Lexical Analysis (Scanning)

Chapter 2

Lexical Analysis (Scanning)

- Basic Ideas
  - divide character stream into tokens
  - a token is the smallest logical unit in code
  - common categories:

easy to enum.

hard to enum.

keywords: "`if`", "`for`", "`while`", …

special symbols: "`+`", "`-`", "`=`", "`[`", …

number: "`4`", "`23`", "`6.63`", "001", …

ID: "`a`", "`abs`", "`sum`", …

…

Scanning

- Token Categories
  - common categories: keywords, special symbols, number, and ID.
  - e.g.,

```
int bigger(int a, int b)
{
   int c = 0;
   if (a > b)
      c = a;
   else
      c = b;
   return c;
}
```

Scanning

- Define Tokens
  - define different kinds of tokens in enum

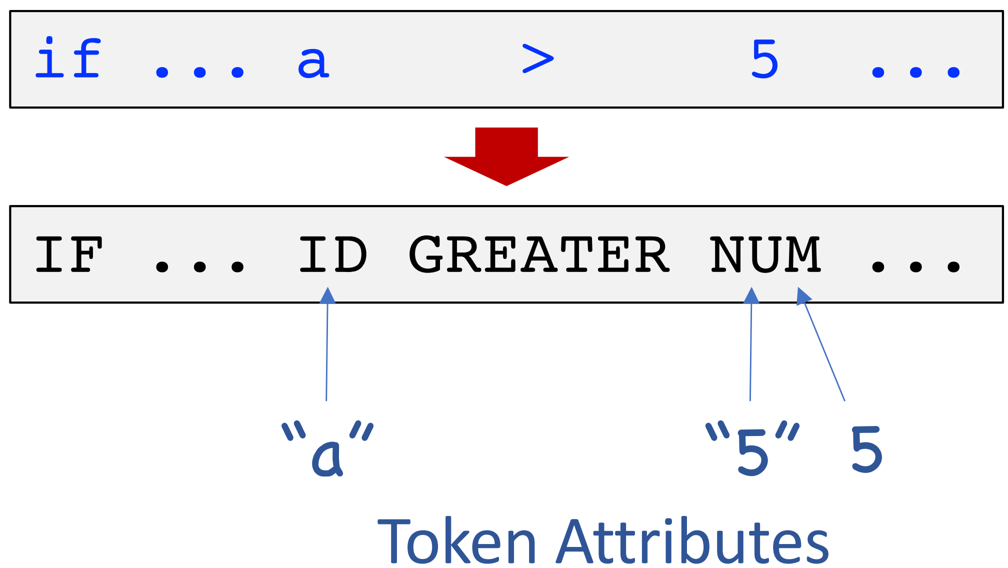
```
typedef enum
{
   IF,    // "if"
   ELSE,  // "else"
   PLUS,  // "+"
   NUM,   // "23"
   ID,    // "a"
   ...
} TokenType;
```

"Lexemes"

Scanning

- Token Attributes
  - A token may carry attributes (e.g., *stringval*, *numberval*, ...)

```
typedef enum
{
  IF,    // "if"
  ELSE, // "else"
  PLUS, // "+"
  NUM,  // "23"
  ID,   // "a"
  ...
} TokenType;
```



Scanning

- Token Attributes
  - A token may carry attributes (e.g., *stringval*, *numberval*, ...)

```
typedef struct
{
  TokenType tokenval;
  char *stringval;
  int numval;
  ...
} TokenRecord;
```

```
if ... a      >      5   ...
```

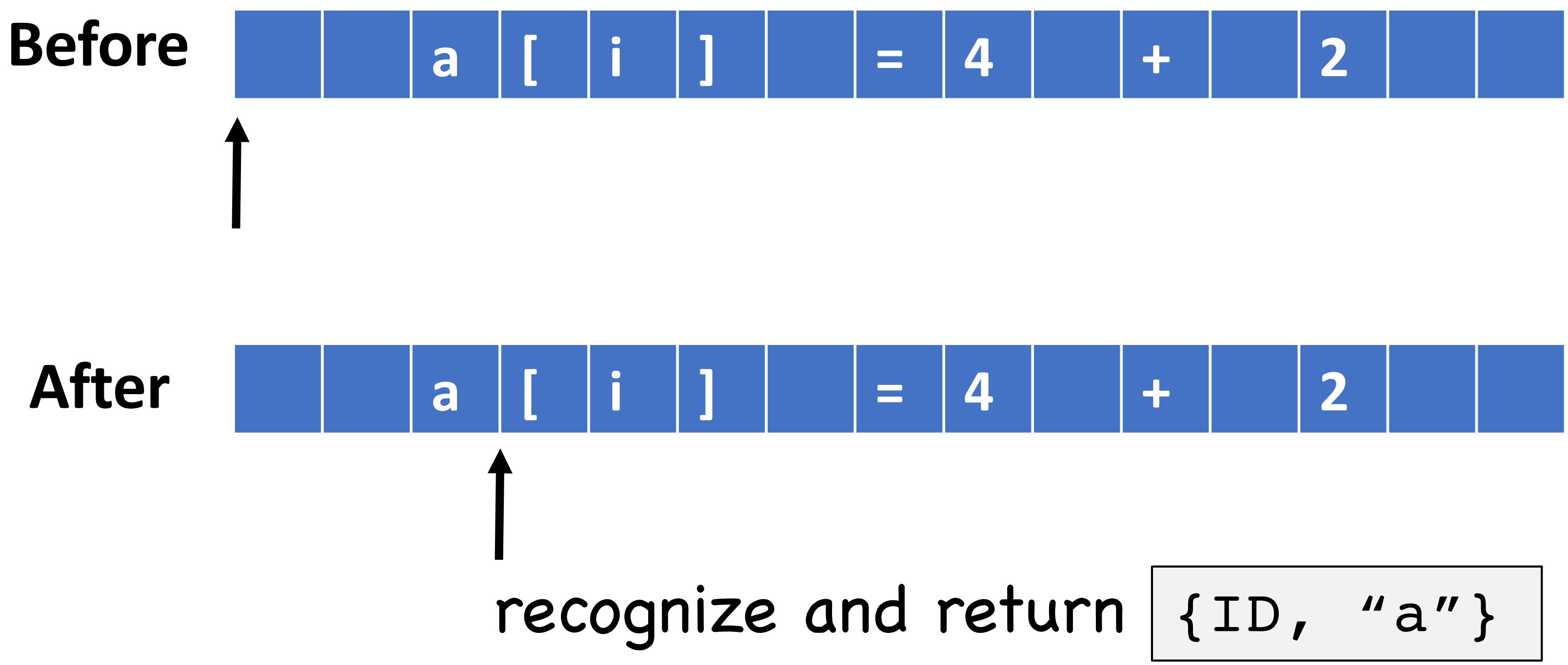
```
IF ... ID GREATER NUM ...
```

"a" "5" 5

Token Attributes

Scanning

- getToken()
  - scanner is often driven by the parser



Regular Expressions

Regular Expressions

- Basics
  - A regex r represents a pattern of strings, where
  - the set of strings is called regular language $L(r)$
  - the character set is called alphabet Σ
  - Given an alphabet Σ, we can construct regex r:

if r = a, a in Σ	$L(r) = \{a\}$	
if $r = \phi$	$L(r) = \{\ \}$	empty set
if $r = \varepsilon$	$L(r) = \{\varepsilon\}$	a set w/ an empty string

Regular Expressions

- Operations
  - alternation “a|b”
  - concatenation “ab”
  - repetition “a*”

given regex r and s, $L(r|s) = L(r) \cup L(s)$

given regex r and s, $L(rs) = L(r)L(s)$

given regex r, $L(r^*) = \{\varepsilon\} \cup L(r) \cup L(rr) \cup L(rrr) \ldots$

Regular Expressions

- Examples
  - What is the language of (a|b)* ?

    {ε, a, b, aa, ab, ba, bb, aaa, ...}

  - What is the language of a|b* ?

