Principles of Programming Languages

http://www.di.unipi.it/~andrea/Didattica/PLP-16/

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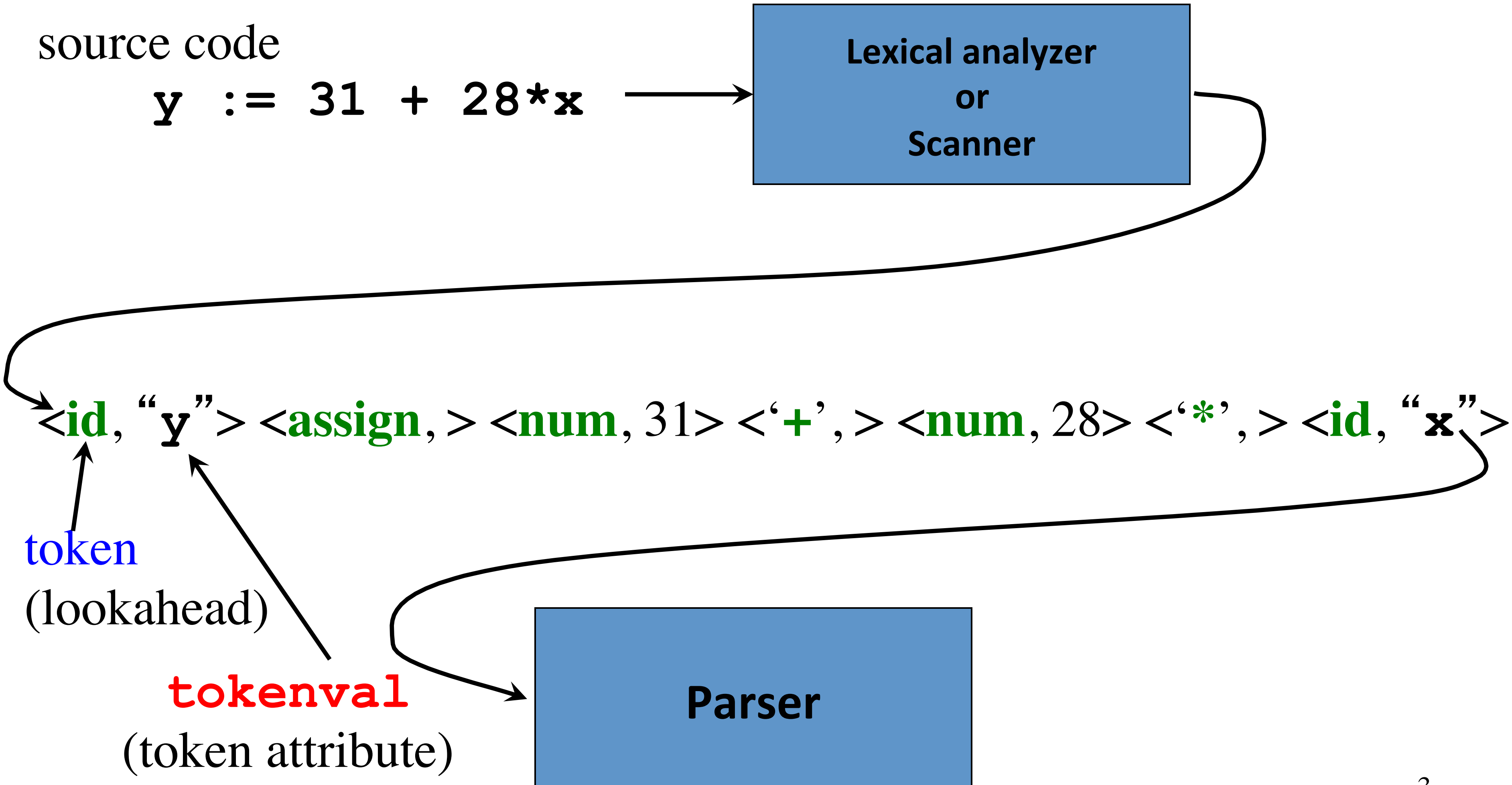
Lesson 5

