CS335: Lexical Analysis

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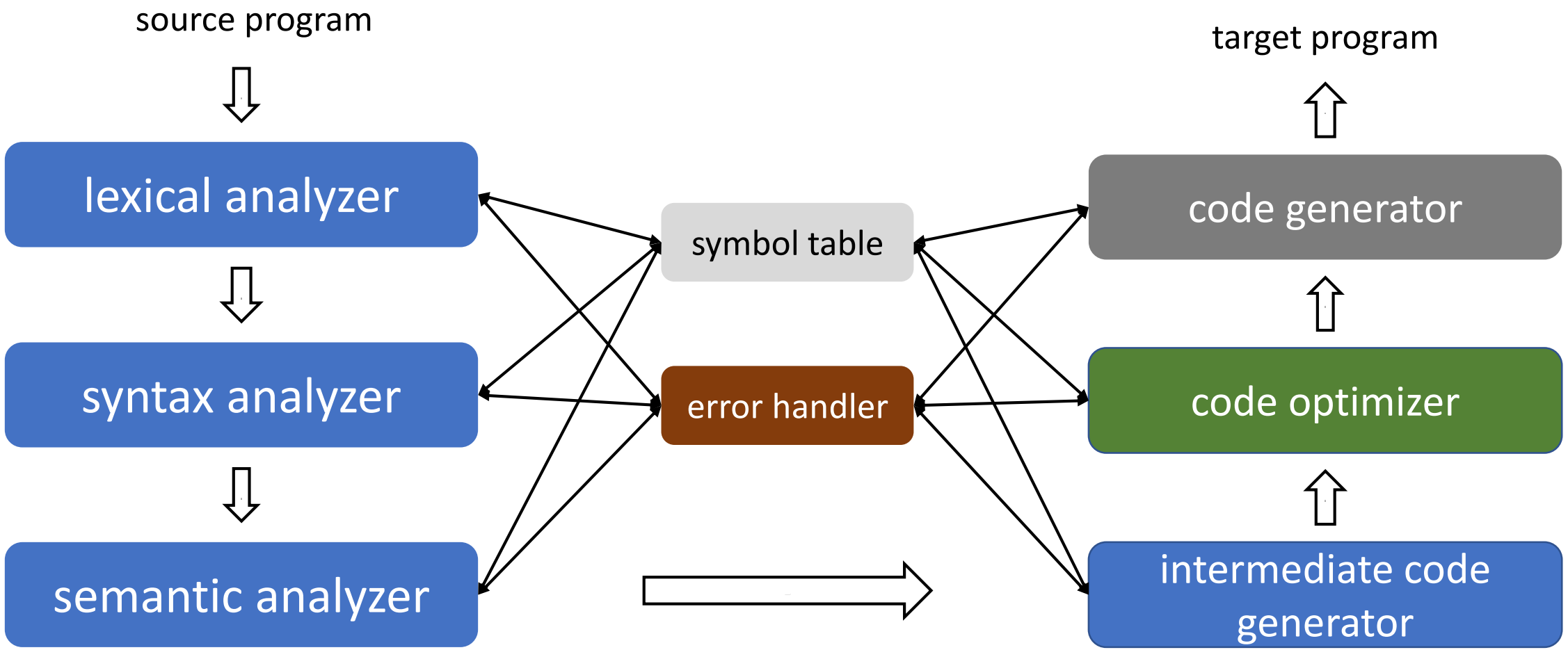
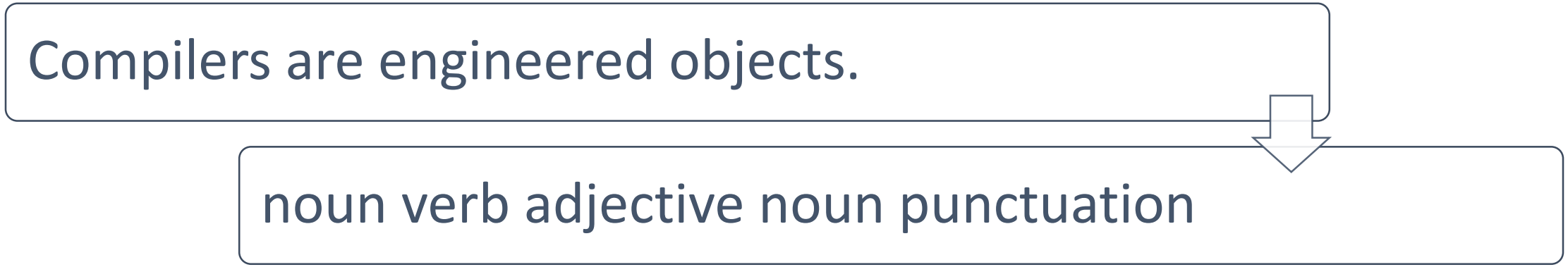
Content influenced by many excellent references, see References slide for acknowledgements.

An Overview of Compilation



Overview of Lexical Analysis

- First stage of a three-part frontend to help understand the source program
  - Processes every character in the input program
  - If a word is valid, then it is assigned to a syntactic category
    - This is similar to identifying the part of speech of an English word

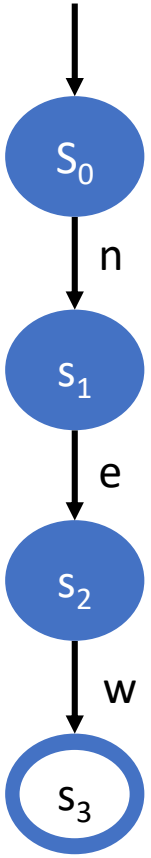


Description of Lexical Analysis

- **Input:**
  - A high level language program, such as a C or Java program, in the form of a sequence of ASCII characters
- **Output:**
  - A sequence of tokens along with attributes corresponding to different syntactic categories that is forwarded to the parser for syntax analysis
- **Functionality:**
  - Strips off blanks, tabs, newlines, and comments from the source program
  - Keeps track of line numbers and associates error messages from various parts of a compiler with line numbers
  - Performs some preprocessor functions in languages like C

Recognizing Word “new”

```
c = getNextChar();
if (c == ‘n’)
  c = getNextChar();
  if (c == ‘e’)
    c = getNextChar();
    if (c == ‘w’)
      report success;
    else
      // Other logic
  else
    // Other logic
else
  // Other logic
```



Formalism for Scanners

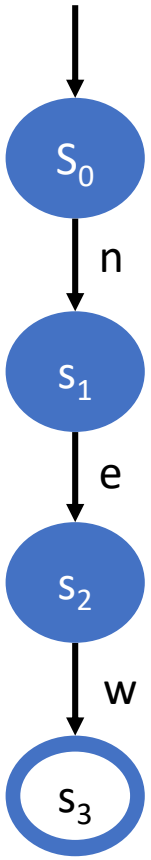
Definitions

- An **alphabet** is a finite set of symbols
  - Typical symbols are letters, digits, and punctuations
  - ASCII and UNICODE are examples of alphabets
- A **string** over an alphabet is a finite sequence of symbols drawn from that alphabet
- A **language** is any countable set of strings over a fixed alphabet