    {ε, a, b, bb, bbb, bbbb, ...}

<u>Precedence:</u> <u>repetition > concatenation > alternation</u>

Regular Expressions

- Names
  - As a notational simplification

$(0|1|2|...|9)\ (0|1|2|...|9)^*$

$\mathit{digit} = 0|1|2|...|9$
$\mathit{numseq} = \mathit{digit}\ \mathit{digit}^*$

Regular Expressions

- Extended Regex
  - one or more repetitions `a+` = `aa*`
  - any character `.b` = `(a|b|c)b` if Σ = {a,b,c}
  - a range of characters

    `[abc]` or `[a-c]` = `(a|b|c)`

    `[acd]` = `(a|c|d)`
  - not `~(a|b)` or `[^ab]` = `c` if Σ = {a,b,c}
  - optional subexpressions

    `(a|b)?c = ac|bc|c`

Regular Expression

- Example
  - Rewrite the regex with only three core operators (concatenation/alternation/repetition)

(x+y)? . [^x-y] assume Σ = {x,y,z}

xx*y (x|y|z) z | (x|y|z)z

Token Specification

- Specify tokens with regex
  - Given the complexity, regex is perfect for this purpose

easy to enum.

hard to enum.

keywords: "`if`", "`for`", "`while`", …

special symbols: "`+`", "`-`", "`=`", "`[`", …

number: "`4`", "`23`", "`6.63`", "001", …

ID: "`a`", "`abs`", "`sum`", …

…

Token Specification

- Numbers
  - sequence of digits “23”
  - signed numbers “-12”, “+17”
  - decimal numbers “1.24”
  - scientific numbers “2.74E+2”

```
nat = [0-9]+

signedNat = [+-]? nat

decimalNum = signedNat \. nat

scientificNum = signedNat \. nat E signedNat

number = signedNat (\. nat)? (E signedNat)?
```

Token Specification

- Reserved Words

```
reserved = if | while | do | ...
```

- Identifiers
  - Begins with a letter; contains only letters and digits

```
letter = [a-zA-Z]

digits = [0-9]

identifier = letter(letter|digit)*
```

Token Specification

- Comments
  - Typically are “skipped” during scanning
  - Still need to be recognized so they can be skipped

```
{this is a Pascal comment}        \{[^\}]*\}

// this is a C/C++ comment        //[^\n]*
```

Token Specification

- Ambiguity
  - Token specification may contain ambiguities
  - Existing multiple ways to interpret the same substring

"if"	IF
"if"	identifier

"<>"	not equal
"<" ">"	less than, greater than

Keyword is preferred!

Longer token is preferred!

*(principle of **longest** substring)*

Token Specification

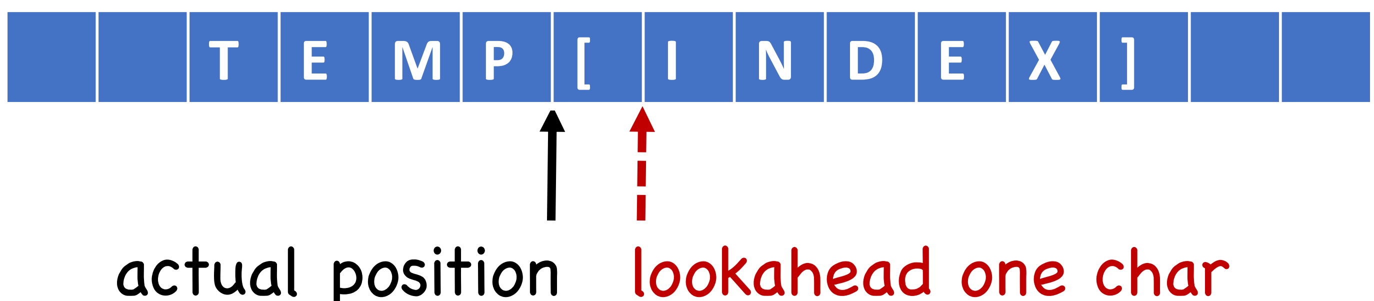
- Token Delimiters
  - Characters that imply a longer string cannot be a token
  - White spaces are delimiters
  - Comments could also be delimiters

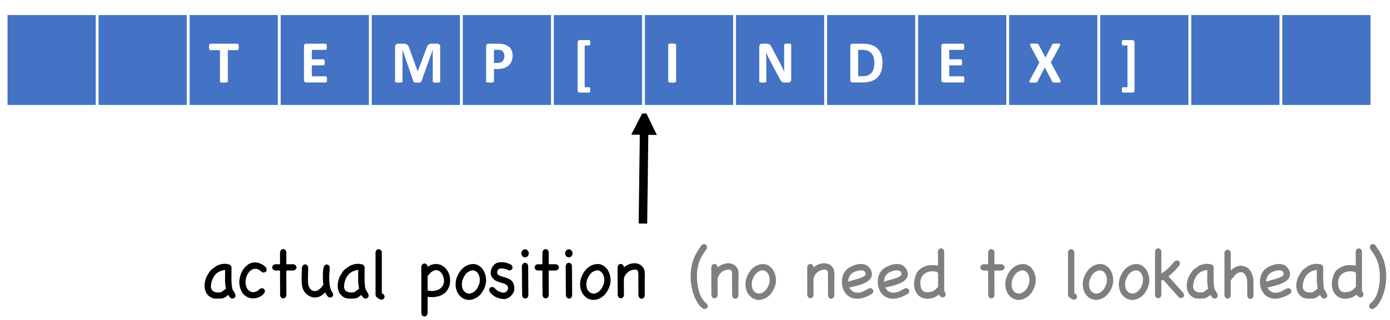
“xtemp=ytemp”	*“=”* is not part of any token
“int x”	*blank/newline/tab* are neither
“do//if”	*comments* are neither

whitespace=(newline|blank|tab|comment)+

Token Specification

- Token Delimiters
  - A delimiter ends a token, but not part of that token
  - Should not be consumed, but just be examined - Lookahead





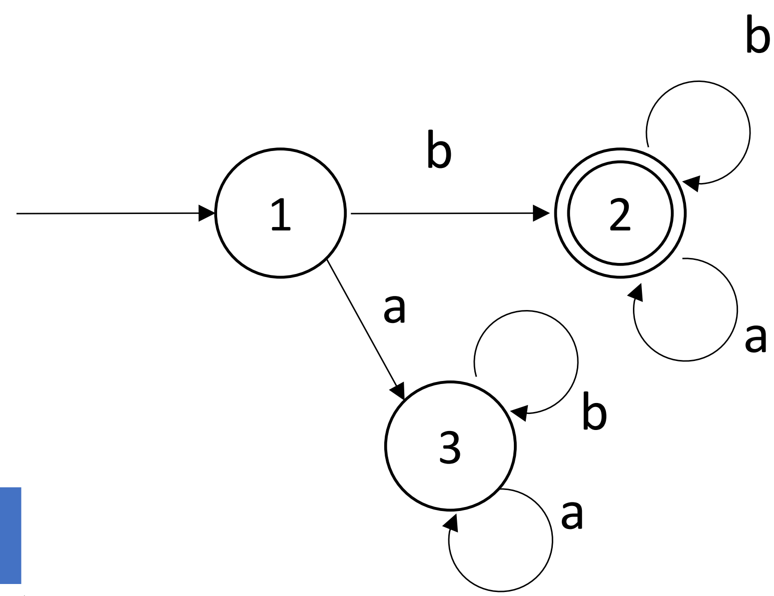
Finite Automata

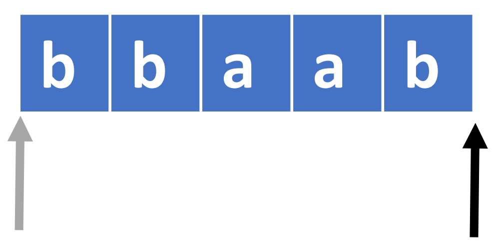
Finite Automata

- Equivalence
  - a regex specifies a regular language
  - FA accepts a regular language
  - regex ←→ FA