- 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)

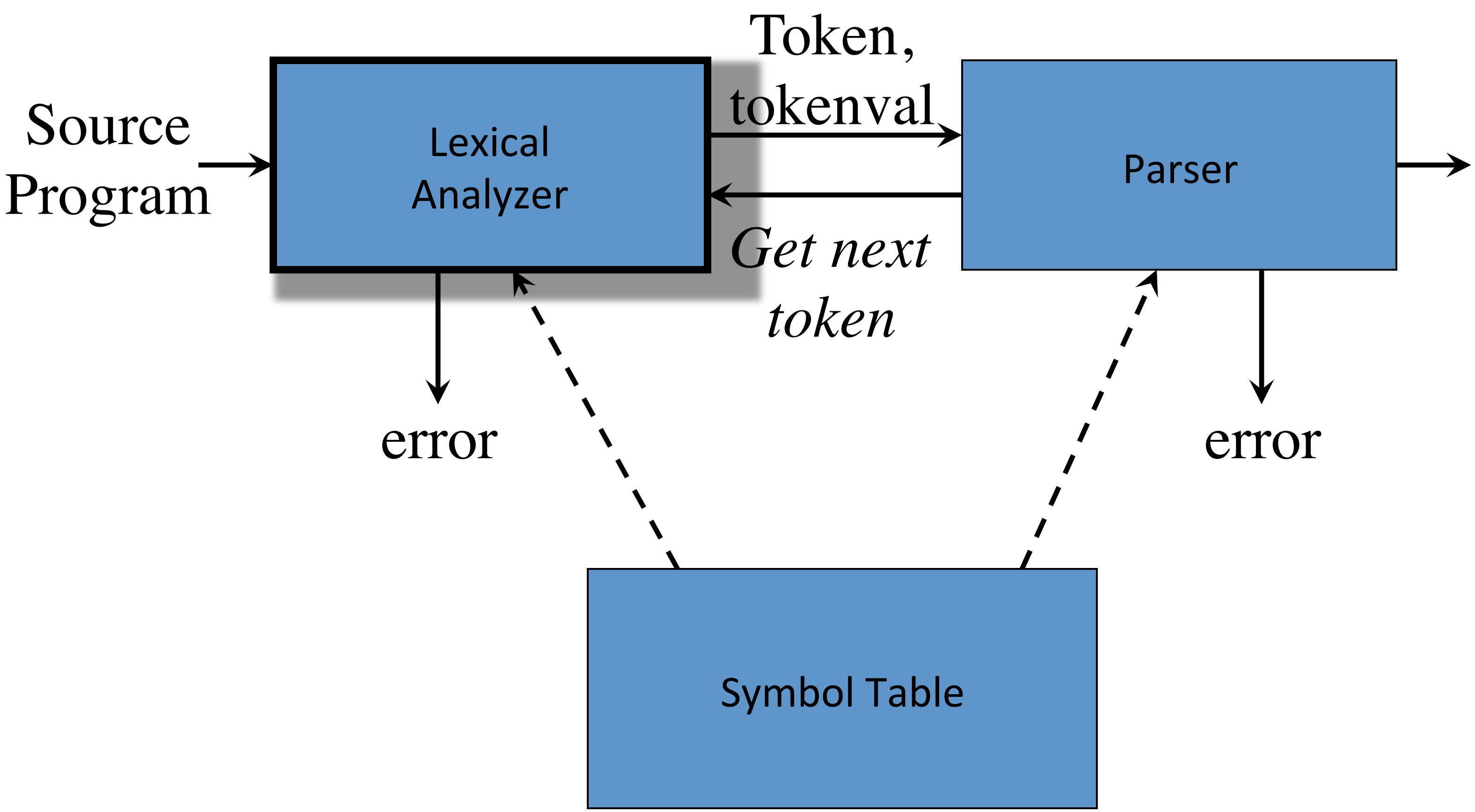
Main goal of lexical analysis: tokenization



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



How are tokens determined?