Finite State Automaton

- A finite state automaton (FSA) is a five-tuple or quintuple $(S, \Sigma, \delta, s_0, S_F)$
  - S is a finite set of states
  - Σ is the alphabet or character set
    - It is the union of all edge labels in the FSA, and is finite.
  - $\delta(s, c)$ represents the transition from state s on input c
  - $s_0 \in S$ is the designated start state
  - $S_F \subseteq S$ is the set of final states
- A FSA accepts a string x if and only if
  - FSA starts in s_0
  - Execute transitions for the sequence of characters in x
  - Final state is an accepting state $\in S_F$ after x has been consumed

FSA for recognizing “new”



- FSA = $(S, \Sigma, \delta, s_0, S_F)$
- $S = (s_0, s_1, s_2, s_3)$
- $\Sigma = \{n, e, w\}$
- $\delta = \{s_0 \xrightarrow{n} s_1, s_1 \xrightarrow{e} s_2, s_2 \xrightarrow{w} s_3\}$
- $s_0 = s_0$
- $S_F = \{s_3\}$

String is recognized in time proportional to the input

FSA for Unsigned Integers

```
char = getNextChar( )
state = s_0
while (char ≠ EOF and state ≠ s_e)
  state = δ(state,char)
  char = getNextChar()

if (state ∈ S_F)
  report success
else
  report failure
```

- FSA = $(S, \Sigma, \delta, s_0, S_F)$
- $S = (s_0, s_1, s_2, s_e)$
- $\Sigma = \{0,1,2,3,4,5,6,7,8,9\}$
- $\delta = \{s_0 \xrightarrow{0} s_1, s_0 \xrightarrow{1-9} s_2, s_2 \xrightarrow{0-9} s_2, s_1 \xrightarrow{0-9} s_e\}$
- $s_0 = s_0$
- $S_F = \{s_1, s_2\}$

Dealing with Erroneous Situations

1. FSA is in state s, the next input character is c, and $\delta(s, c)$ is not defined
2. FSA might process the complete input and still not be in the final state
   - Input string is a proper prefix for some word accepted by the FSA

Nondeterministic Finite Automaton

- Nondeterministic finite automaton (NFA)
  - A FSA that allows transitions on the empty string ϵ and states that have multiple transitions on the same input character

- Simulating an NFA
  1. Always make the correct nondeterministic choice to follow transitions that lead to accepting state(s) for the input string, if such transitions exist
  2. Try all nondeterministic choices in parallel to search the space of all possible configurations

Regular Expressions

- The set of words accepted by an FSA F is called its language $L(F)$

- For any FSA F, we can also describe $L(F)$ using a notation called a regular expressions (RE)
- The language described by a RE r is called a regular language (denoted by $L(r)$)

Regular Expressions

- ϵ is a RE, $L(\epsilon) = \{\epsilon\}$
- Let Σ be an alphabet, for each $a \in \Sigma$, a is a RE, and $L(a) = \{a\}$

- r and s are REs denoting the languages R and S respectively
  - **Alternation** (or **union**): $(r|s)$ is a RE, $L(r|s) = R|S = \{x|x \in R \text{ or } x \in S\} = L(r) \cup L(s)$
  - **Concatenation**: (rs) is a RE, $L(rs) = R.S = \{xy \mid x \in R \wedge y \in S\}$
  - **Closure**: (r^*) is an RE, $L(r^*) = R^* = \bigcup_{i=0}^{\infty} R^i$
    - L^* is called the Kleene closure or closure of L

Examples of Regular Expressions

$L =$ set of all strings of $0's$ and $1's$

$$r = (0 + 1)^*$$

$L = \{w \in \{0,1\}^* | \, w$ has two or three occurences of 1, the first and second are not consecutive$\}$

$$r = 0^*10^*010^*(10^* + \epsilon)$$

$L = \{w | \, w \in \{a, b\}^* \wedge w$ ends with $a\}$

$$r = (a + b)^*a$$

Examples of Regular Expressions

Unsigned real numbers with exponents

$$r = (0|[1 \ldots 9][0 \ldots 9]^*)(.[0 \ldots 9]^*|\epsilon)E(+|-|\epsilon)(0|[1 \ldots 9][0 \ldots 9]^*)$$

$$L = \{w \in \{0,1\}^* \mid w \text{ has no pair of consecutive zeros}\}$$

$$r = (1 + 01)^*(0 + \epsilon)$$

Regular Expressions

- We can reduce the use of parentheses by introducing precedence and associativity rules
  - Binary operators, closure, concatenation, and alternation are left associative

- Precedence rule is

$$\text{parentheses} > \text{closure} > \text{concatenation} > \text{alternation}$$

Algebraic Laws for REs

Law	Description
$r\|s = s\|r$	| is commutative
$r\|(s\|t) = (r\|s)\|t$	| is associative
$r(st) = (rs)t$	Concatenation is commutative
$r(s\|t) = rs\|rt; (s\|t)r = sr\|tr$	Concatenation distributes over |
$\epsilon r = r\epsilon = r$	ϵ is the identity of concatenation
$r^* = (r\|\epsilon)^*$	ϵ is guaranteed in a closure
$r^{**} = r^*$	$*$ is idempotent

Regular Definitions

- Let r_i be a regular expression and d_i be a distinct name
- Regular Definition is a sequence of definitions of the form

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

- Each r_i is a regular expression over the symbols $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$
- Each d_i is a new symbol not in Σ

Example of Regular Definitions

- Unsigned numbers
  - Example: `5280`, `0.01234`, `6.336E4`, or `1.89E-4`

$$digit = 0|1|2|3|4|5|6|7|8|9$$
$$digits = digit\ digit^*$$
…
…
…

Example of Regular Definitions

- Unsigned numbers
  - Example: `5280`, `0.01234`, `6.336E4`, or `1.89E-4`

$$digit = 0|1|2|3|4|5|6|7|8|9$$
$$digits = digit\ digit^*$$
$$optfrac = .\ digits|\epsilon$$
$$optexp = (E(+|-|\epsilon)\ digits)|\epsilon$$
$$unsignednum = digits\ optfrac\ optexp$$

Extensions of Regular Expressions

"." is any character other than "\n"

