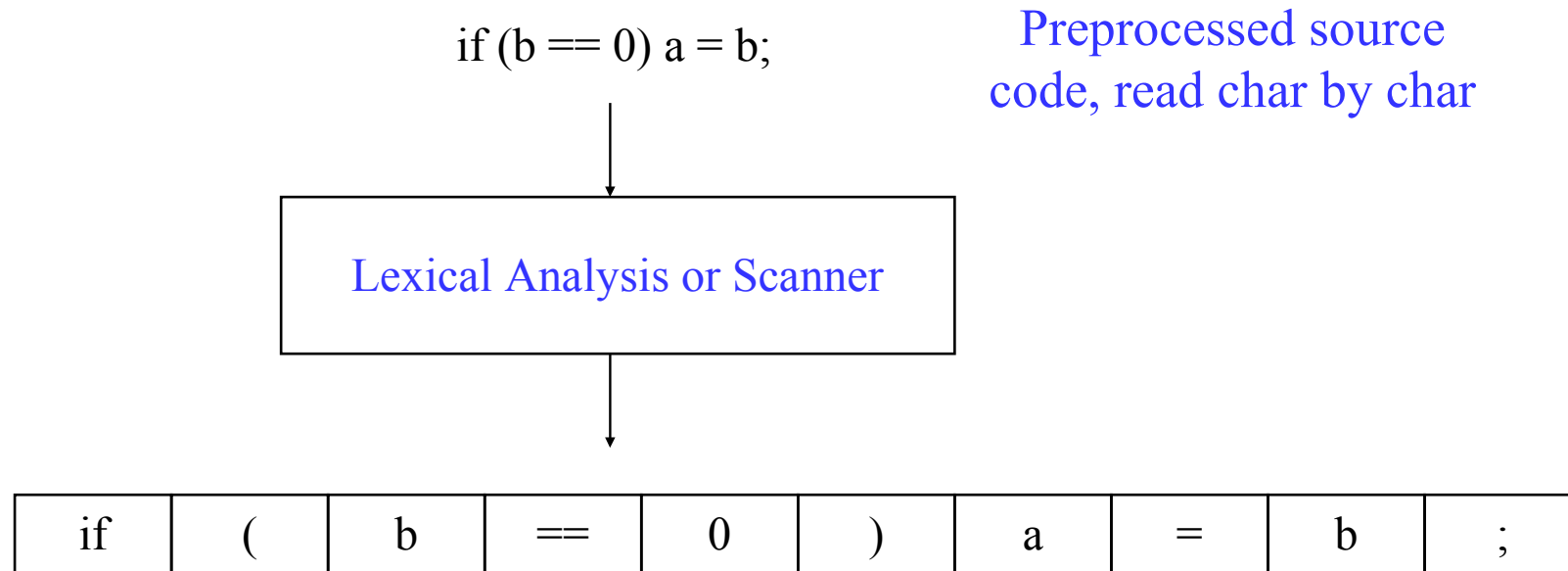


The Lexical Analysis

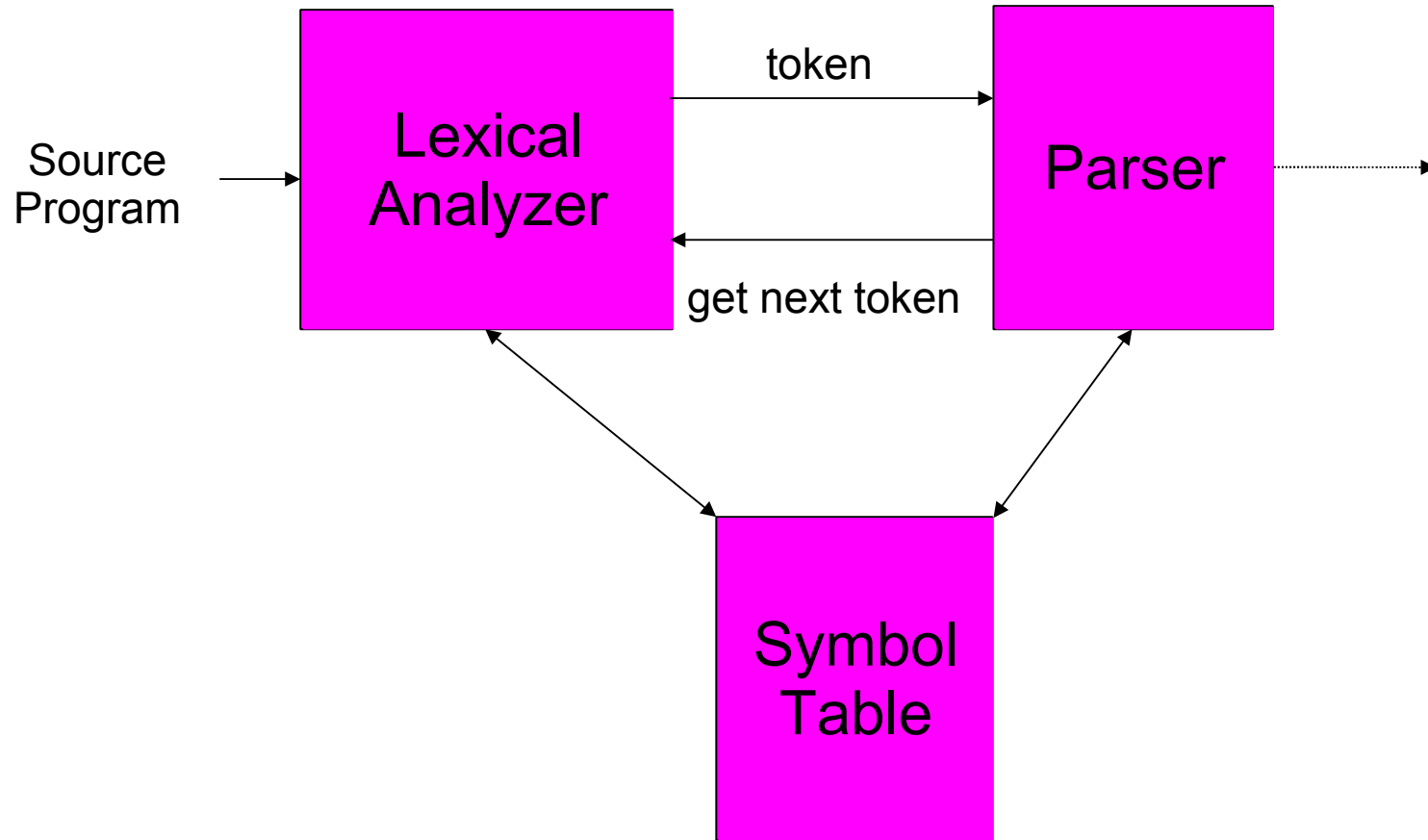
Lexical Analysis Process



Lexical analysis

- Transform multi-character input stream to token stream
- Reduce length of program representation (remove spaces)

Lexical Analyzer and Its Role in A Compiler



Tokens

- Identifiers: x y11 elsex
- Keywords: if else while for break
- Integers: 2 1000 -20
- Floating-point: 2.0 -0.0010 .02 1e5
- Symbols: + * { } ++ << < <= []
- Strings: "x" "He said, \"I luv CC\""

How to Describe Tokens

- Use regular expressions to describe programming language tokens!
- A regular expression (RE) is defined inductively
 - a ordinary character stands for itself
 - ϵ empty symbol
 - $R|S$ either R or S (alteration), where $R, S = \text{RE}$
 - RS R followed by S (concatenation)
 - R^* concatenation of R, 0 or more times (Kleene closure)

Language

- A regular expression R describes a set of strings of characters denoted $L(R)$
- $L(R)$ = the language defined by R
 - $L(abc) = \{ abc \}$
 - $L(\text{hello|goodbye}) = \{ \text{hello, goodbye} \}$
 - $L(1(0|1)^*) = \text{all binary numbers that start with a 1}$
- Each token can be defined using a regular expression