r = b(b|a)*

Σ = {a,b}



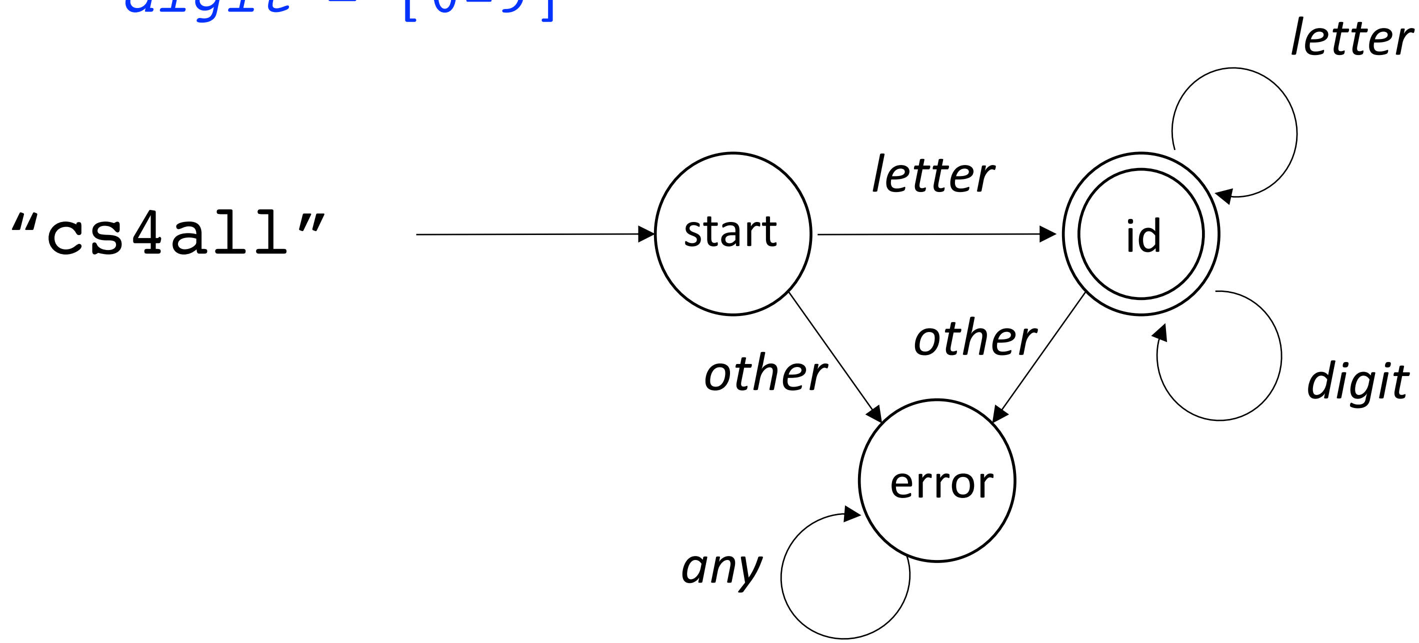


1 2 2 2 2 **2** **accept!**

Finite Automata

- Extensions and Simplification
  - name transitions w/ regex names (also, *other* and *any*)
  - error state

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

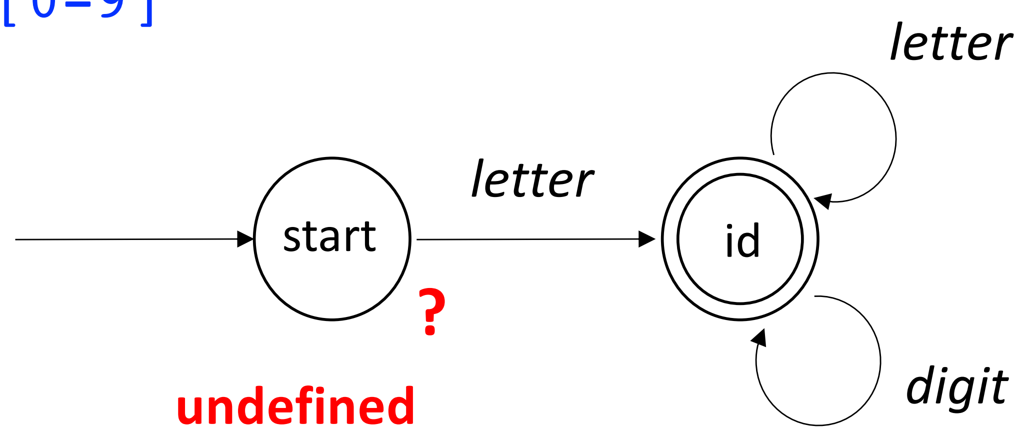


Finite Automata

- Extensions and Simplification
  - name transitions w/ regex names (also, *other* and *any*)
  - error state is often omitted

```
identifier = letter(letter|digit)*
letter = [a-zA-Z]
digit = [0-9]
```

“4all”

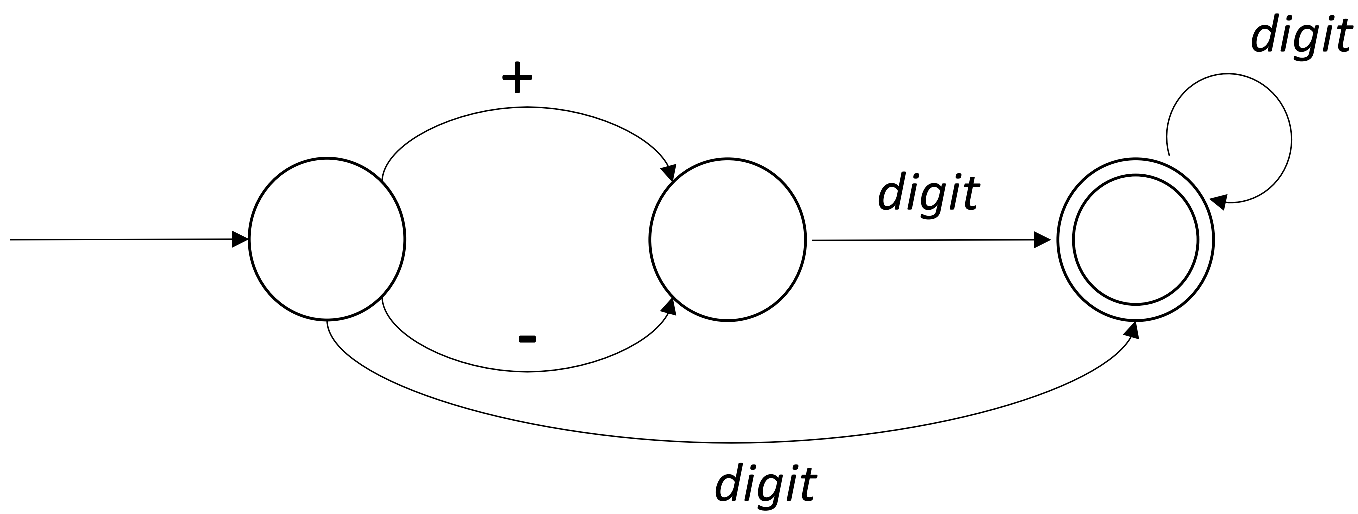


undefined transition: Error!

Finite Automata

- Exercise
  - FA for recognizing signed numbers

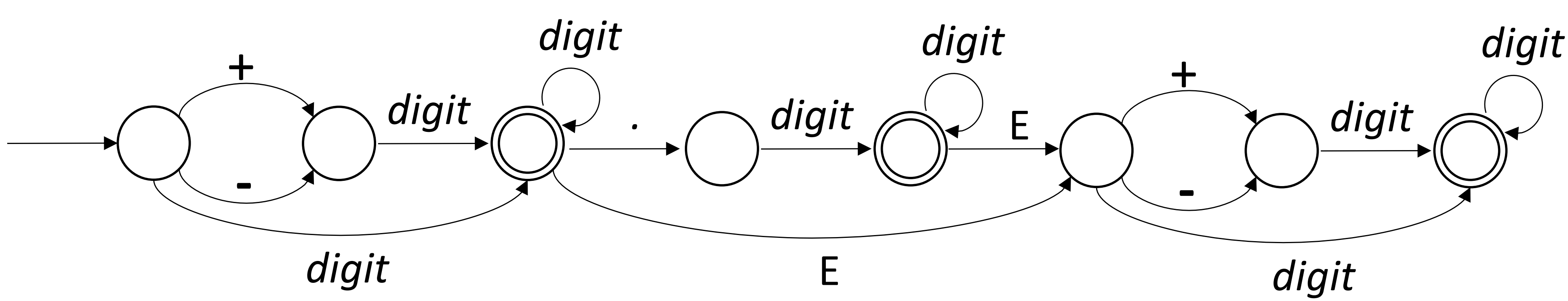
```
digit = [0-9]
nat = digit+
signedNat = (+|-)? nat
```



Finite Automata

- Exercise
  - FA for recognizing numbers

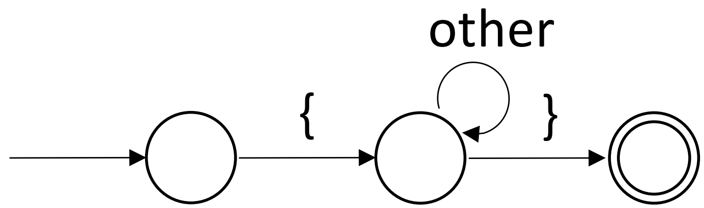
```
digit = [0-9]
nat = digit+
signedNat = (+|-)? nat
number = signedNat ("." nat)? (E signedNat)?
```