$[xyz]$ is $x|y|z$

$[abg{-}pT{-}Y]$ is any character $a, b, g, \ldots, p, T, \ldots, Y$

[^$G{-}Q$] is not any one of $G, H, \ldots, Q$

r+ is one or more r's

r? is zero or one r

Regular Definition for Unsigned Numbers

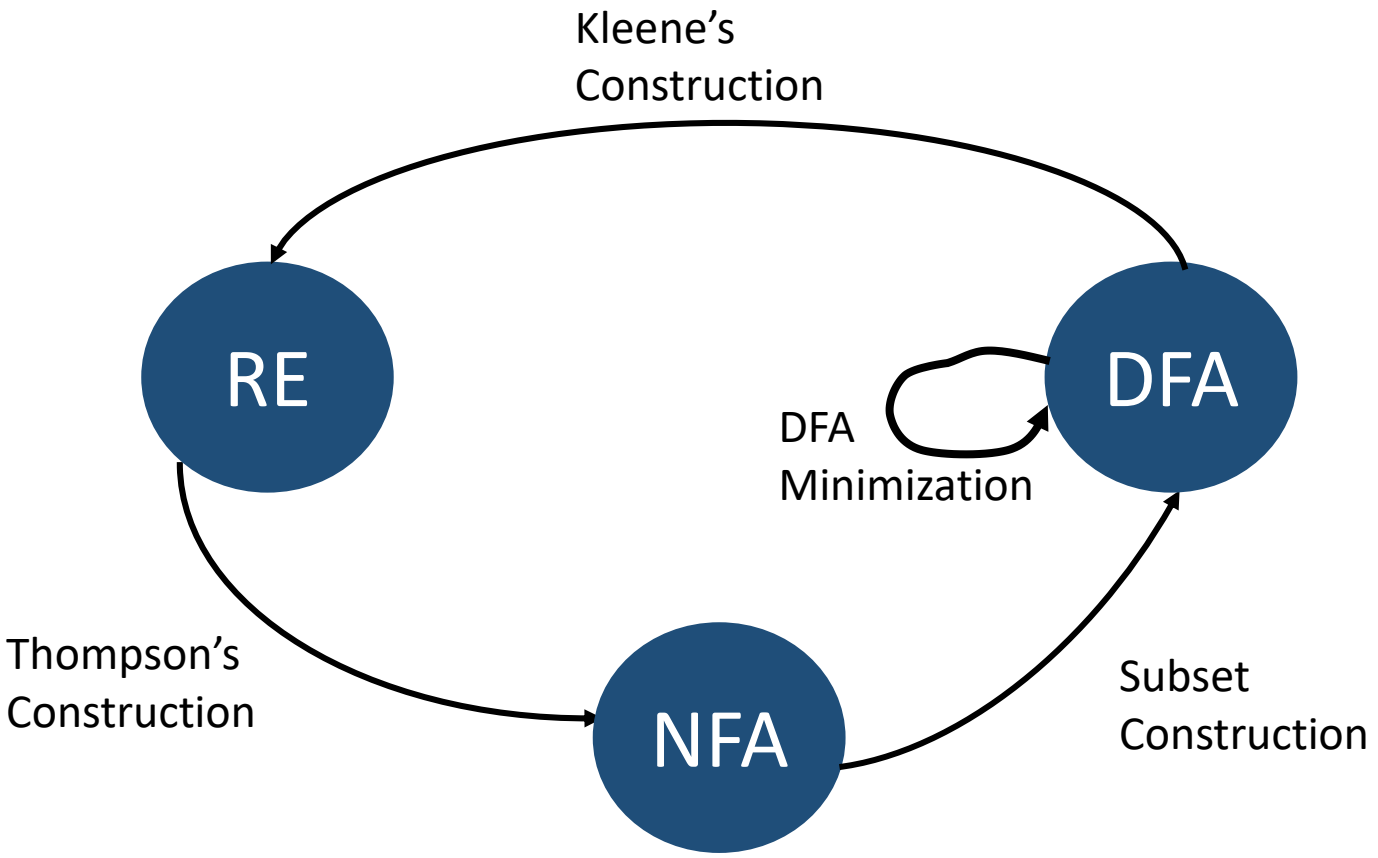
$$digits = 0|1|2|3|4|5|6|7|8|9$$
$$digits = digit\ digit^*$$
$$optfrac = .\ digits|\epsilon$$
$$optexp = (E(+|-|\epsilon)digits)|\epsilon$$
$$unsignednum = digits\ optfrac\ optexp$$

$$digits = [0-9]$$
$$digits = \ digit^+$$
$$unsignednum = digits\ (.\ digits)?\ (E[+-]?\ digits)?$$

Equivalence of RE and FSA

- Let r be an RE. Then there exists an NFA with ϵ-transitions that accepts $L(r)$
- If L is accepted by a DFA, then L is generated by a RE
- …

Equivalence of RE and FSA



NFA = $(N, \Sigma, \delta_N, n_0, N_A)$

DFA = $(D, \Sigma, \delta_D, d_0, D_A)$

NFA to DFA: Subset Construction

Subset Construction

q_0 = ϵ-closure($\{s_0\}$)
Q = q_0
WorkList = $\{q_0\}$
while (WorkList $\neq \phi$) do
  remove q from WorkList
  for each character $c \in \Sigma$ do
    t = ϵ-closure($\delta(q, c)$)
    $T[q, c] = t$
    if $t \notin Q$ then
      add t to Q and to WorkList

ϵ-closure

for each state $n \in N$ do
  $E(n) = \{n\}$
WorkList = N
while (WorkList $\neq \phi$) do
  remove n from WorkList
  $t = \{n\} \cup \bigcup_{n \xrightarrow{\epsilon} p \in \delta_N} E(p)$
  if $t \neq E(n)$
    $E(n) = t$
    WorkList = WorkList $\cup \{m | m \xrightarrow{\epsilon} n \in \delta_N\}$

DFA to Minimal DFA: Hopcroft's Algorithm

- A DFA from Subset construction can have a large number of states
  - Does not increase the time needed to scan a string
- Increases the space requirement of the scanner in memory
  - Speed of accesses to main memory may turn out to be the bottleneck
  - Smaller scanner has better chances of fitting in the processor cache

DFA to Minimal DFA: Hopcroft's Algorithm

Minimization

$T = \{D_A, \{D - D_A\}\}$

$P = \phi$

while($P \neq T$) do

  $P = T$

  $T = \phi$

  for each set $p \in P$ do

    $T = T \cup \text{Split}(p)$

Split(S)

for each $c \in \Sigma$ do

  if c splits S into s_1 and s_2

    return $\{s_1, s_2\}$

return S

Realizing Scanners

Tokens, Patterns, and Lexemes

f	l	o	a	t		a	b	s	_	z	e	r	o		=		-	2	7	3	;	/	*	K	e	l	v	i	n	*	/

- **Token**
  - A string of characters which logically belong together in a syntactic category
  - Sentences consist of a string of tokens
  - For example, **float**, **identifier**, **equal**, **minus**, **intnum**, **semicolon**
  - Tokens are treated as terminal symbols of the grammar specifying the source language
  - May have an optional attribute

Tokens, Patterns, and Lexemes

- **Pattern**
  - The rule describing the set of strings for which the same token is produced
  - The pattern is said to match each string in the set
  - **`float`**, letter(letter|digit|_)*, =, -, digit^{+}, ;
- **Lexeme**
  - The sequence of characters matched by a pattern to form the corresponding token
  - “`float`”, “`abs_zero`”, “`=`”, “`-`”, “`273`”, “`;`”

- An attribute of a token is a value that the scanner extracts from the corresponding lexeme and supplies to the syntax analyzer
  - What can be important attributes? Where is this information stored?