RE Notational Shorthand

- R^+ one or more strings of R : $R(R^*)$
- $R?$ optional R : $(R|\epsilon)$
- $[abcd]$ one of listed characters: $(a|b|c|d)$
- $[a-z]$ one character from this range:
 $(a|b|c|d\dots|z)$
- $[^ab]$ anything but one of the listed chars
- $[^a-z]$ one character not from this range

Lexical and Syntax Analysis

$stmt \rightarrow$ **if** *expr* **then** *stmt*
 | **if** *expr* **then** *stmt* **else** *stmt*
 | ϵ
 $expr \rightarrow$ *term* **relop** *term*
 | *term*
 $term \rightarrow$ **id**
 | **num**

if \rightarrow if

then \rightarrow then

else \rightarrow else

relop \rightarrow < | <= | = | <> | > | >=

id \rightarrow letter (letter | digit)*

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

How to Break up Text

elsex = 0;

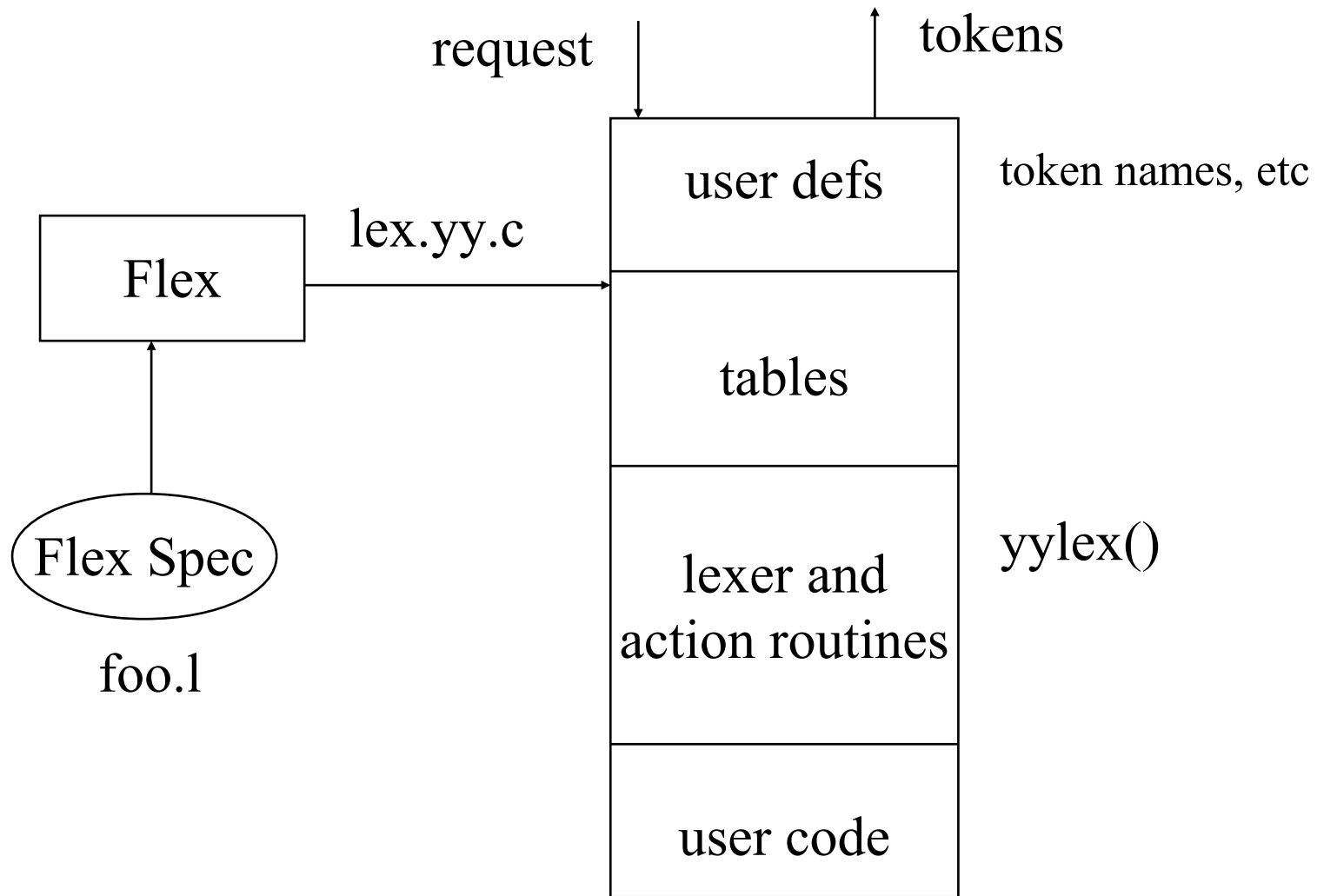
1	else	x	=	0	;
2	elsex	=	0	;	

