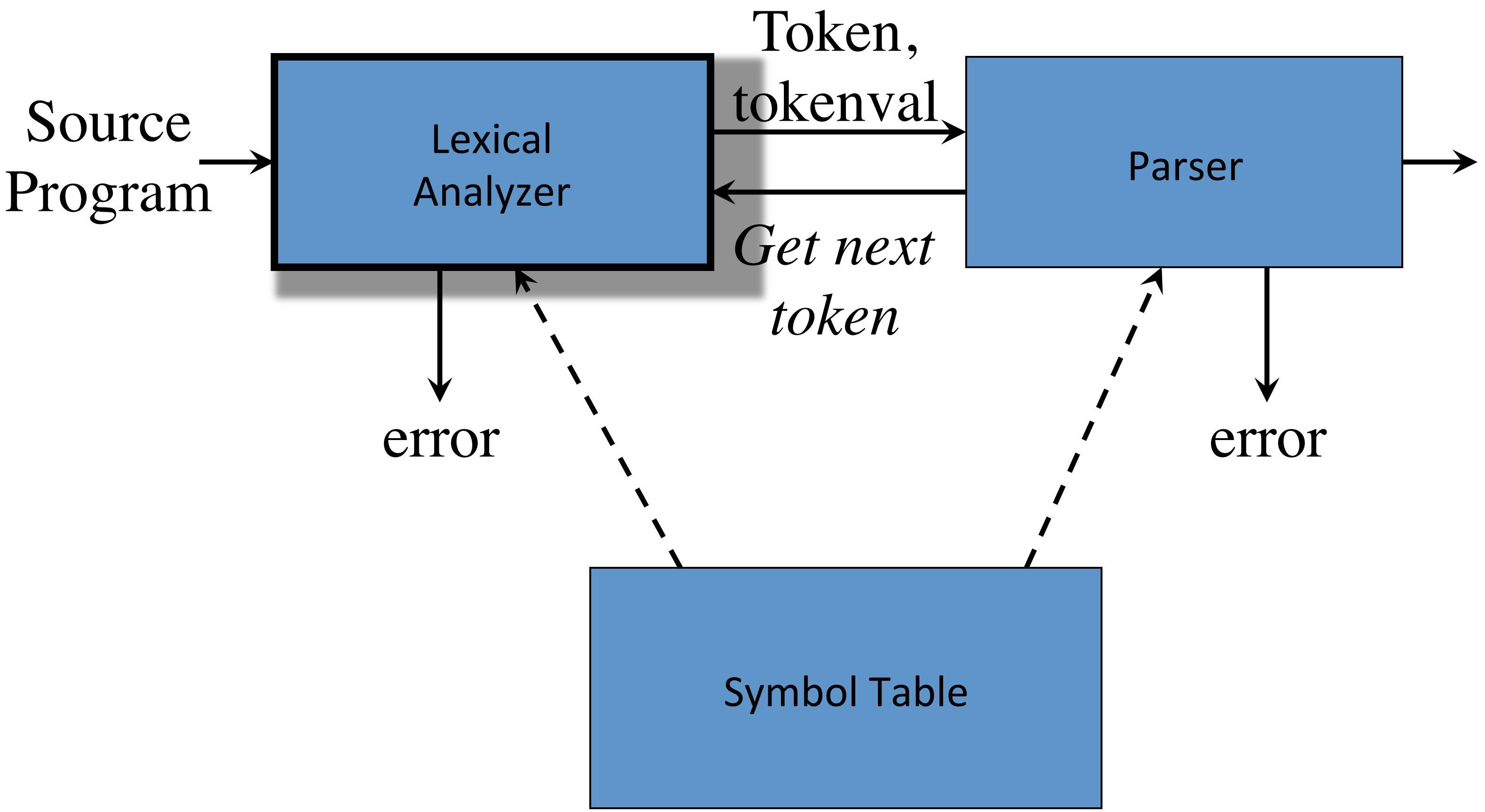
Main goal of lexical analysis: tokenization



Additional tasks of the Lexical Analyzer

- Remove comments and useless white spaces / tabs from the source code
- Correlate error messages of the parser with source code (e.g. keeping track of line numbers)
- Expansion of macros