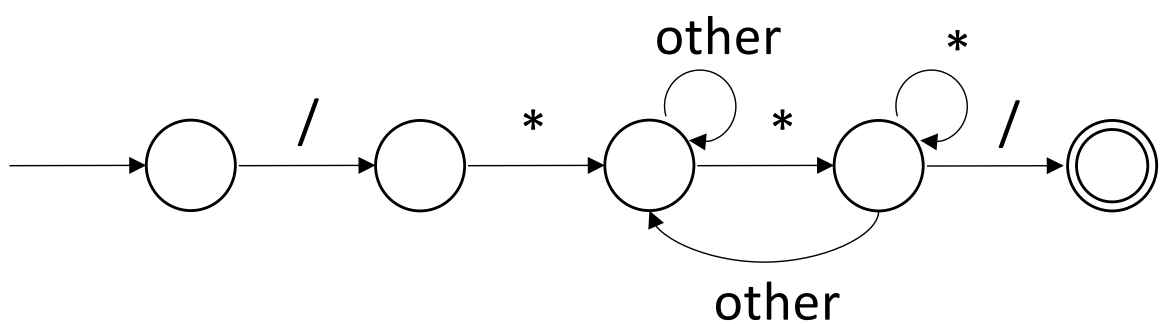
Finite Automata

- Exercise
  - FA for recognizing comments

```
\{[^\}]*\}
```

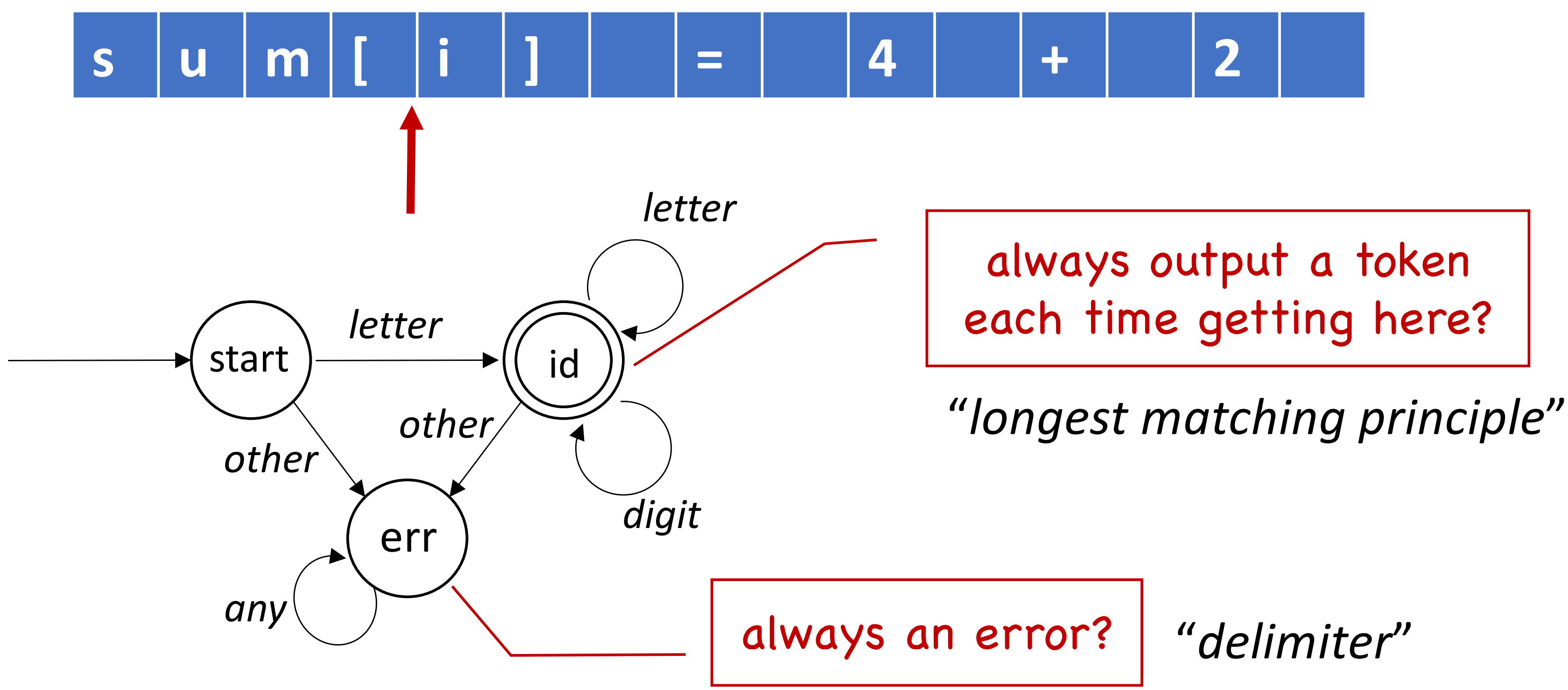



```
/* hello */
```



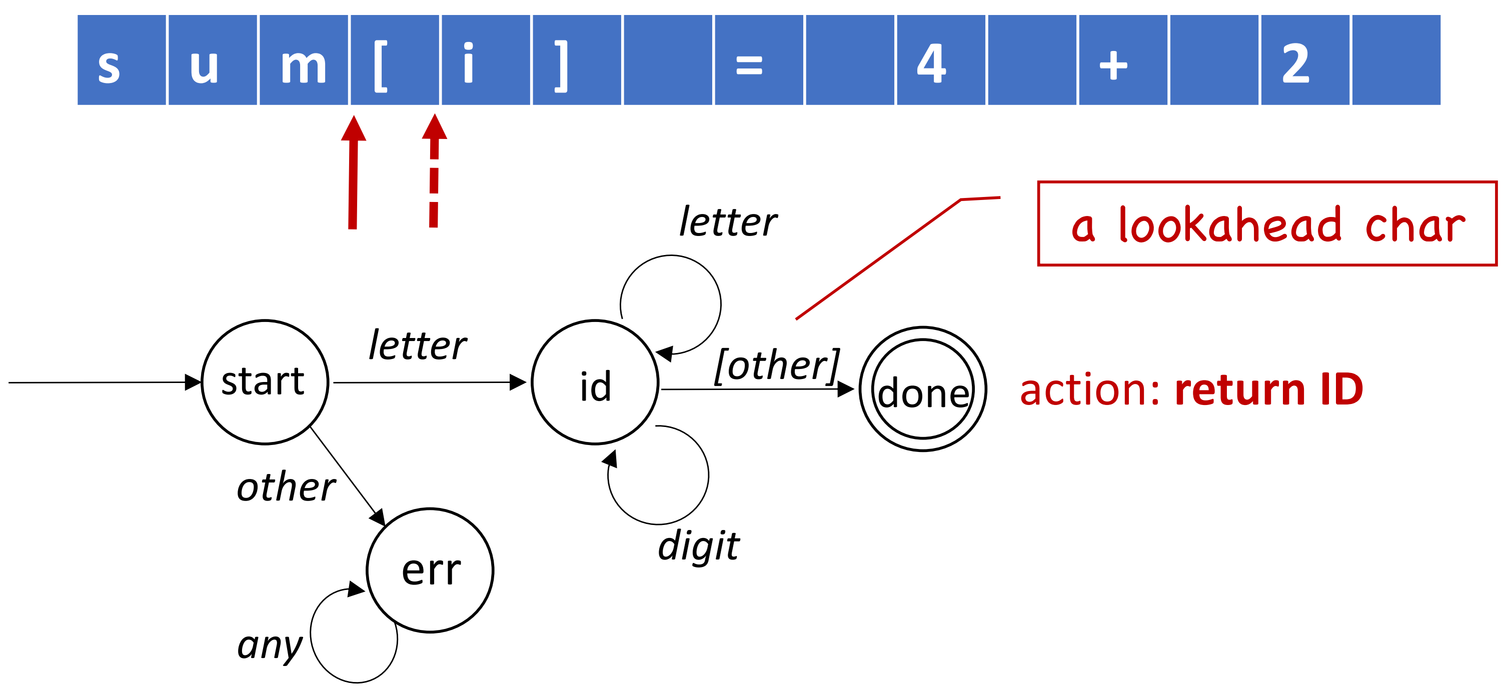
Finite Automata

- FA Actions
  - ”normal” state: copy a character to a token buffer
  - accept state: return a token & go back to intial state
  - error state: generate an error