- REs alone not enough, need rule for choosing when get multiple matches
- Longest matching token wins
- Ties in length resolved by priorities
- Token specification order often defines priority
- RE's + priorities + longest matching token rule = definition of a lexer

Automatic Generation of Lexers

- 2 programs developed at Bell Labs in mid 70's for use with UNIX
 - Lex – transducer, transforms an input stream into the alphabet of the grammar processed by yacc
 - Written by Mike E. Lesk
 - Flex = fast lex, later developed by Free Software Foundation
 - Yacc/bison – yet another compiler/compiler (next week)
- Input to lexer generator
 - List of regular expressions in priority order
 - Associated action with each RE
- Output
 - Program that reads input stream and breaks it up into tokens according the the REs

Lex/Flex



Lex Specification

- Definition section
 - All code contained within “%{“ and “%}” is copied to the resultant program. Usually has token defns established by the parser
 - User can provide names for complex patterns used in rules
 - Any additional lexing states (states prefaced by %s directive)
 - Pattern and state definitions must start in column 1 (All lines with a blank in column 1 are copied to resulting C file)

lex file always has 3 sections:

definition section

%%

rules section

%%

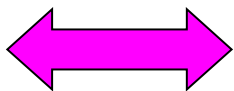
user functions section

Lex Specification

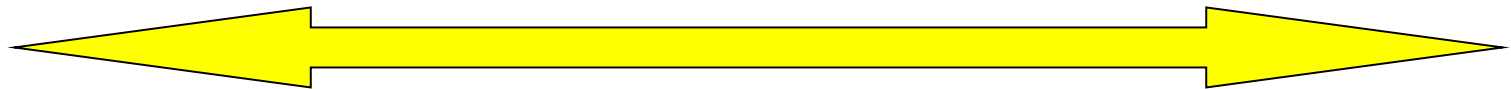
- Rules section
 - Contains lexical patterns and semantic actions to be performed upon a pattern match. Actions should be surrounded by `{}` (though not always necessary)
 - Again, all lines with a blank in column 1 are copied to the resulting C program
- User function section
 - All lines in this section are copied to the final `.c` file
 - Unless the functions are very immediate support routines, better to put these in a separate file

Partial Flex Program

```
D          [0-9]
%%
if         printf ("IF statement\n");
[a-z]+    printf ("tag, value %s\n", yytext);
{D}+      printf ("decimal number %s\n", yytext);
"++"      printf ("unary op\n");
"+"       printf ("binary op\n");
```



pattern



action

Flex Program

```
%{
    #include <stdio.h>
    int num_lines = 0, num_chars = 0;
}%

%%
\n    ++num_lines; ++num_chars;
.     ++num_chars;

%%
main()
{
    yylex();
    printf( "# of lines = %d, # of chars = %d \n", num_lines, num_chars );
}
```

- Running the above program:

```
neo$ flex count.1
```

```
neo$ gcc lex.yy.c -lf1
```

```
neo$ a.out < count.1
```

```
# of lines = 16, # of chars = 217
```

Another Flex Program

```
%{
/* recognize articles a, an, the */
#include <stdio.h>
}%

%%
[ \t]+      /* skip white space - action: do nothing */ ;
a |        /* | indicates do same action as next pattern */
an |
the        {printf("%s: is an article\n", yytext);}
[a-zA-Z]+  {printf("%s: ???\n", yytext);}

%%
main()
{
    yylex();
}
```

Note: `yytext` is a pointer to first char of the token
`yylen` = length of token

Lex Program for A Lexer in a Compiler

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT,
    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}+)?