- The source programming language is defined by a CFG, used by the parser
- The tokens are just the ***terminal symbols*** of the CFG

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

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Examples of tokens

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"

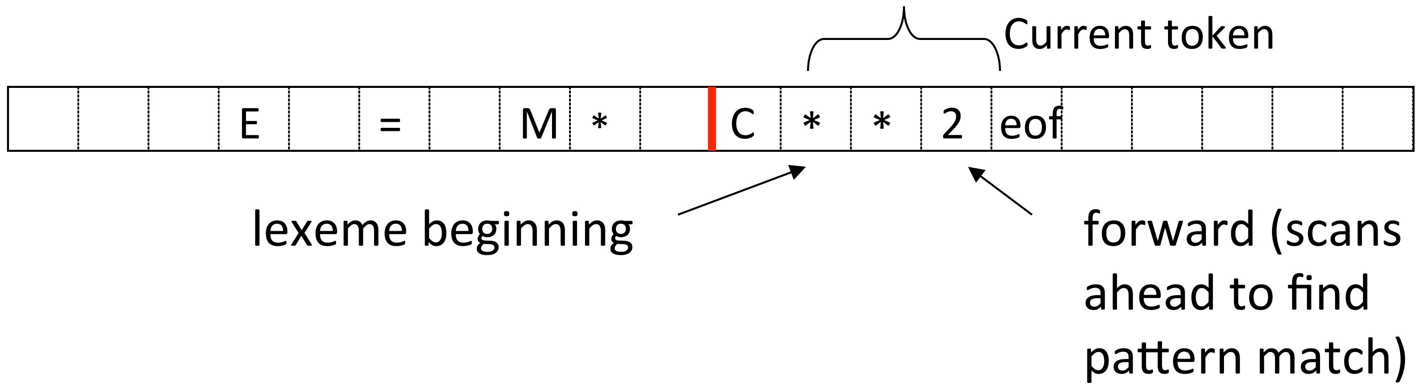
Attributes of tokens

- 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
- Naive 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