Interaction of the Lexical Analyzer with the Parser



Tokens, Patterns, and Lexemes

- A ***token*** is a pair **<token name, attribute>**
  - The token name (e.g. **id**, **num**, **div**, **geq**, …) identifies the category of lexical units
  - The attribute is optional
  - **NOTE:** most often, one refers to a **token** using the **token name** only
- A ***lexeme*** is a character string that makes up a token
  - For example: **abc**, **123**, ****, **>=**
- A ***pattern*** is a rule describing the set of lexemes belonging to a token
  - For example: *"letter followed by letters and digits"*, *"non-empty sequence of digits"*, *"character '\'"*, *"character '>' followed by '='"*
- The scanner reads characters from the input till when it recognizes a lexeme that matches the patterns for a token

Example

Token name	Informal description	Sample lexemes
if	Characters i, f	if
else	Characters e, l, s, e	else
relation	< or > or <= or >= or == or !=	<=, !=
id	Letter followed by letter and digits	pi, score, D2
number	Any numeric constant	3.14159, 0, 6.02e23
literal	Anything but " sorrounded by "	"core dumped"

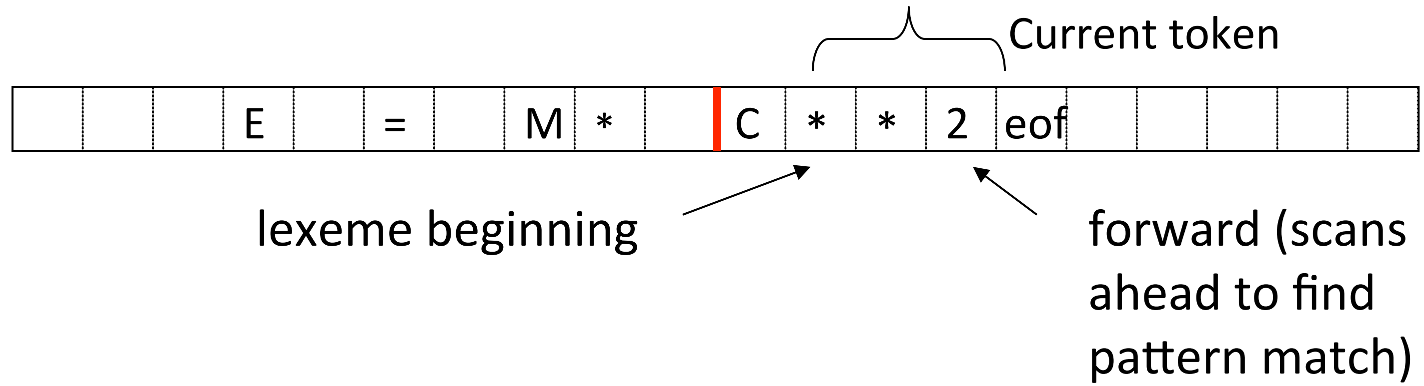
Attributes of tokens

- Needed when the pattern of a token matches different lexemes
- We assume single attribute, but can be structured
- Typically ignored by parsing, but used in subsequent compilation phases (static analysis, code generation, optimization)
- Kind of attribute depends on the token name
- Identifiers have several info associated (lexeme, type, position of definition,…)
  - Typically inserted as entries in a symbol table, and the attribute is a pointer to the simbol-table entry

Reading input characters

- Requires I/O operations: efficiency is crucial
- Lookahead can be necessary to identify a token
- Buffered input reduces I/O operations
- Naïve implementation makes two tests for each character
  - End of buffer?
  - Multiway branch on the character itself
- Use of "sentinels" encapsulate the end-of-buffer test into the multiway branch