Tokens in Programming Languages

- Keywords, operators, identifiers (names), constants, literal strings, punctuation symbols (parentheses, brackets, commas, semicolons, and colons)
- Attributes for tokens (apart from the integer representing the token)
  - identifier: the lexeme of the token, or a pointer into the symbol table where the lexeme is stored by the LA
  - intnum: the value of the integer (similarly for floatnum, etc.)
  - string: the string itself
  - The exact set of attributes are dependent on the compiler designer

Role of a Lexical Analyzer

- Identify tokens and corresponding lexemes
- Construct constants: for example, convert a number to token `num` and pass the value as its attribute
  - `31` becomes `<num, 31>`
- Recognize keyword and identifiers
  - `counter = counter + increment` becomes `id = id + id`
  - Check that `id` here is not a keyword
- Discard whatever does not contribute to parsing
  - White spaces (blanks, tabs, newlines) and comments

Specifying and Recognizing Patterns and Tokens

- Patterns are denoted with regular expressions, and recognized with finite state automata

- Regular definitions, a mechanism based on regular expressions, are popular for specification of tokens
- Transition diagrams, a variant of finite state automata, are used to implement regular definitions and to recognize tokens
  - Usually used to model LA before translating them to executable programs

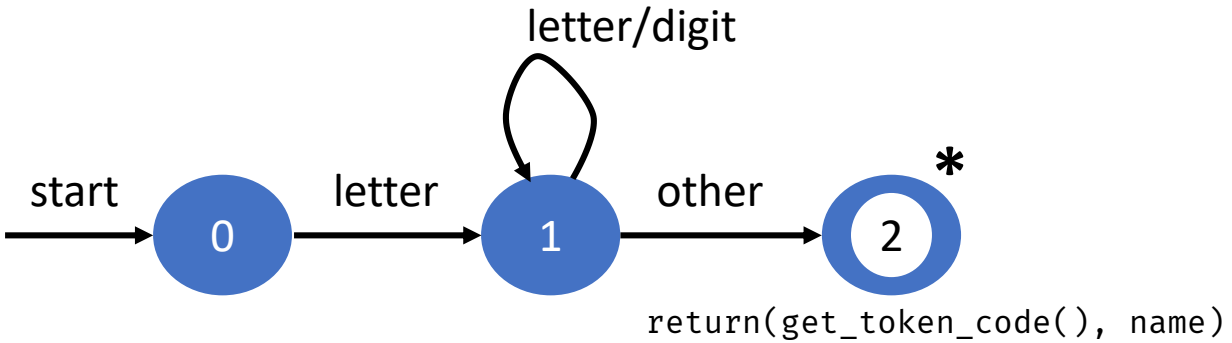
Transition Diagrams

- Transition diagrams (TDs) are generalized DFAs with the following differences
  - Edges may be labelled by a symbol, a set of symbols, or a regular definition
  - Few accepting states may be indicated as retracting states
    - Indicates that the lexeme does not include the symbol that transitions to the accepting state
  - Each accepting state has an action attached to it
    - Action is executed when the state is reached
    - Typically, such an action returns a token and its attribute value

Examples of Transition Diagrams

Identifiers and reserved words

$letter = [a{-}zA{-}Z]$
$digit = [0{-}9]$
$identifier = letter(letter|digit)^*$



- * indicates a retraction state
- `get_token_code()` searches a table to check if the name is a reserved word and returns its integer code if so
- Otherwise, it returns the integer code of the IDENTIFIER token, with `name` containing the string of characters forming the token
  - Name is not relevant for reserved words

A Sample Specification

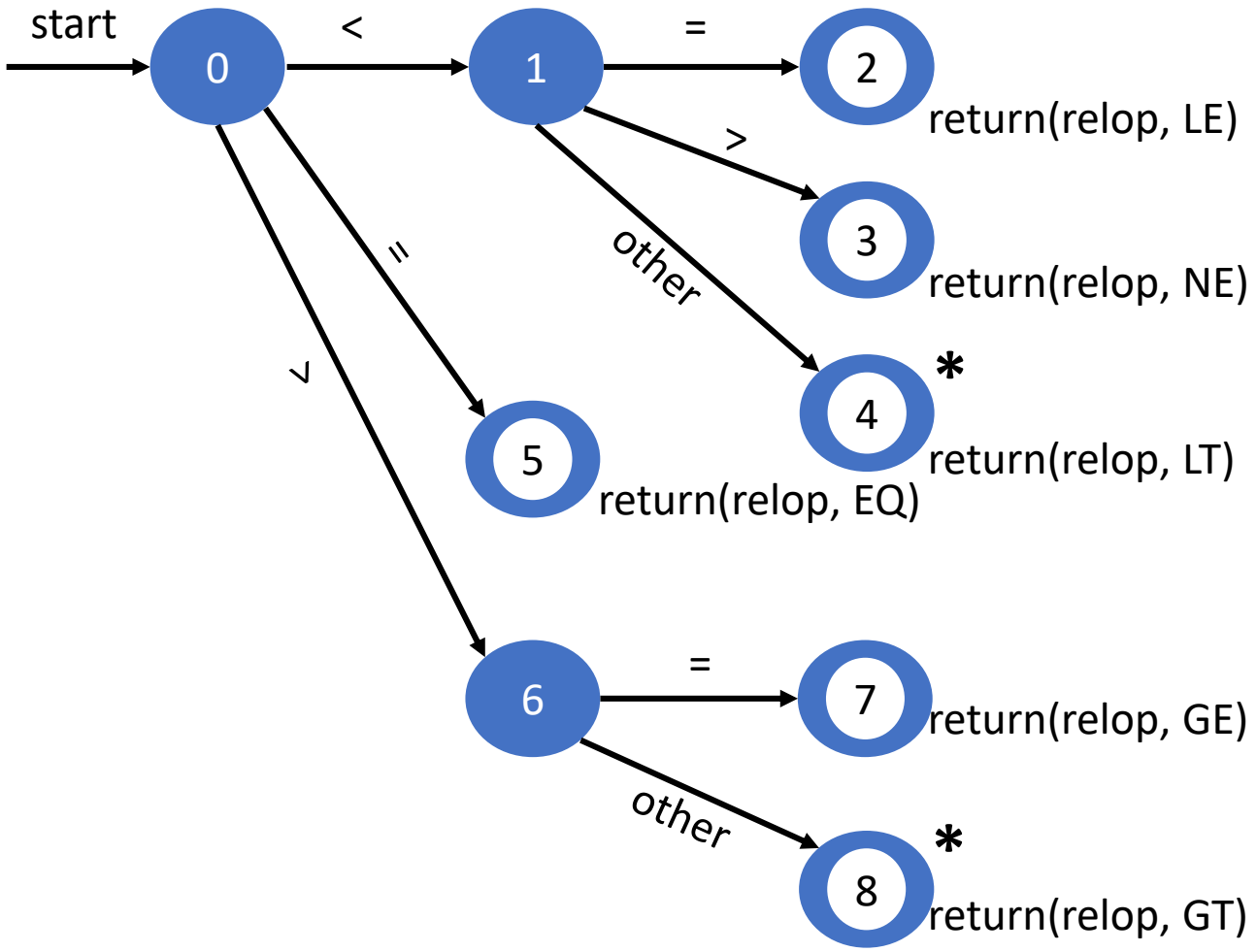
$stmt \longrightarrow$ **if** $expr$ **then** $stmt$
| **if** $expr$ **then** $stmt$ **else** $stmt$
| ϵ
$expr \longrightarrow term$ **relop** $term$
| $term$
$term \longrightarrow$ **id**
| **number**