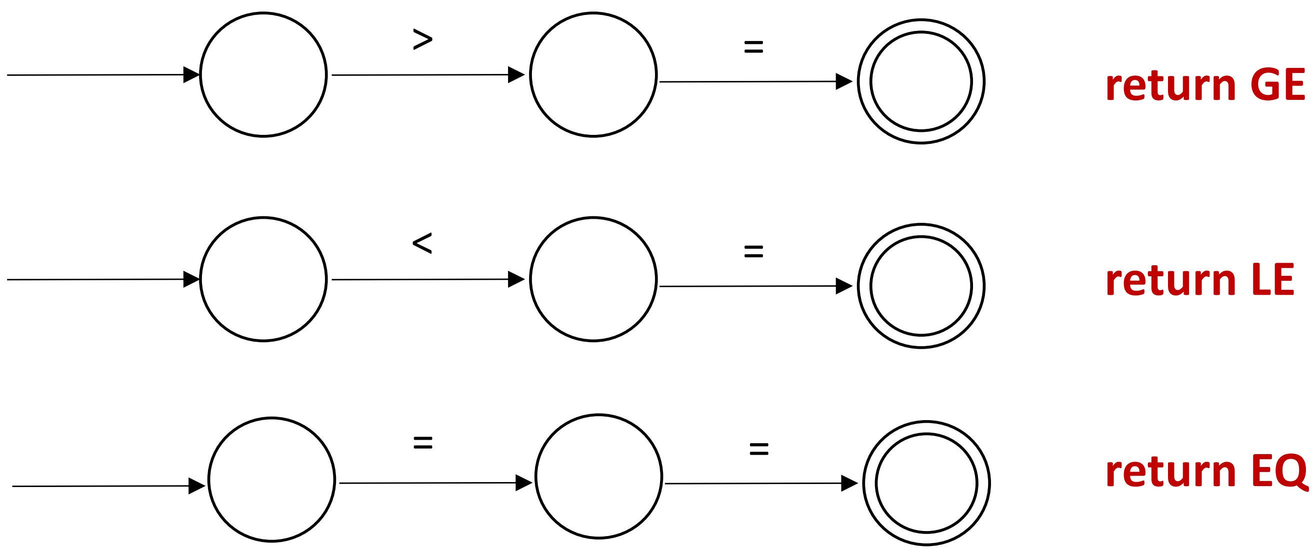
Finite Automata

- Adjusted FA
  - “error” state becomes an accept state
  - which has no further transition edges
  - *[other]* is from lookahead



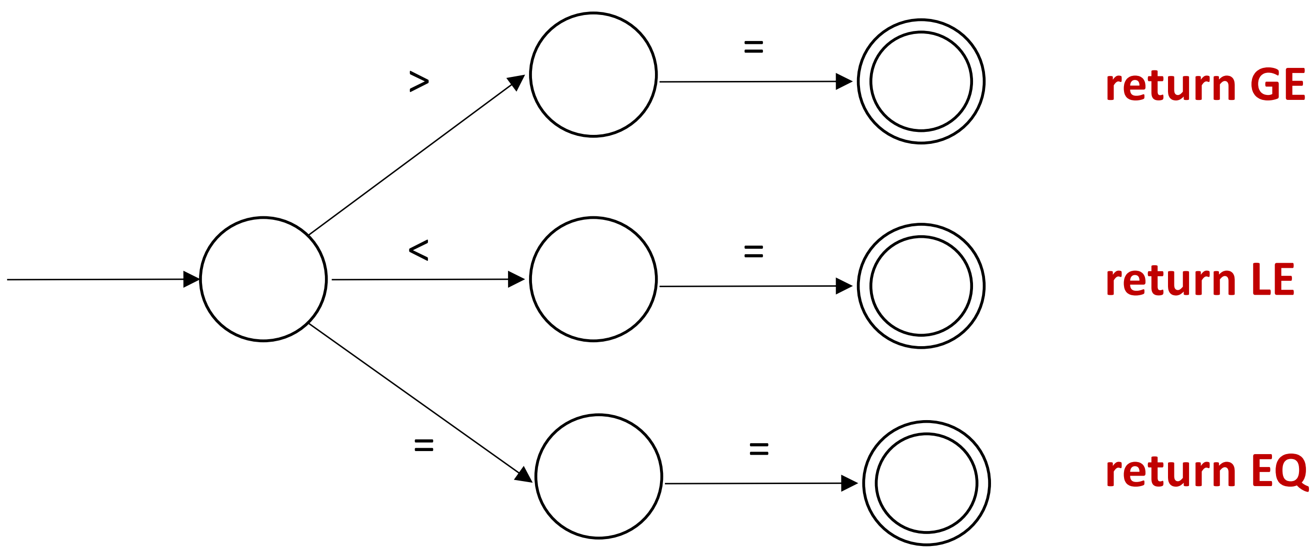
Finite Automata

- Recognize Multiple Types of Tokens
  - cannot track the states of all different FAs - too expensive!
  - **solution**: merge different FAs



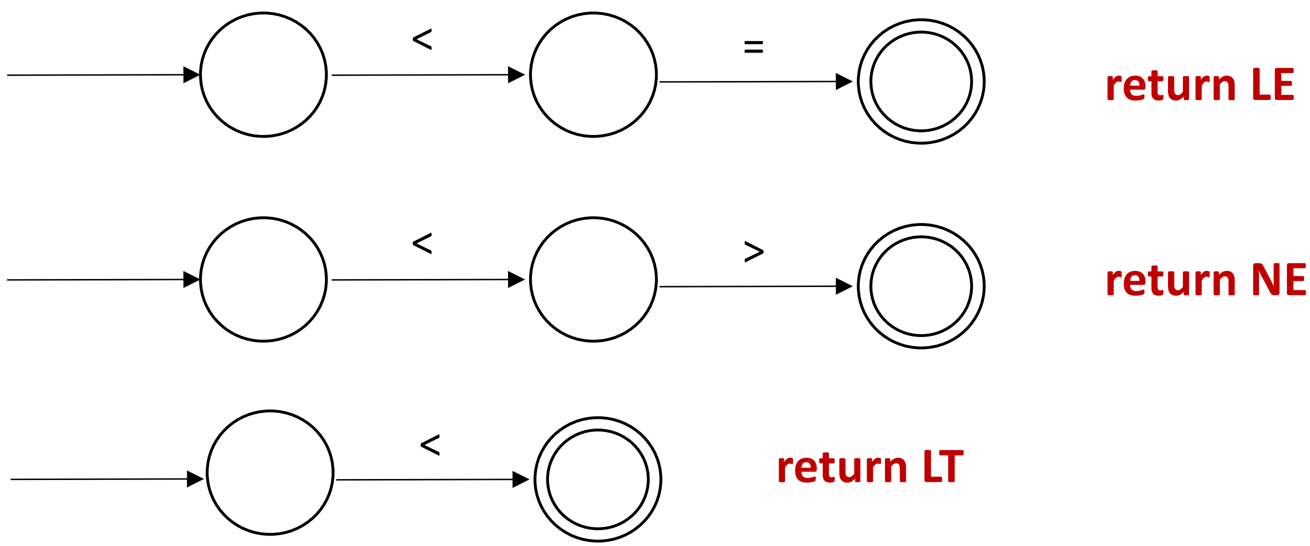
Finite Automata

- Recognize Multiple Tokens
  - tokens starting with different characters
  - easier to merge: simply combine their starting states