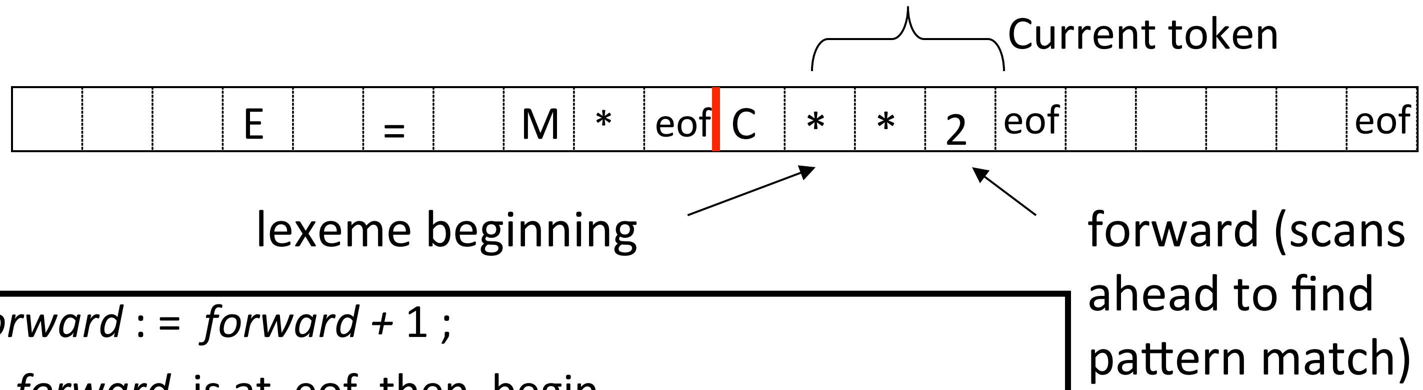
Buffered input to Enhance Efficiency




```
if forward at end of first half then begin
    reload second half ;          Block I/O
    forward : = forward + 1
  end
  else if forward at end of second half then begin
    reload first half ;           Block I/O
    move forward to beginning of first half
  end
  else forward : = forward + 1 ;
```

Executed for each input character

Algorithm: Buffered I/O with Sentinels




```
forward : =  forward + 1 ;
if  forward  is at  eof  then  begin
   if  forward  at end of first half  then  begin
        reload second half ;    <- Block I/O
        forward  : =  forward  + 1
   end
   else if  forward  at end of second half  then  begin
        reload first half ;    <- Block I/O
        move  forward  to beginning of first half
   end
   else  / * eof within buffer signifying end of input  * /
        terminate lexical analysis
end          2nd eof ⇒ no more input !
```

Executed only is next character is eof

Specification of Patterns for Tokens: Recalling some basic definitions

- An *alphabet* Σ is a finite set of symbols (characters)
- A *string s* is a finite sequence of symbols from Σ
  - $|s|$ denotes the length of string *s*
  - ε denotes the empty string, thus $|\varepsilon| = 0$
  - Σ^* denotes the set of strings over Σ
- A *language L over* Σ is a set of strings over alphabet Σ
- Thus $L \subseteq \Sigma^*$, or $L \in 2^{\Sigma^*}$
  - 2^X is the powerset of X, i.e. the set of all subsets of X
- The *concatenation* of strings **x** and **y** is denoted by **xy**
- *Exponentiation* of a string *s*: $s^0 = \varepsilon$ $s^i = s^{i-1}s$ for i > 0

Operations on Languages

- Languages are sets (of strings) thus all operations on sets are defined over them
  - *Eg. Union:* $L \cup M = \{s \mid s \in L \text{ or } s \in M\}$
- Additional operations lift to languages operations on strings
  - *Concatenation* $LM = \{xy \mid x \in L \text{ and } y \in M\}$
  - *Exponentiation* $L^0 = \{\varepsilon\}$; $L^i = L^{i-1}L$
  - *Kleene closure* $L^* = \cup_{i=0,\dots,\infty} L^i$
  - *Positive closure* $L^+ = \cup_{i=1,\dots,\infty} L^i$

Language Operations: Examples

$L = \{a, b, ab, ba\}$ $D = \{1, 2, ab, b\}$ Assuming $\Sigma = \{a,b,1,2\}$

- $L \cup D = \{ a, b, ab, ba, 1, 2 \}$
- LD = {a1, a2, aab, ab, b1, b2, bab, bb, ab1, ab2, abab, abb, ba1, ba2, baab, ~~bab~~ }
- L^2 = { aa, ab, aab, aba, ba, bb, bab, bba, abb, abab, abba, baa, bab, baab, baba}
- L* = { ε, 1, 2, ab, b, 11, 12, …, 111, 112, …, 1111, 1112, … }
- $L^+ = L^* - \{ \varepsilon \}$