%%
{ws}     { /* no action and no return */ }
if       {return(IF);}
then     {return(THEN);}
else     {return(ELSE);}
{id}     {yylval = install_id(); return(ID);}
{number} {yylval = install_num(); 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);}

%%

int install_id() {
    /* procedure to install the lexeme, whose first character is pointed by yytext
    and whose length is yyleng, into the symbol table and return a pointer thereto */
}

int install_num() {
    /* similar procedure to install a lexeme that is a number */
}
```

Lex Regular Expression Meta Chars

Meta Char Meaning

.	match any single char (except \n)
*	Kleene closure (0 or more)
[]	Match any character within brackets - in first position matches - ^ in first position inverts set
^	matches beginning of line
\$	matches end of line
{a,b}	match count of preceding pattern from a to b times, b optional
\	escape for metacharacters
+	positive closure (1 or more)
?	matches 0 or 1 REs
	alteration
/	provides lookahead
()	grouping of RE
<>	restricts pattern to matching only in that state

How Does Lex Work?

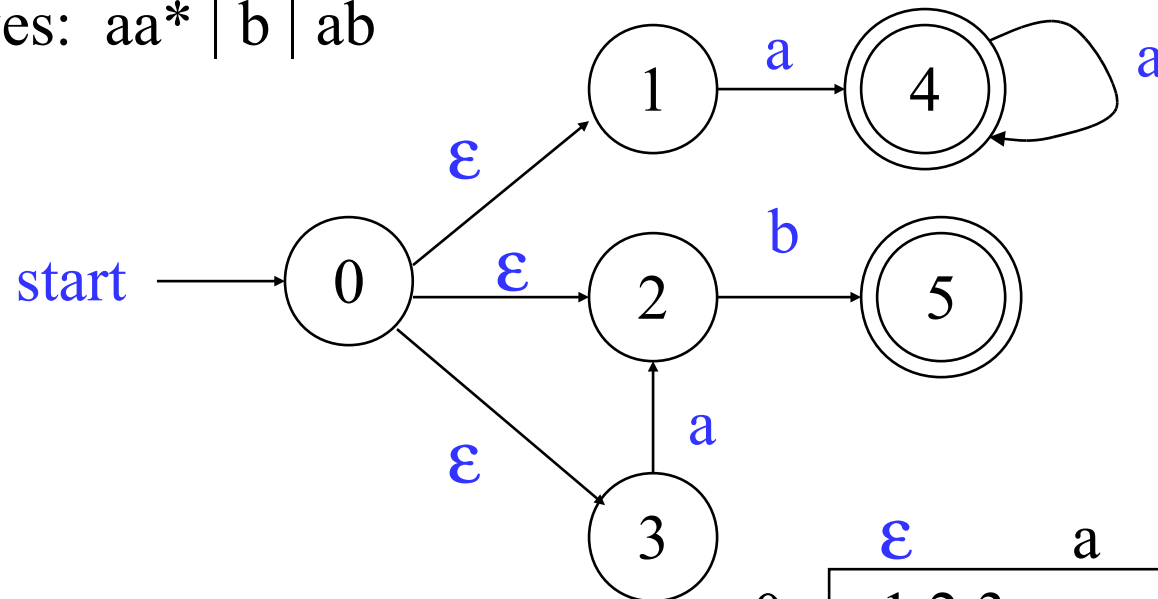
- Formal basis for lexical analysis is the finite state automaton (FSA)
 - REs generate regular sets
 - FSAs recognize regular sets
- FSA – informal defn:
 - A finite set of states
 - Transitions between states
 - An initial state (start)
 - A set of final states (accepting states)

Two Kinds of FSA

- Non-deterministic finite automata (NFA)
 - There may be multiple possible transitions or some transitions that do not require an input (ϵ)
- Deterministic finite automata (DFA)