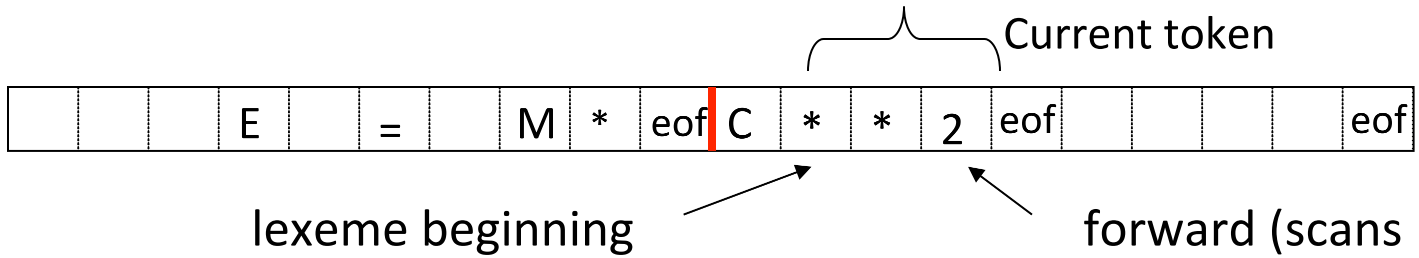
Buffered input to Enhance Efficiency



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 ;
        forward  : =  forward  + 1
    end
    else if  (forward  at end of second half)  then  begin
        reload first half ;
        move  forward  to beginning of first half
    end
    else  / * eof within buffer signifying end of input  * /
        terminate lexical analysis
end
```

Block I/O

Block I/O

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* $L^0 = \{\varepsilon\}$; $L^i = L^{i-1}L$
- Closure operators
  - *Kleene closure* $L^* = \cup_{i=0,\ldots,\infty} L^i$
  - *Positive closure* $L^+ = \cup_{i=1,\ldots,\infty} L^i$

Language Operations: Examples

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

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

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 $L(s)$ respectively, then
  - $(r) \mid (s)$ is a regular expression denoting $L(r) \cup L(s)$
  - $(r)(s)$ is a regular expression denoting $L(r)L(s)$
  - $(r)^*$ 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: $(a)\,|\,((b)^*(c))$ can be written as $a\,|\,b^*c$
- 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, introducing names to denote regular expressions.