Regular Expressions: syntax and semantics

- Given an alphabet Σ, a *regular expression over* Σ denotes a language over Σ and is defined as follows:
- Basis symbols:
  - ε is a regular expression denoting language $\{\varepsilon\}$
  - a is a regular expression denoting $\{a\}$, for each $a \in \Sigma$
- If r and s are regular expressions denoting languages $L(r)$ and $M(s)$ respectively, then
  - $(r) \mid (s)$ is a regular expression denoting $L(r) \cup M(s)$
  - $(r)(s)$ is a regular expression denoting $L(r)M(s)$
  - $(r)^*$ is a regular expression denoting $L(r)^*$
  - (r) is a regular expression denoting $L(r)$
- A language defined by a regular expression is called a *regular language*

Regular Expressions: conventions and examples

- Syntactical conventions to avoid too many brackets:
  - Precedence of operators: $(\_)^*$ > $(\_)(\_)$ > $(\_)|(\_)$
  - Left-associativity of all operators
  - Example: $(a) \mid ((b)^*(c))$ can be written as $a \mid b^*c$
- Examples of regular expressions (over $\Sigma = \{a, b\}$):
  - $a|b$ denotes $\{ a, b \}$
  - $(a|b)(a|b)$ denotes $\{ aa, ab, ba, bb \}$
  - a^* denotes $\{ \varepsilon, a, aa, aaa, aaaa, \ldots \}$
  - $(a|b)^*$ denotes $\{ \varepsilon, a, b, aa, ab, \ldots, aaa, aab, \ldots \} = \Sigma^*$
  - $(a^*b^*)^*$ denotes ?
- Two regular expressions are *equivalent* if they denote the same language. Eg: $(a|b)^* = (a^*b^*)^*$

Some Algebraic Properties of Regular Expressions

LAW	DESCRIPTION
$r \mid s = s \mid r$	$\mid$ is commutative
$r \mid (s \mid t) = (r \mid s) \mid t$	$\mid$ is associative
$(r\ s)\ t = r\ (s\ t)$	concatenation is associative
$r\ (s \mid t) = r\ s \mid r\ t$ $(s \mid t)\ r = s\ r \mid t\ r$	concatenation distributes over $\mid$
$\varepsilon r = r$ $r \varepsilon = r$	ε Is the identity element for concatenation
$r^* = (r \mid \varepsilon)^*$	relation between * and ε
$r^{**} = r^*$	* is idempotent

- Equivalence of regular expressions is decidable
- There exist complete axiomatizations

Regular Definitions

- Provide a convenient syntax, similar to BNF, for regular expressions, introducing name-to-regular-expression bindings.
- A *regular definition* has the form

  $d_1 \to r_1$
  $d_2 \to r_2$
  …
  $d_n \to r_n$

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

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

- **Recursion is forbidden!** *digits* → *digit* | *digit digits* *wrong!*
- Iteratively replacing names with the corresponding definition yields a single regular expression for d_n

Extensions of Regular Expressions

- Several operators on regular expressions have been proposed, improving expressivity and conciseness
- Modern scripting languages are very rich
- Clearly, each new operator must be definable with a regular expression
- Here are some common conventions

`[xyz]`	match one character **`x`**, **`y`**, or **`z`**
`[^xyz]`	match any character except **`x`**, **`y`**, and **`z`**
`[a-z]`	match one of **`a`** to **`z`**
r^+	positive closure (match one or more occurrences)
$r^?$	optional (match zero or one occurrence)

Recognizing Tokens

- We described how to specify patterns of tokens using regular expressions/definitions
- Let's show how to write code for recognizing tokens
- Recall: in the CFG of a language, *terminal symbols* correspond to the tokens the parser will use.
- Running example CFG:

$$
\begin{aligned}
stmt &\rightarrow \textbf{if}\ expr\ \textbf{then}\ stmt \\
&\quad \mid \textbf{if}\ expr\ \textbf{then}\ stmt\ \textbf{else}\ stmt \\
&\quad \mid \varepsilon \\
expr &\rightarrow term\ \textbf{relop}\ term \\
&\quad \mid term \\
term &\rightarrow \textbf{id} \\
&\quad \mid \textbf{num}
\end{aligned}
$$