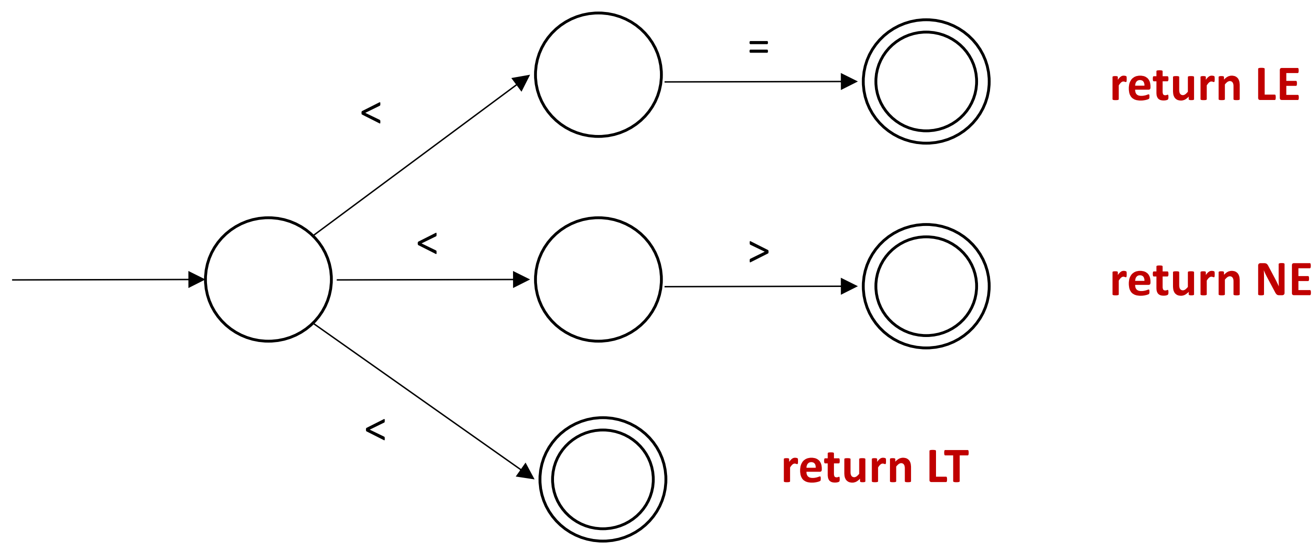
Finite Automata

- Recognize Multiple Tokens
  - tokens starting with the same character



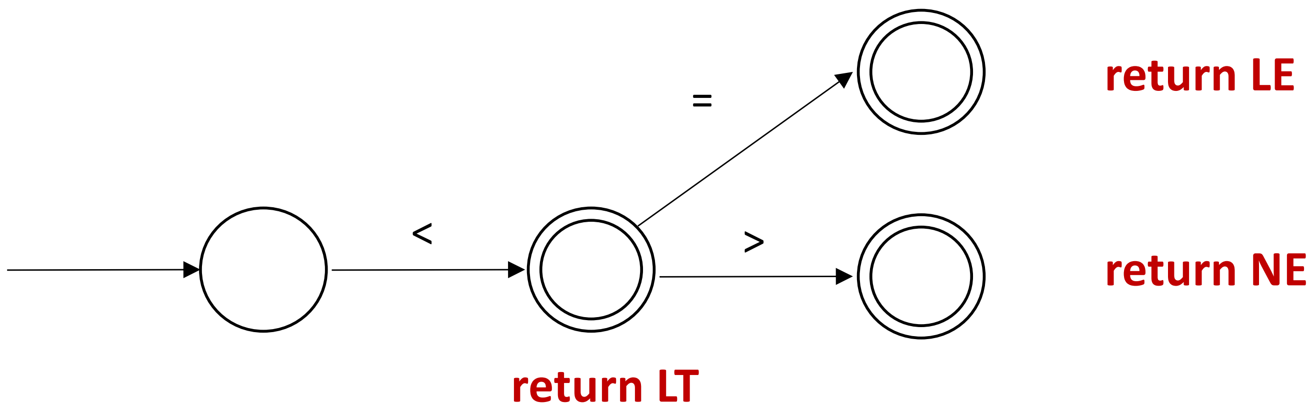
Finite Automata

- Recognize Multiple Tokens
  - it becomes an NFA (*non-deterministic finite automaton*)
  - expensive to run an NFA!



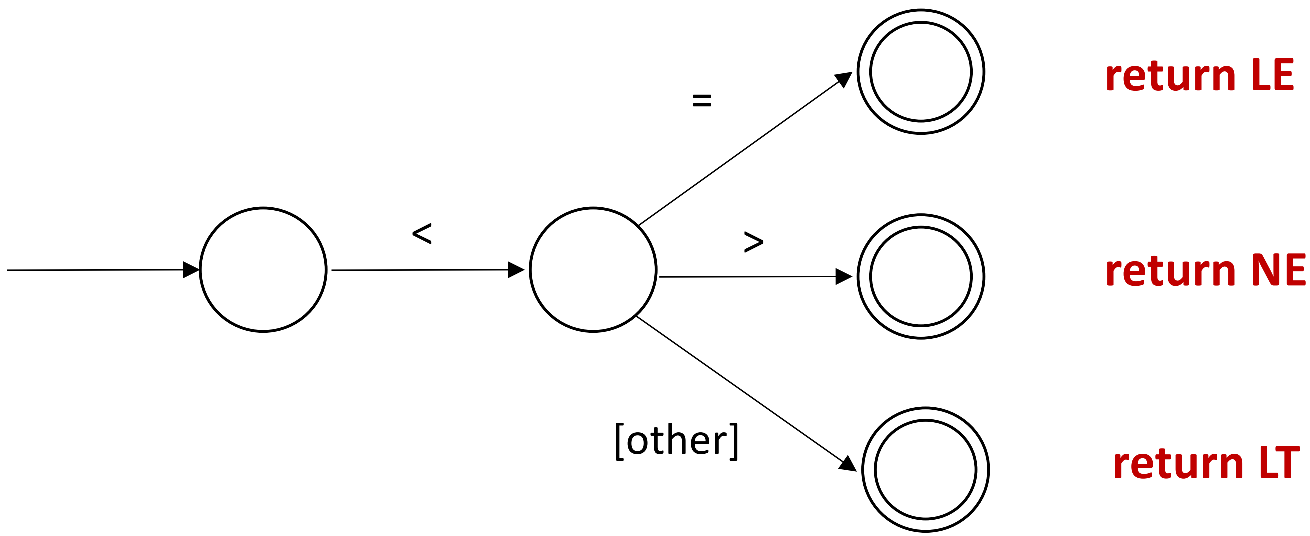
Finite Automata

- Recognize Multiple Tokens
  - it becomes an NFA (*non-deterministic finite automaton*)
  - NFA → DFA (deterministic ...)



Finite Automata

- Recognize Multiple Tokens
  - it becomes an NFA (*non-deterministic finite automaton*)
  - NFA → DFA (deterministic ...)
  - DFA adjustment

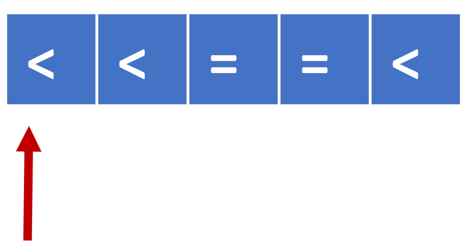


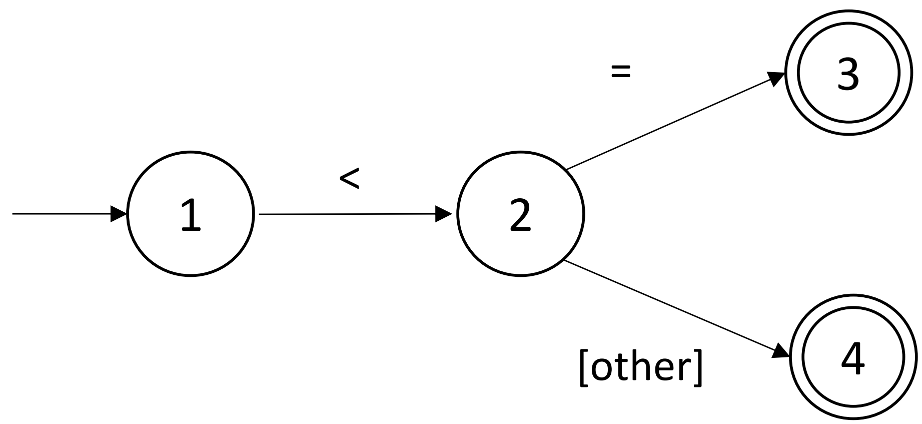
Finite Automata

- Example:
  - Draw the FA for recognizing the following two kinds of tokens in a token string:

LT : <

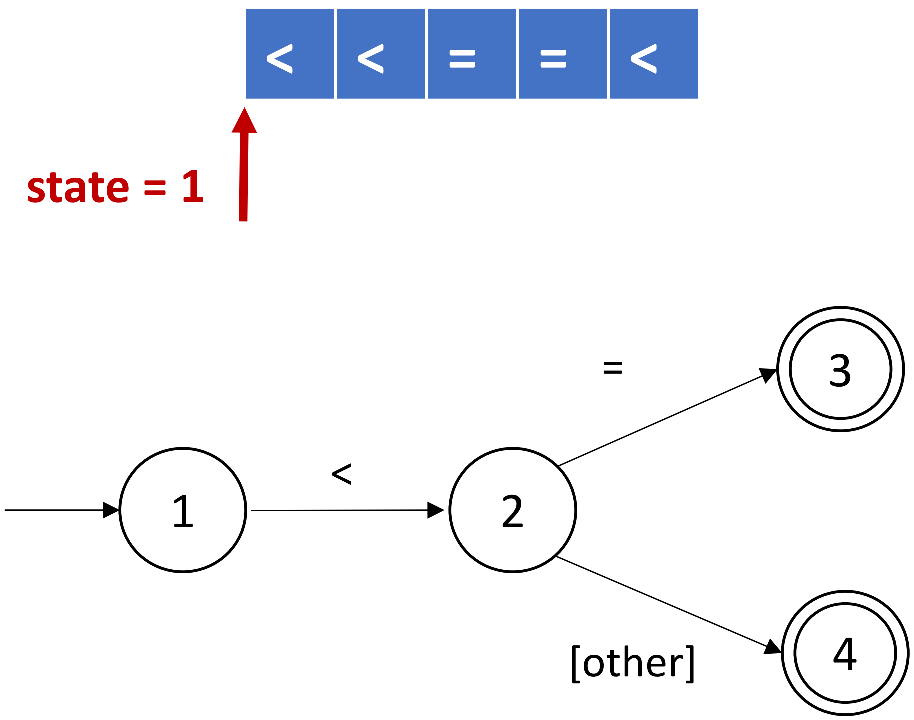
LE : <=





Finite Automata

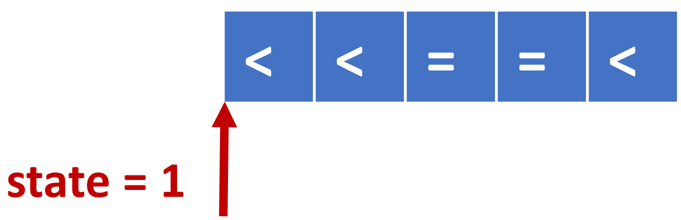
- Implementation
  - hard-coded

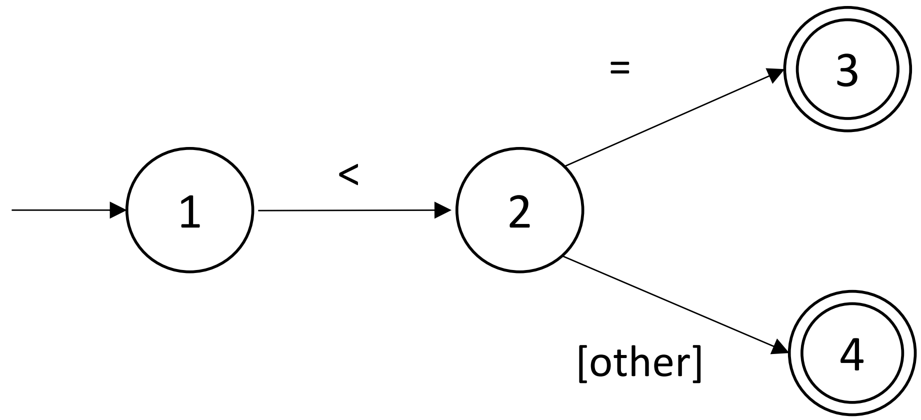



```
state = 1
while (!EOF)
{
  switch(state)
    case 1:
      if(advance() == '<')
        state = 2
      else
        error & break
    case 2:
      if(advance() == '=')
        state = 3
      else
        state = 4
    case 3:
      output token LE
      state = 1
    case 4:
      output token LT
      stepback()
      state = 1
}
```

Finite Automata

- Implementation
  - transition table





state

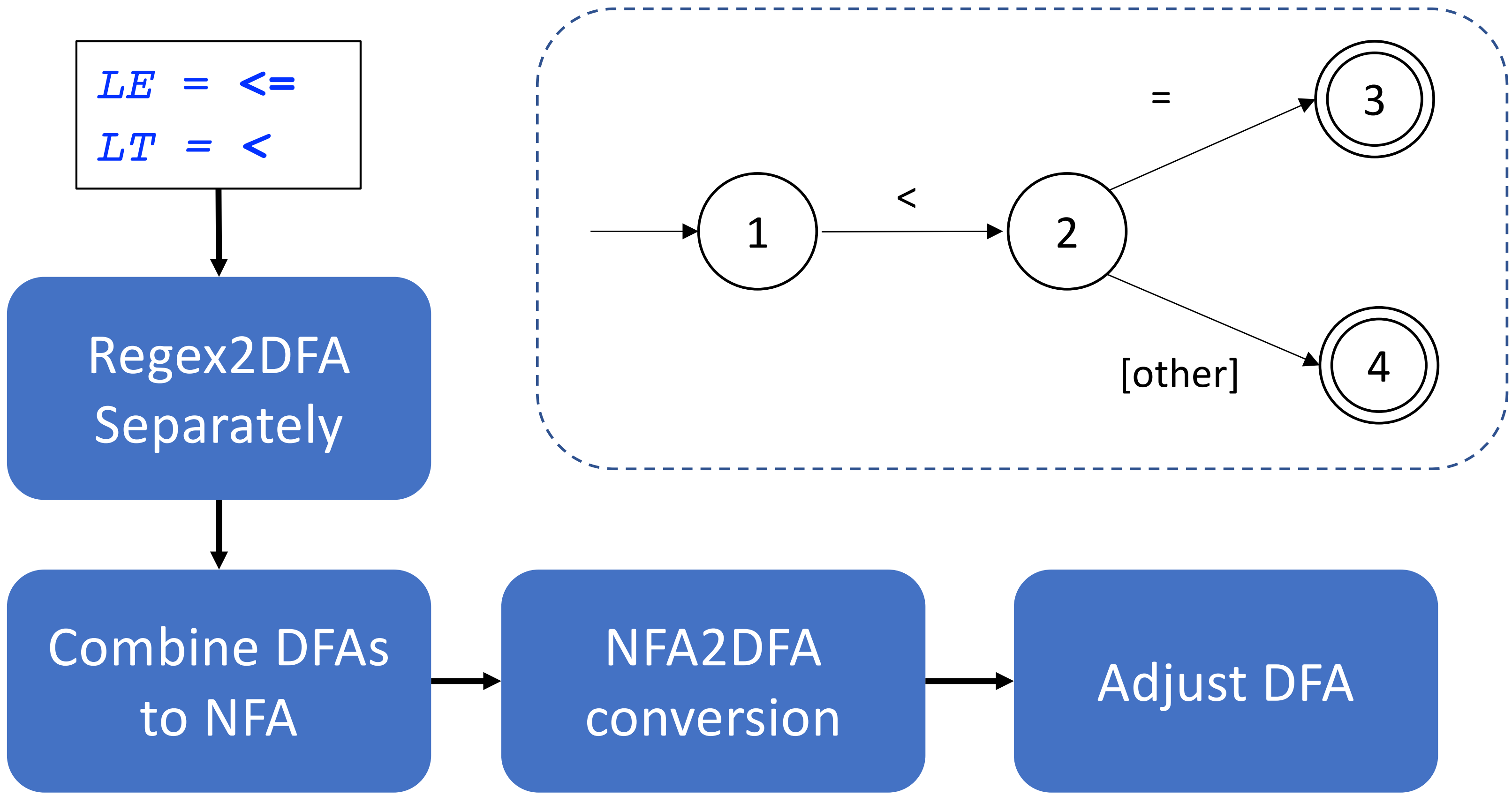
	<	=	action
1	2	err	c = advance()
2	4	3	c = advance()
3	1	1	output LE
4	1	1	output LT; c = stepback()
err	-	-	print error; break

```
state = 1
c = advance()
while (!EOF)
{
  state = Trans[state][c]
  action(state)
}
```