$digit \longrightarrow [0-9]$
$digits \longrightarrow digit^+$
$number \longrightarrow digits\ (.digits)?\ (E[+-]?\ digits)?$
$letter \longrightarrow [A-Za-z]$
$id \longrightarrow letter\ (letter \mid digit)^*$
$if \longrightarrow$ if
$then \longrightarrow$ then
$else \longrightarrow$ else
$relop \longrightarrow$ < | > | <= | >= | = | <>
$ws \longrightarrow$ (blank | tab | newline)$^+$

Tokens, Lexemes, and Attributes

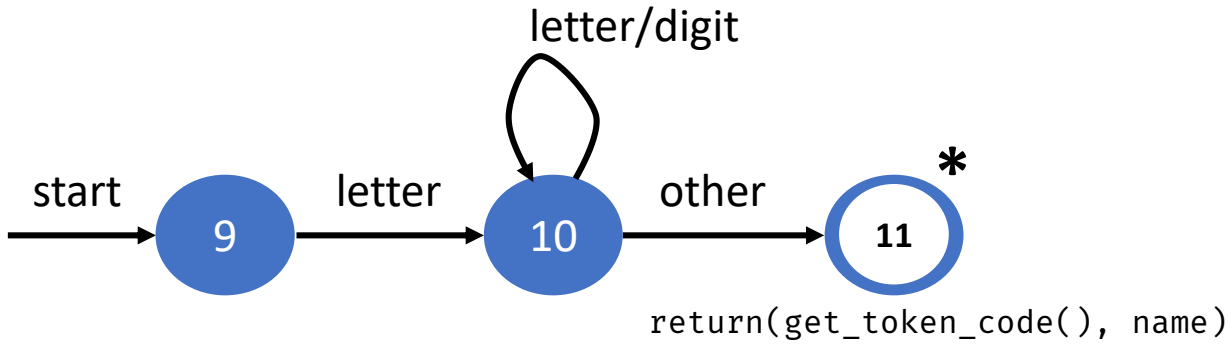
Lexemes	Token Name	Attribute Value
Any ws	--	--
if	**if**	--
$then$	**then**	--
$else$	**else**	--
Any id	**id**	Pointer to symbol table entry
Any $number$	**number**	Pointer to symbol table entry
<	**relop**	LT
<=	**relop**	LE
=	**relop**	EQ
<>	**relop**	NE
>	**relop**	GT
>=	**relop**	GE

Transition Diagram for **relop**

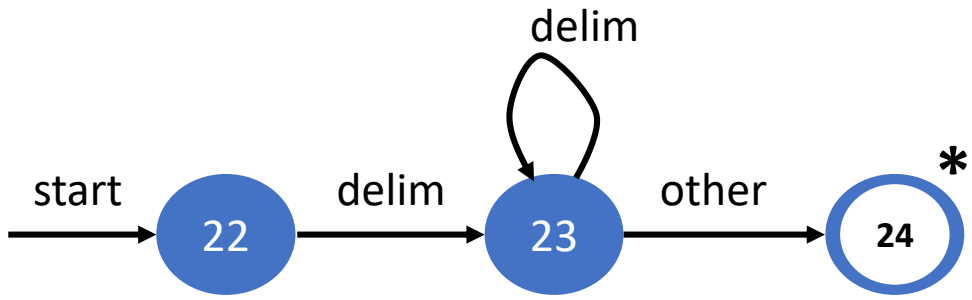


Transition Diagrams for IDs and Keywords

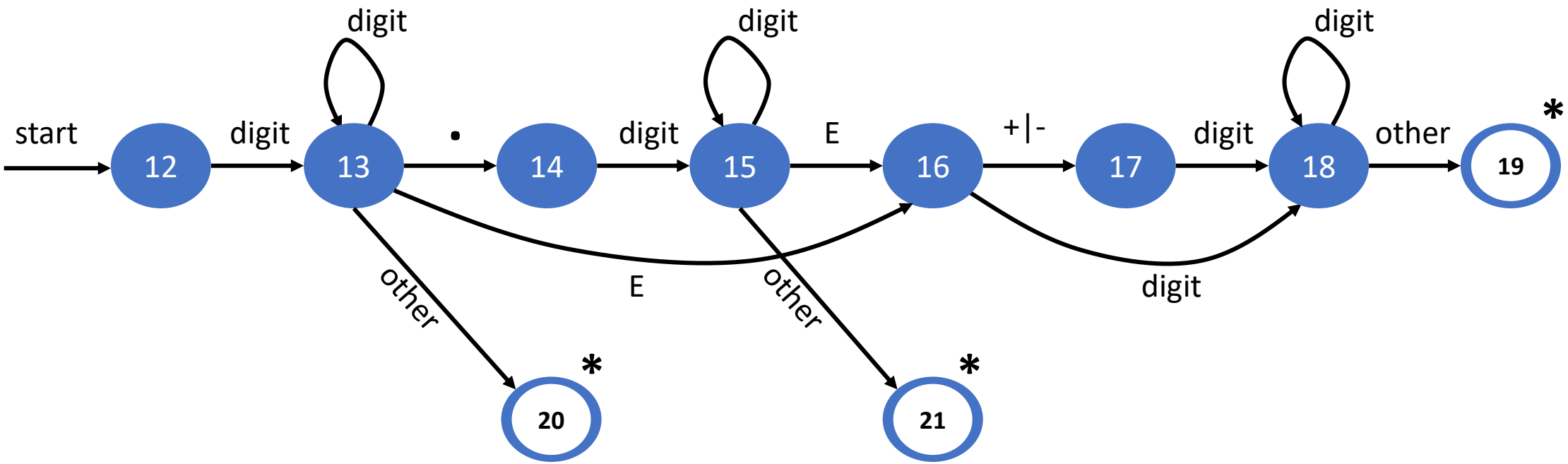
IDs and Keywords



Whitespace



Transition Diagram for Unsigned Numbers



Combining Transition Diagrams to form a Lexical Analyzer

- Different transition diagrams (TDs) must be combined appropriately to yield a scanner

How do we do this?