- A *regular definition* has the form

$$d_1 \rightarrow r_1$$
$$d_2 \rightarrow r_2$$
$$\ldots$$
$$d_n \rightarrow r_n$$

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

  where each r_i is a regular expression over $\Sigma \cup \{d_1, \ldots, d_{i-1}\}$
- **Recursion is forbidden!** *digits* → *digit* | *digit digits* *wrong!*
- Iteratively replacing names with the corresponding definition yields a single regular expression for d_n

$$\mathit{id} \rightarrow (\mathtt{A} \mid \mathtt{B} \mid \ldots \mid \mathtt{Z} \mid \mathtt{a} \mid \mathtt{b} \mid \ldots \mid \mathtt{z})(\mathtt{A} \mid \mathtt{B} \mid \ldots \mid \mathtt{Z} \mid \mathtt{a} \mid \mathtt{b} \mid \ldots \mid \mathtt{z} \mid \mathtt{0} \mid \mathtt{1} \mid \ldots \mid \mathtt{9})^*$$

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

- Tokens are specified using regular expressions/ definitions
- From the regular definition we can generate the code for recognizing tokens
- Running example CFG:

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

- 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

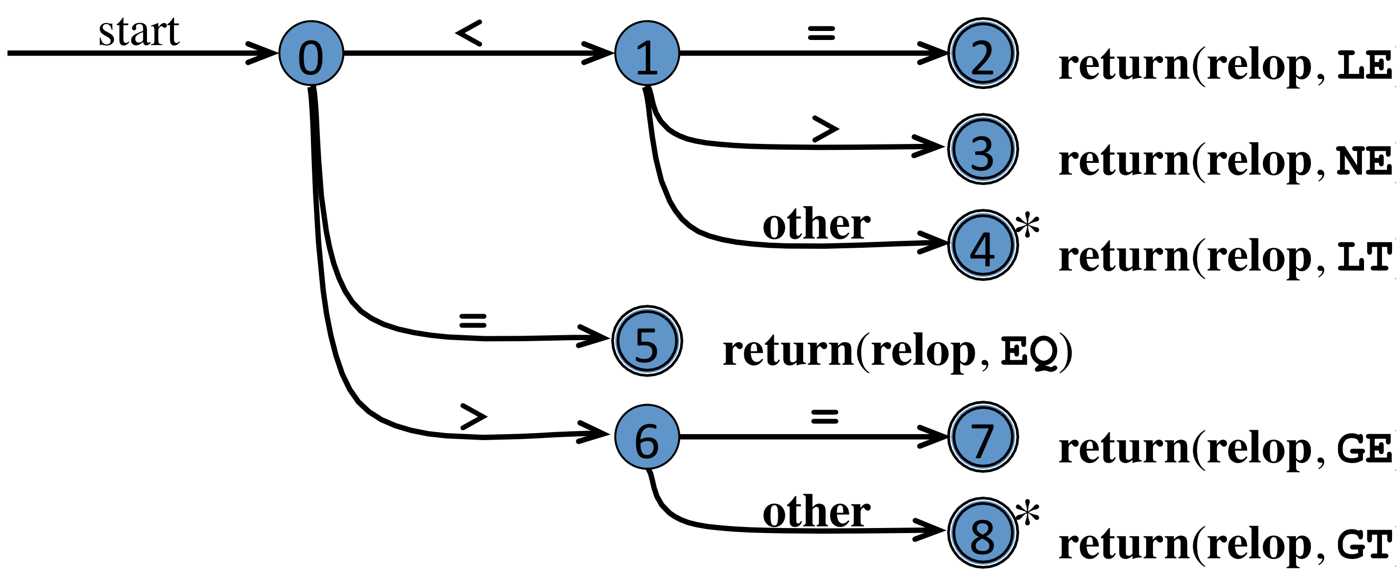
$$
\begin{aligned}
\textit{letter} &\rightarrow \texttt{[A-Za-z]} \\