- The tokens are:

`if, then, else, relop, id, num`

Running example: Informal specification of tokens and their attributes

Pattern of lexeme	Token	Attribute-Value
Any ws	-	-
if	if	-
then	then	-
else	else	-
Any id	id	pointer to table entry
Any num	num	pointer to table entry
<	relop	LT
<=	relop	LE
=	relop	EQ
< >	relop	NE
>	relop	GT
>=	relop	GE

Regular Definitions for tokens

- The specification of the patterns for the tokens is provided with regular definitions

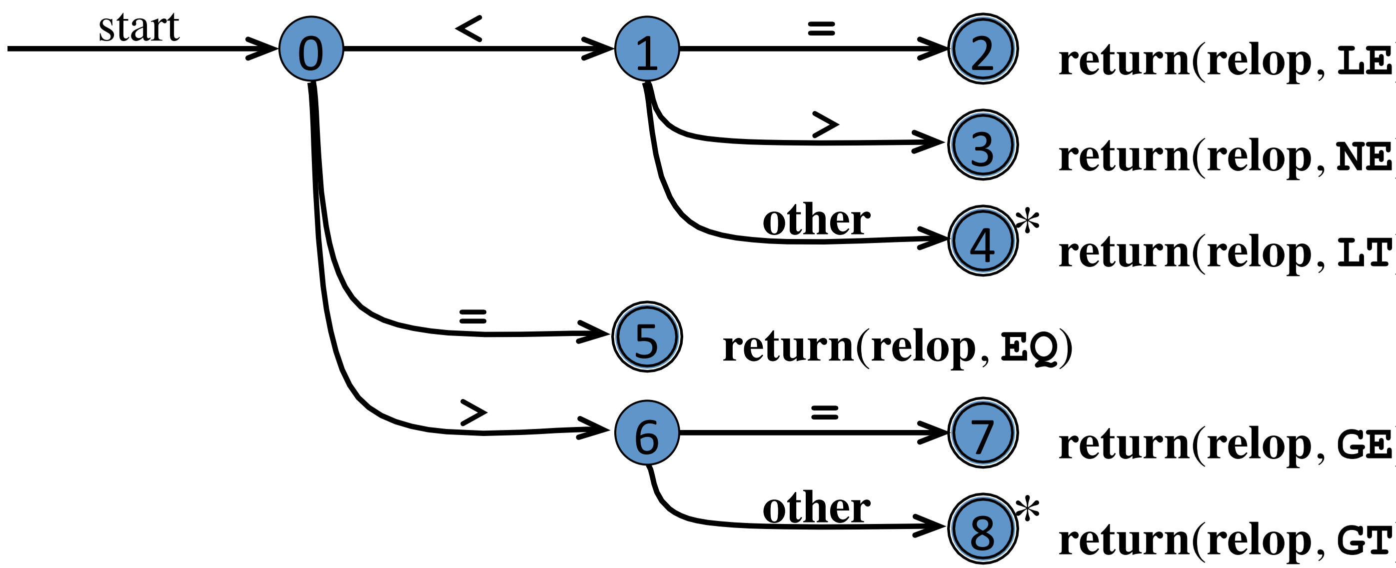
$$letter \rightarrow \texttt{[A-Za-z]}$$
$$digit \rightarrow \texttt{[0-9]}$$
$$digits \rightarrow digit^{+}$$
$$if \rightarrow \texttt{if}$$
$$then \rightarrow \texttt{then}$$
$$else \rightarrow \texttt{else}$$
$$relop \rightarrow \texttt{<} \mid \texttt{<=} \mid \texttt{<>} \mid \texttt{>} \mid \texttt{>=} \mid \texttt{=}$$
$$id \rightarrow letter\ (letter \mid digit)^{*}$$
$$num \rightarrow digits\ (\mathbf{.}\ digits)?\ (\ \mathbf{E}\ (\mathbf{+} \mid \mathbf{-})?\ digits\ )?$$