Putting it All Together

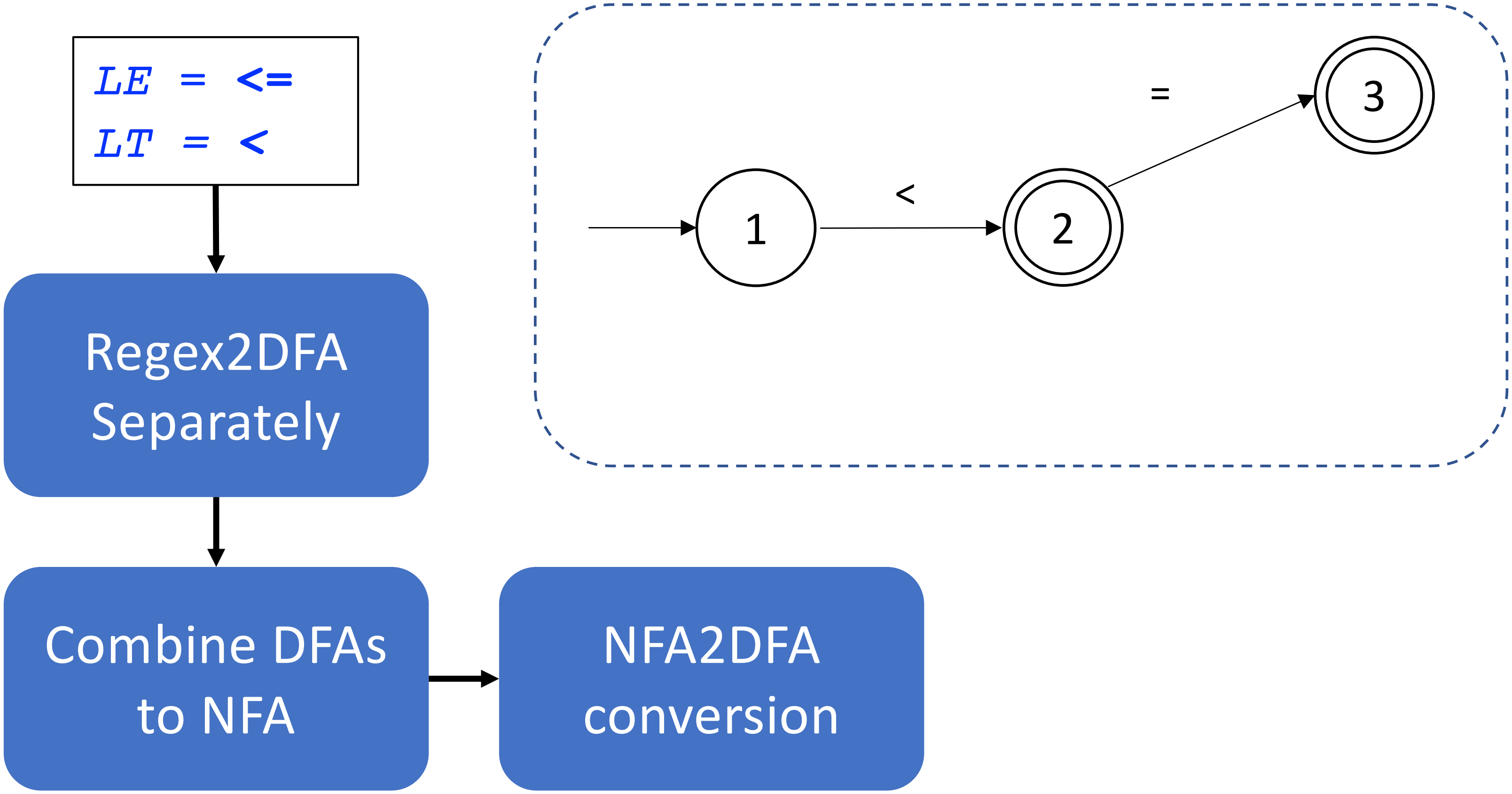
Putting It All Together

- [Louden Ch. 2]



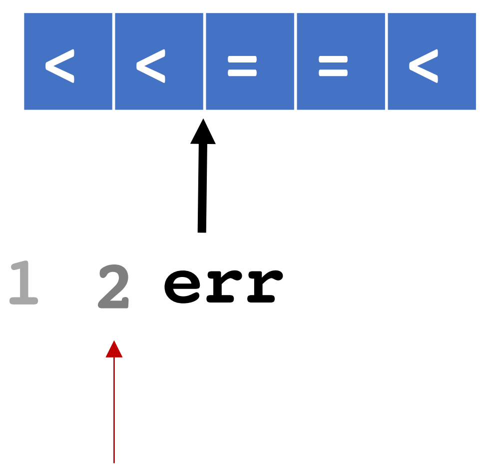
Putting It All Together (flex)

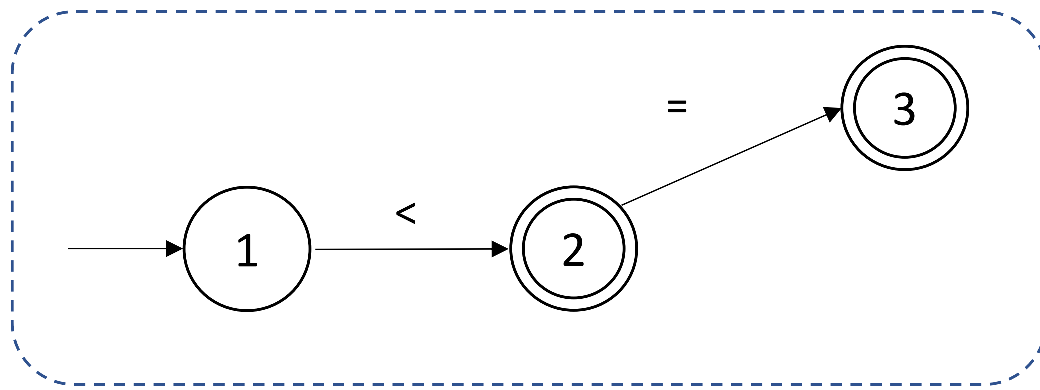
- flex-generated scanner



Putting It All Together (flex)

- flex-generated scanner
  - Move forward until impossible (meeting an “error”)
  - Backtrack to find the latest accept state

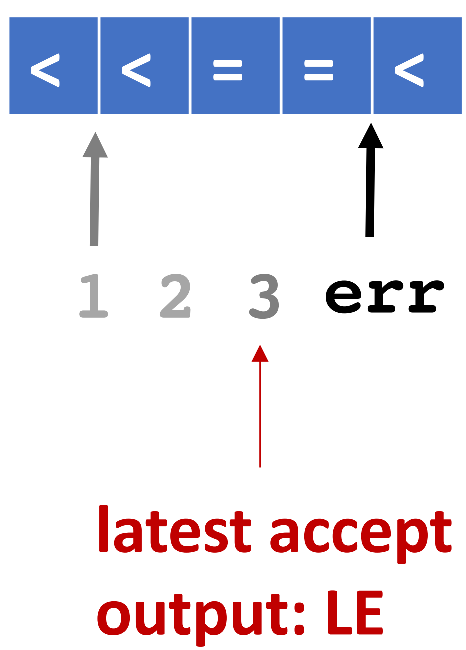


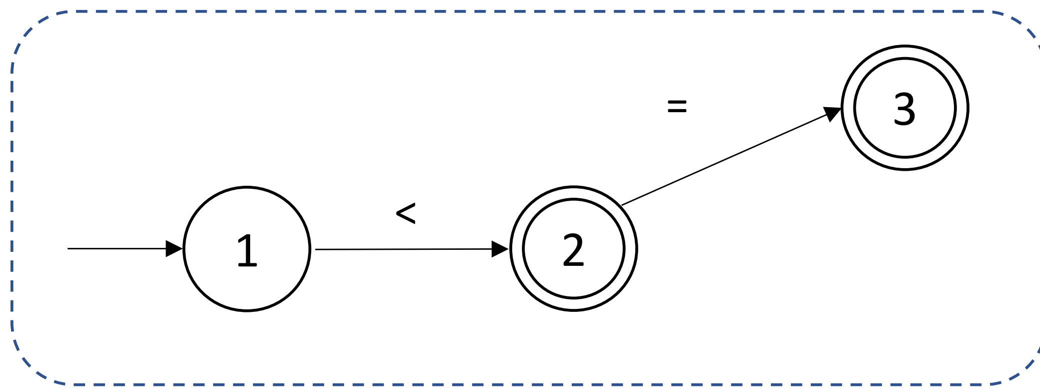


latest accept
output: LT

Putting It All Together (flex)

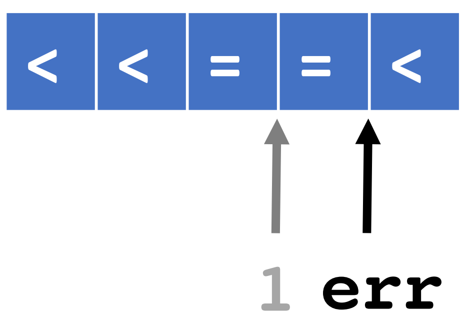
- flex-generated scanner
  - Move forward until impossible (meeting an “error”)
  - Backtrack to find the latest accept state

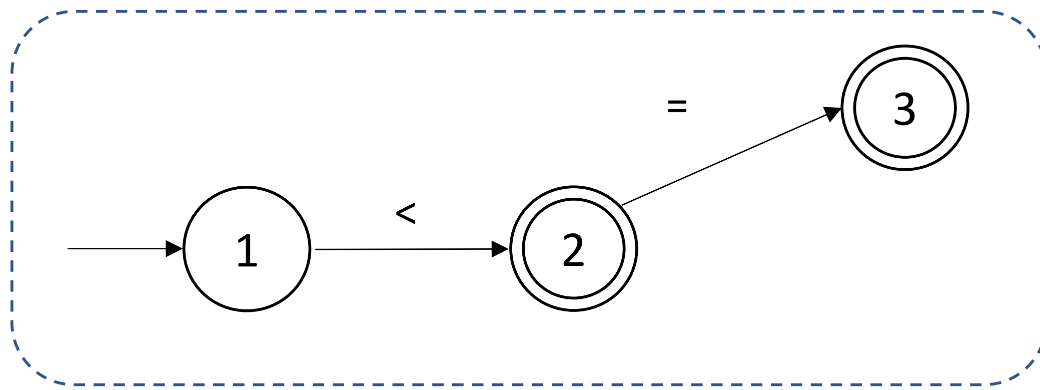




Putting It All Together (flex)

- flex-generated scanner
  - Move forward until impossible (meeting an “error”)
  - Backtrack to find the latest accept state





no accept state! real error!