Combining Transition Diagrams to form a Lexical Analyzer

- Different transition diagrams (TDs) must be combined appropriately to yield a scanner
  - Try different transition diagrams one after another
    - For example, TDs for reserved words, constants, identifiers, and operators could be tried in that order
  - However, this does not use the “longest match” characteristic
    - `thenext` would be an identifier, and not reserved word `then` followed by identifier `ext`
- To find the longest match, all TDs must be tried and the longest match must be used

Challenges in Lexical Analysis

- Certain languages like PL/I do not have any reserved words
  - **`while`**, **`do`**, **`if`**, and **`else`** are reserved in C but not in PL/I
  - Makes it difficult for the scanner to distinguish between keywords and user-defined identifiers

```
if then then then = else else else = then

if if then then = then + 1
```

Challenges in Lexical Analysis

- Certain languages like PL/I do not have any reserved words
  - **`while`**, **`do`**, **`if`**, and **`else`** are reserved in C but not in PL/I
  - Makes it difficult for the scanner to distinguish between keywords and user-defined identifiers

- PL/I declarations
  - `DECLARE(`arg_1`,`arg_2`,`arg_3`,…,`arg_n`)`
  - Cannot tell whether `DECLARE` is a keyword with variable definitions or is a procedure with arguments until after "`)`"
- Requires arbitrary lookahead and very large buffers
  - Worse, the buffers may have to be reloaded in case of wrong inferences

Challenges in Lexical Analysis

```
fi (a == g(x)) …
```

- Is `fi` a typo or a function call?
  - Remember, `fi` is a valid lexeme for IDENTIFIER

- Think C++
  - Template syntax: `Foo<Bar>`
  - Stream syntax: `cin >> var;`
  - Nested templates: `Foo<Bar<Bazz>>`

- Can these problems be resolved by lexical analysers alone?

Challenges in Lexical Analysis

- Consider a fixed-format language like Fortran
  - 80 columns per line
  - Column 1-5 for the statement number/label column
  - Column 6 for continuation mark
  - Column 7-72 for the program statements
  - Column 73-80 Ignored (used for other purposes)
  - Letter C in Column 1 meant the current line is a comment

Challenges in Lexical Analysis

- In fixed-format Fortran, some keywords are context-dependent
  - In the statement, `DO 10 I = 10.86`, `DO10I` is an identifier, and **DO** is not a keyword
  - But in the statement, `DO 10 I = 10, 86`, **DO** is a keyword
  - Blanks are not significant in Fortran and can appear in the midst of identifiers, but not so in C
    - Variable "`counter`" is same as "`count er`"
  - In Fortran, blanks are important only in literal strings
  - Reading from left to right, one cannot distinguish between the two until the "," or "." is reached
    - Requires look ahead for resolution

Programming Languages vs Natural Languages

- Meaning of words in natural languages is often context-sensitive
  - An English word can be a noun or a verb (for e.g., “stress”)
  - “are” is a verb, “art” is a noun, and “arz” is undefined

- Grammars are rigorously specified to provide meaning
  - Words in a programming language are always lexically specified
    - Any string in `(1…9)(0…9)*` is a positive integer

Why separate tokens and lexemes?

- Rules to govern the lexical structure of a programming language is called its microsyntax

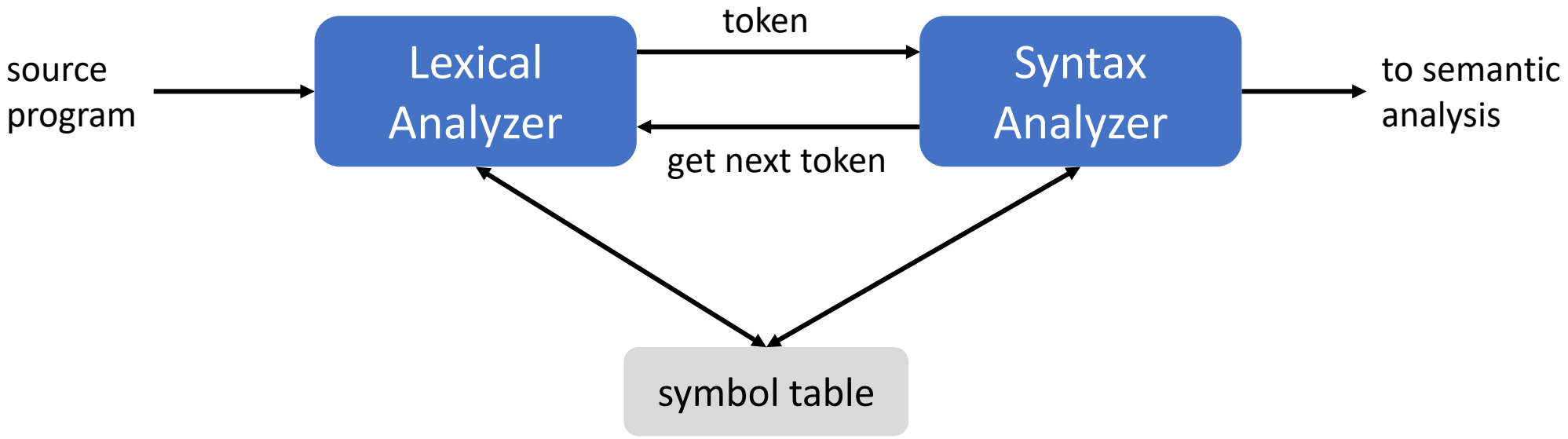
- Separating syntax and microsyntax allows for a simpler parser
  - Parser only needs to deal with syntactic categories like IDENTIFIER

Lexical Analysis as a Separate Phase

- Simplifies the compiler design
  - I/O issues are limited to only the lexical analyzer, so better portability
- Allows designing a more compact and faster parser
  - Comments and whitespace need not be handled by the parser
    - A parser is more complicated than a lexical analyzer and shrinking the grammar makes the parser faster
  - No rules for numbers, names, and comments are needed in the parser
- Scanners based on finite automata are more efficient to implement than pushdown automata used for parsing (due to stack)

Interfacing with Parser

- A unique integer representing the token is passed by LA to the parser



Error Handling in Lexical Analysis

- LA cannot catch any other errors except for simple errors such as illegal symbols
- In such cases, LA skips characters in the input until a well-formed token is found
  - This is called “panic mode” recovery
- We can think of other possible recovery strategies
  - Delete one character from the remaining input, or insert a missing character
  - Replace a character, or transpose two adjacent characters
  - Idea is to see if a single (or few) transformation(s) can repair the error

Other Uses of Lexical Analysis Concepts

- UNIX command line tools like grep, awk, and sed
- Search tools in editors
- Word-processing tools

Implementing Scanners

Implementing Scanners

1. Specify REs for each syntactic category
2. Construct an NFA for each RE
3. Join the NFAs with ϵ-transitions
4. Create the equivalent DFA
5. Minimize the DFA
6. Generate code to implement the DFA