From Regular Definitions to code

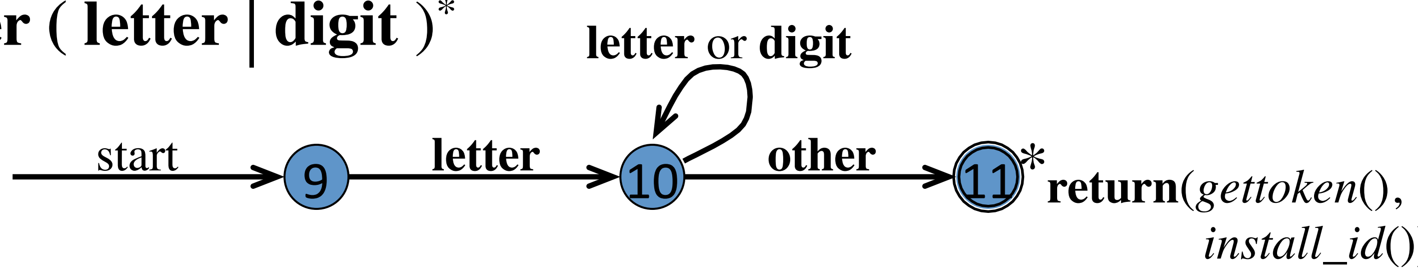
- From the regular definitions we first extract a *transition diagram*, and next the code of the scanner.
- In the example the lexemes are recognized either when they are completed, or at the next character. In real situations a longer lookahead might be necessary.
- The diagrams guarantee that the longest lexeme is identified.

Coding Regular Definitions in *Transition Diagrams*

relop $\rightarrow$ **< | <= | <> | > | >= | =**



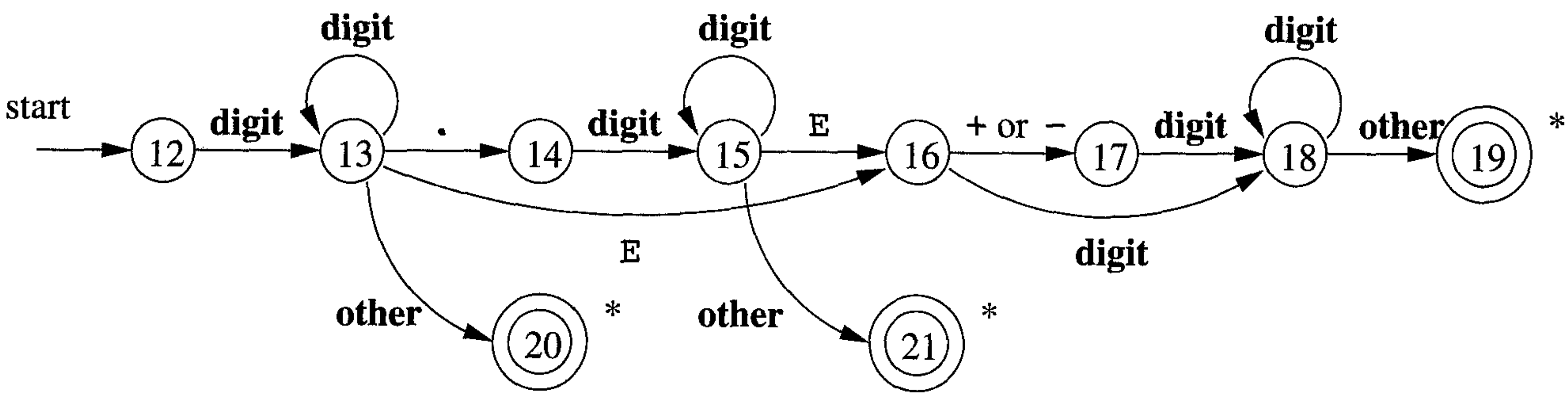
id $\rightarrow$ **letter (letter | digit)***



Coding Regular Definitions in *Transition Diagrams* (cont.)