\textit{digit} &\rightarrow \texttt{[0-9]} \\
\textit{digits} &\rightarrow \textit{digit}^{+} \\
\textit{if} &\rightarrow \textbf{if} \\
\textit{then} &\rightarrow \textbf{then} \\
\textit{else} &\rightarrow \textbf{else} \\
\textit{relop}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

From Regular Definitions to code

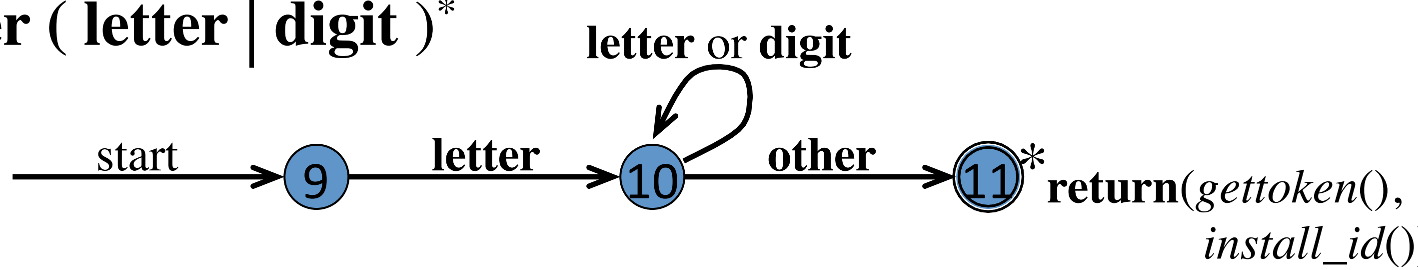
- From the regular definitions we first extract a *transition diagram*, and next the code of the scanner.
- In the example the lexemes are recognized either when they are completed, or at the next character. In real situations a longer lookahead might be necessary.
- The diagrams guarantee that the longest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

Coding Regular Definitions in *Transition Diagrams*

relop → < | <= | <> | > | >= | =



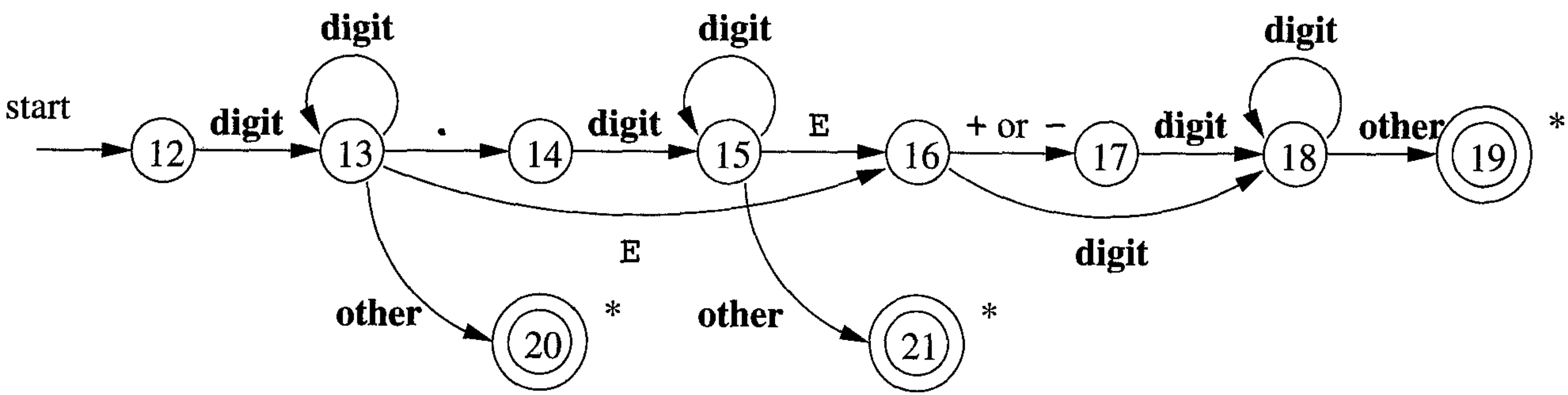
id → **letter** (**letter** | **digit**)*



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

Transition diagram for unsigned numbers

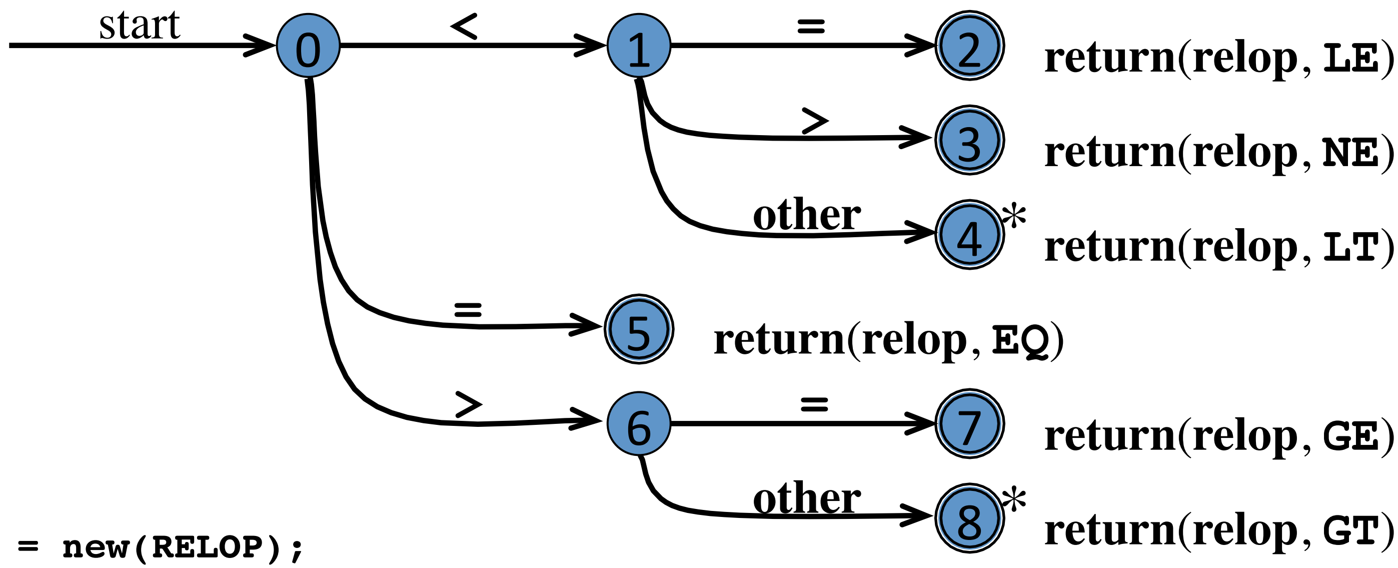
num $\rightarrow$ **digit**$^+$ (. **digit**$^+$)? (**E** (**+** | **-**)? **digit**$^+$)?



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 character

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