 - The transition from each state is uniquely determined by the current input character
 - For each state, at most 1 edge labeled 'a' leaving state
 - No ϵ transitions

NFA Example

Recognizes: $aa^* | b | ab$

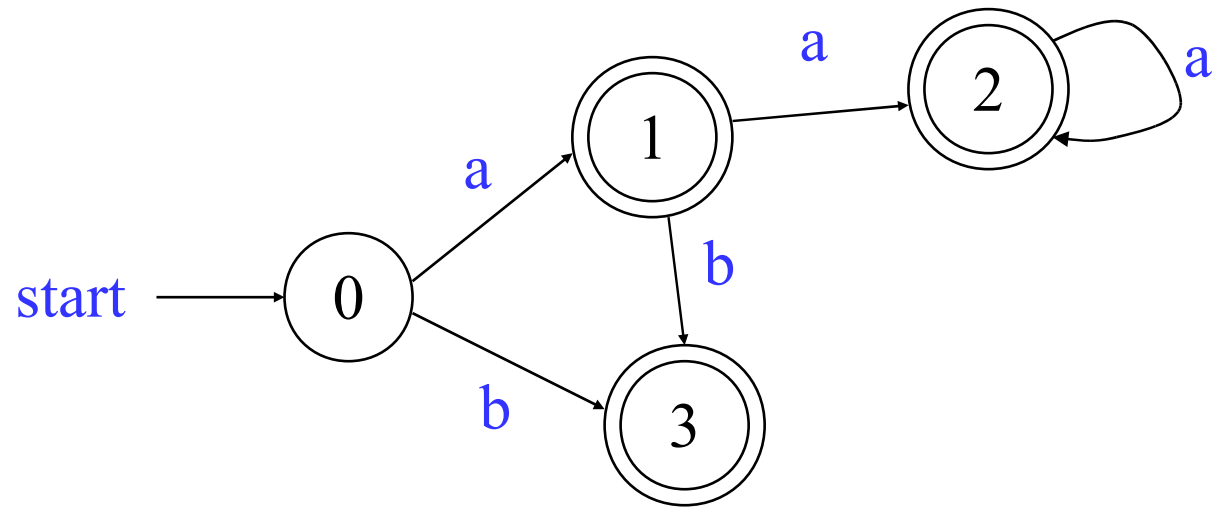


Can represent FA with either graph or transition table

	ϵ	a	b
0	1,2,3	-	-
1	-	4	Error
2	-	Error	5
3	-	2	Error
4	-	4	Error
5	-	Error	Error

DFA Example

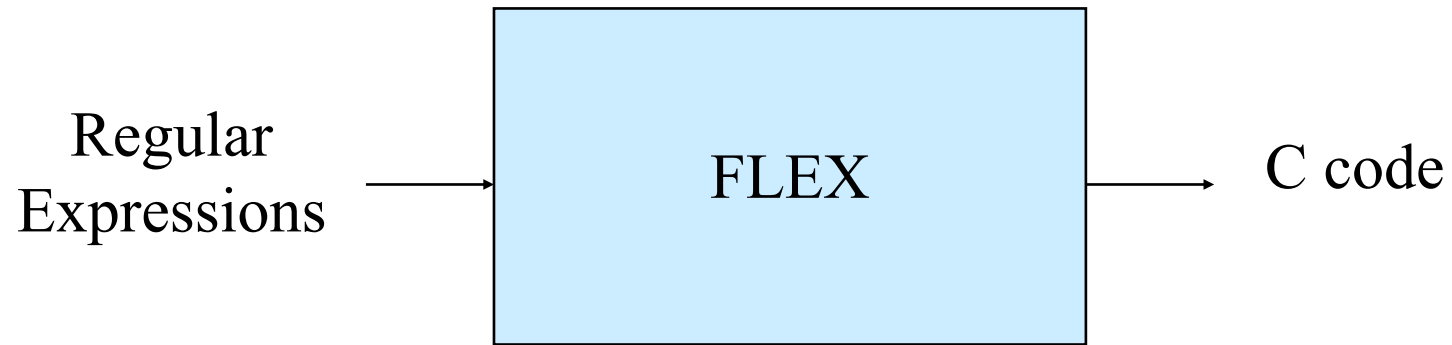
Recognizes: $aa^* \mid b \mid ab$



NFA vs DFA

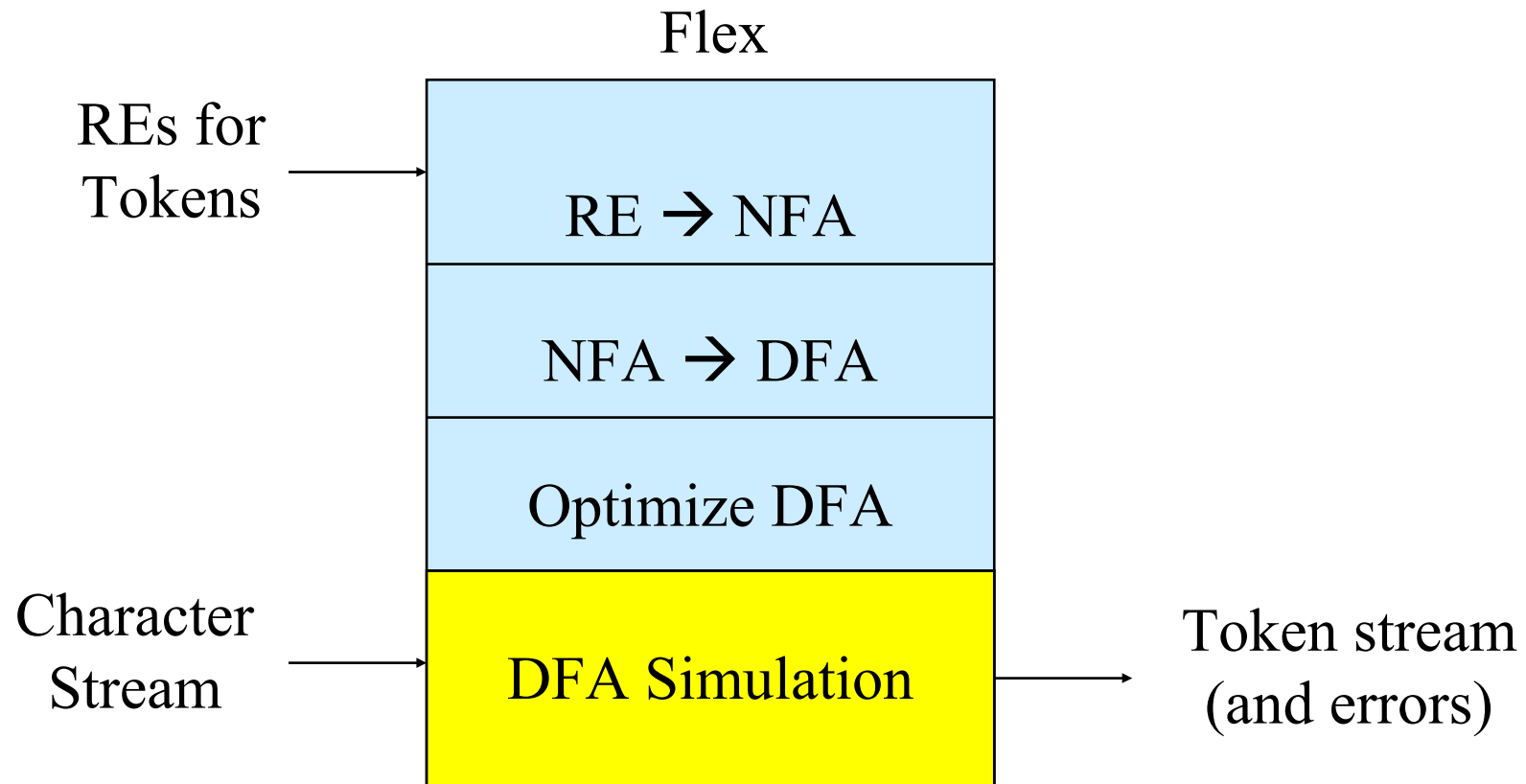
- DFA
 - Action on each input is fully determined
 - Implement using table-driven approach
 - More states generally required to implement RE
- NFA
 - May have choice at each step
 - Accepts string if there is ANY path to an accepting state
 - Not obvious how to implement this

How Does Lex Work?