Implementation Considerations

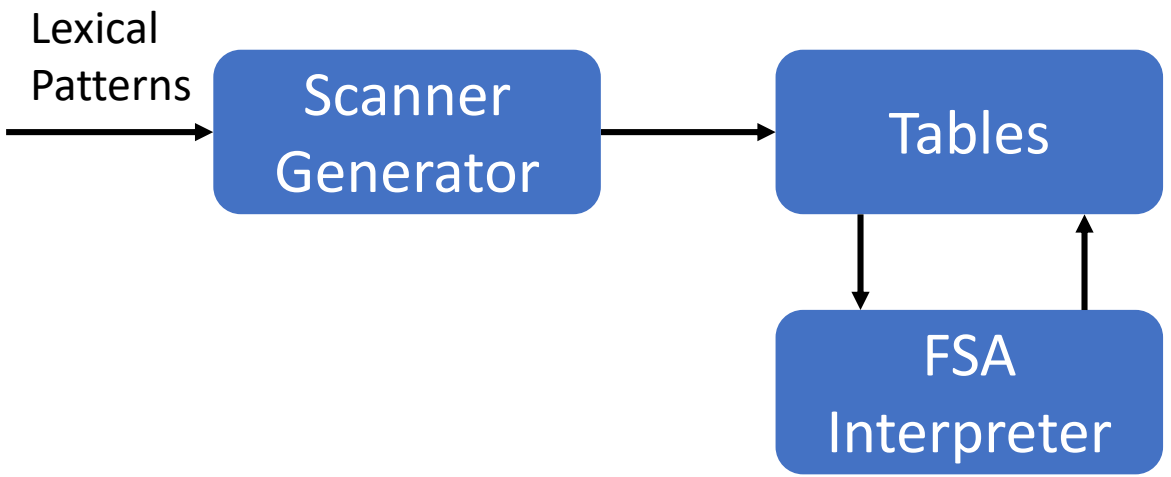
- Speed is paramount for scanning
  - Processes every character from an input source program

- Repeatedly read the input character and simulate the corresponding DFA
  - Table-driven scanners
  - Direct-coded scanners
  - Hand-coded scanners

High-Level Idea in Implementing Scanners

- Read input character one by one
- Look up the transition based on the current state and the input character
- Switch to the new state
- Check for termination conditions, i.e., accept and error
- Repeat

Table-Driven Scanner



- Register specification
  - For example, r1 and r27

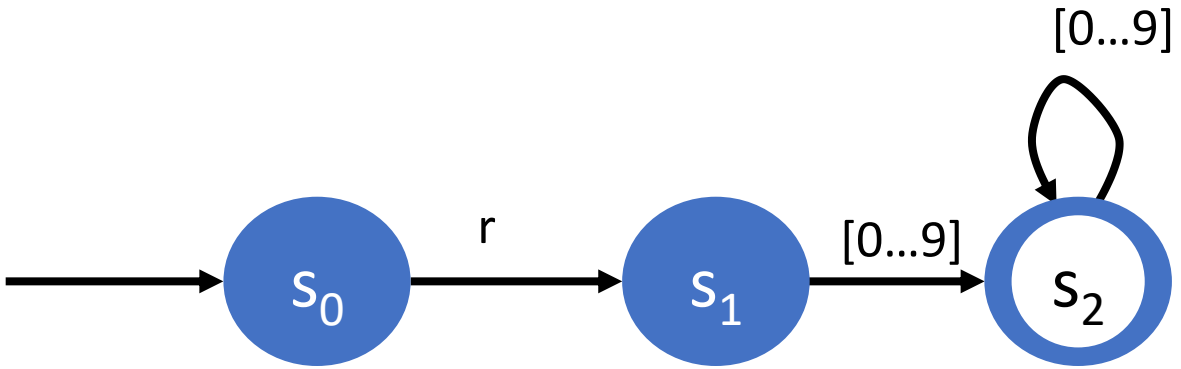


Table-Driven Scanner

```
char = getNextChar()
state = s_0
while (char ≠ EOF)
  state = δ(state, char)
  char = getNextChar()
if (state ∈ S_F)
  accept
else
  error
```

$\boldsymbol{\delta}$	R	0,1,…,9	other
$\boldsymbol{s_0}$	s_1	s_e	s_e
$\boldsymbol{s_1}$	s_e	s_2	s_e
$\boldsymbol{s_2}$	s_e	s_2	s_e
$\boldsymbol{s_e}$	s_e	s_e	s_e

Direct-Coded Scanner

```
goto s0

s0:  char = getNextChar()
     if (char == 'r')
       goto s1
     else
       goto se

s1:  char = getNextChar()
     if ('0' ≤ char ≤ '9')
       goto s2
     else
       goto se

s2:  char = nextChar()
     if ('0' ≤ char ≤ '9')
       goto s2
     else if (char == EOF)
       accept
     else
       goto se

se:  error
```

Hand-Coded Scanner

- Many real-world compilers use hand-coded scanners for further efficiency
  - For e.g., gcc 4.0 uses hand-coded scanners in several of its front ends

1. Fetching a character one-by-one from I/O is expensive
   - Fetch a number of characters in one go and store in a buffer
2. Use double buffering

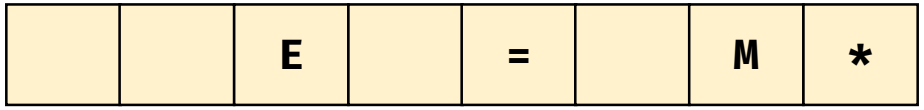
Reading Characters from Input

- A scanner reads the input character by character
  - Reading the input will be very inefficient if it requires a system call for every character read
- Input buffer
  - OS reads a block of data, supplies scanner the required amount, and stores the remaining portion in a buffer called buffer cache
  - In subsequent calls, actual I/O does not take place as long as the data is available in the buffer cache
  - Scanner uses its own buffer since requesting OS for single character is also costly due to context-switching overhead

Optimizing Reads from the Buffer

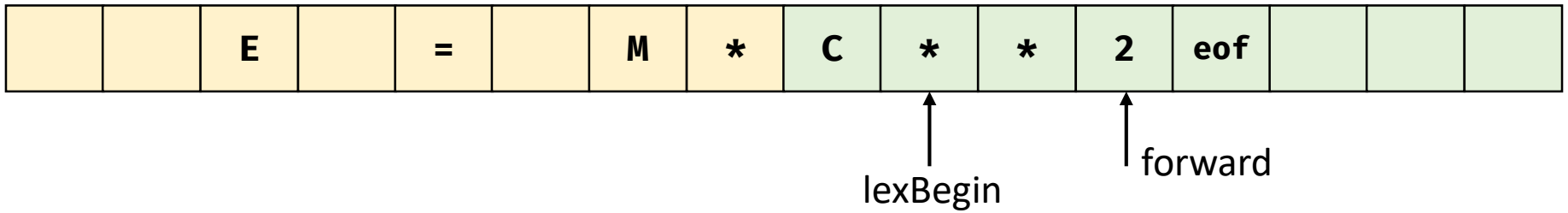
- A buffer at its end may contain an initial portion of a lexeme

```
E = M*C**2
```