Transition diagram for unsigned numbers

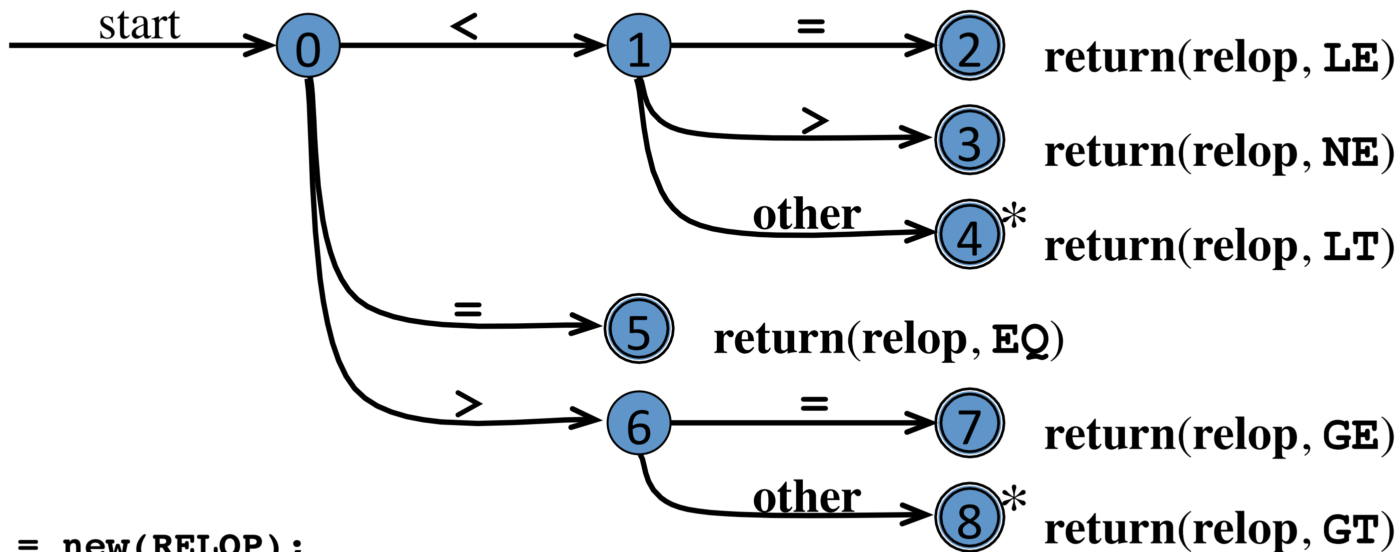
num $\rightarrow$ **digit**$^+$ (**. digit**$^+$)? (**E** (**+** | **-**)? **digit**$^+$)?



From Individual Transition Diagrams to Code

- Easy to convert each Transition Diagram into code
- Loop with multiway branch (switch/case) based on the current state to reach the instructions for that state
- Each state is a multiway branch based on the next input channel

Coding the Transition Diagrams for Relational Operators




```
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);
}    }    }
```

Putting the code together

The transition diagrams for the various tokens can be tried sequentially: on failure, we re-scan the input trying another diagram.

```
token nexttoken()
{ while (1) {
    switch (state) {
    case 0: c = nextchar();
       if (c==blank || c==tab || c==newline) {
         state = 0;
         lexeme_beginning++;
       }
       else if (c=='<') state = 1;
       else if (c=='=') state = 5;
       else if (c=='>') state = 6;
       else state = fail();
       break;
     case 1:
       …
     case 9: c = nextchar();
       if (isletter(c)) state = 10;
       else state = fail();
       break;
     case 10: c = nextchar();
       if (isletter(c)) state = 10;
       else if (isdigit(c)) state = 10;
       else state = 11;
       break;
     …
```

```
int fail()
{ forward = token_beginning;
  switch (state) {
  case  0: start =  9; break;
  case  9: start = 12; break;
  case 12: start = 20; break;
  case 20: start = 25; break;
  case 25: recover(); break;
  default: /* error */
  }
  return start;
}
```

Putting the code together: Alternative solutions

- The diagrams can be checked in parallel
- The diagrams can be merged into a single one, typically *non-deterministic*: this is the approach we will study in depth.

Lexical errors

- Some errors are out of power of lexical analyzer to recognize:

```
fi (a == f(x)) …
```

- However, it may be able to recognize errors like:

```
d = 2r
```

- Such errors are recognized when no pattern for tokens matches a character sequence

Error recovery

- Panic mode: successive characters are ignored until we reach to a well formed token
- Delete one character from the remaining input
- Insert a missing character into the remaining input
- Replace a character by another character
- Transpose two adjacent characters
- Minimal Distance