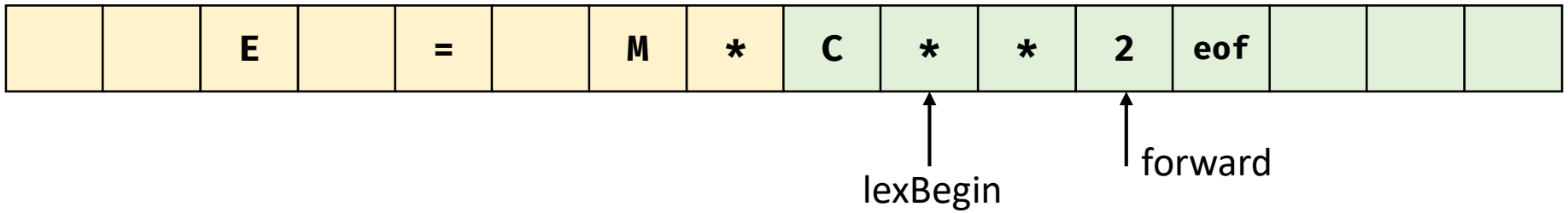
Optimizing Reads from the Buffer

- A buffer at its end may contain an initial portion of a lexeme
  - It creates problem in refilling the buffer, so a two-buffer scheme is used
  - The two buffers are filled alternatively



Optimizing Reads from the Buffer

- Read from buffer
  - (1) Check for end of buffer, and (2) test the type of the input character
  - If end of buffer, then reload the other buffer

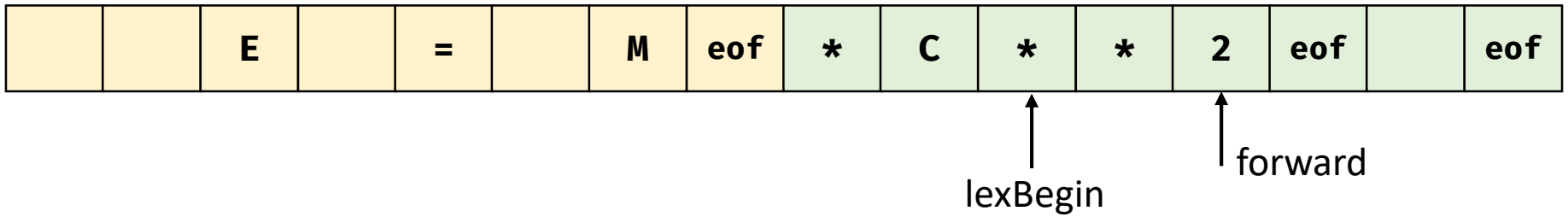


Advance Forward Pointer

```
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 {
  forward++
}
```

Optimizing Reads from the Buffer

- A sentinel character (say `eof`) is placed at the end of buffer to avoid two comparisons



Optimizing Reads from the Buffer

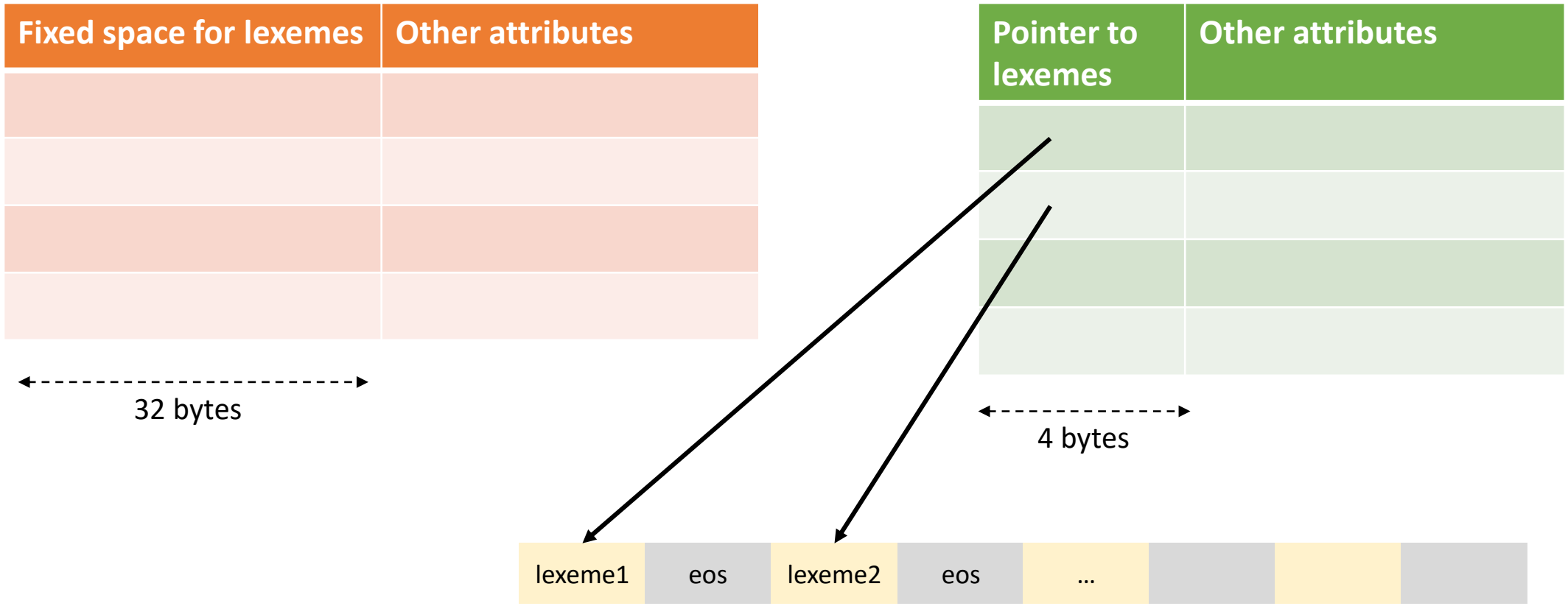
```
switch (*forward++) {
  case eof:
    if (forward is at end of first buffer) {
      reload second buffer
      forward = beginning of second buffer
    } else if (forward is at end of second buffer) {
      reload first buffer
       forward = beginning of first buffer
    } else {  // end of input
      break
    }
  …
  // case for other characters
}
```

Symbol Table

- Stores information for subsequent phases
- Symbol table interface
  - `insert(s, t)`: save lexeme s and token t and return pointer
  - `lookup(s)`: return index of entry for lexeme s or 0 if s is not found

- Fixed amount of space to store lexemes might waste space

Implementation of Symbol Table



Handling Keywords

- Two choices: use separate REs or compare lexemes for ID token

- Consider token DIV and MOD with lexemes `div` and `mod`
- Initialize symbol table with `insert("div", DIV)` and `insert("mod", MOD)` before beginning of scanning
  - Any subsequent insert fails
  - Any subsequent lookup returns the keyword value
  - These lexemes can no longer be used as an identifier

References

- A. Aho et al. Compilers: Principles, Techniques, and Tools, 2nd edition, Chapter 3.
- K. Cooper and L. Torczon. Engineering a Compiler, 2nd edition, Chapter 2.
- A. Karkare. CS 335: Compiler Design, https://www.cse.iitk.ac.in/~karkare/Courses/cs335.