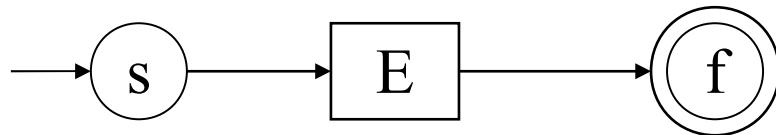
Some kind of DFAs and NFAs
stuff going on inside

How Does Lex Work?



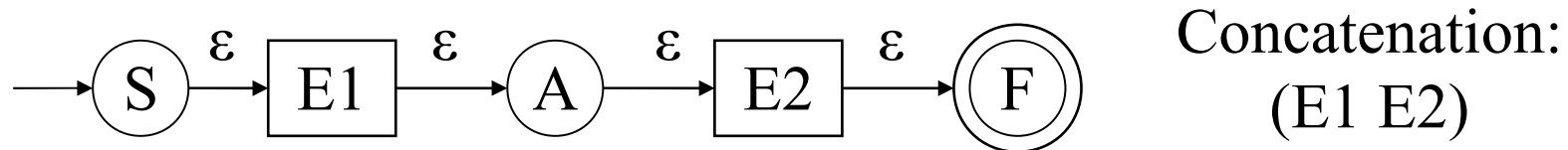
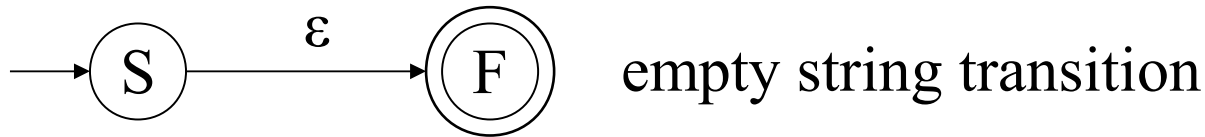
Regular Expression to NFA

- Its possible to construct an NFA from a regular expression
- Thompson's construction algorithm
 - Build the NFA inductively
 - Define rules for each base RE
 - Combine for more complex RE's



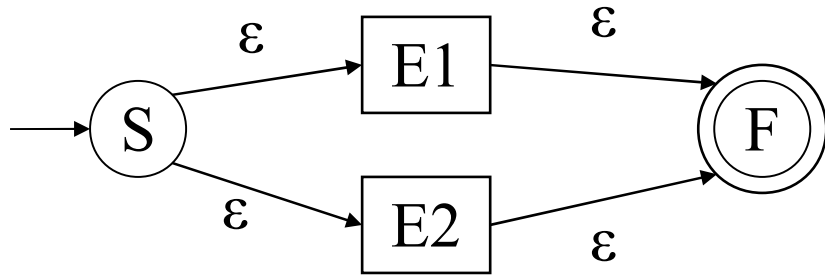
general machine

Thompson Construction



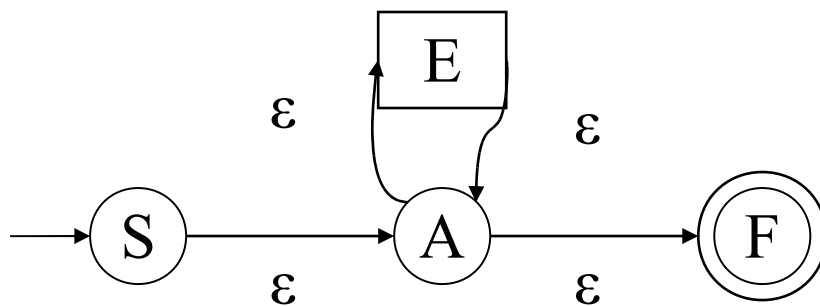
- New start state S ϵ -transition to the start state of E1
- ϵ -transition from final/accepting state of E1 to A, ϵ -transition from A to start state of E2
- ϵ -transitions from the final/accepting state E2 to the new final state F

Thompson Construction



Alteration: $(E1 \mid E2)$

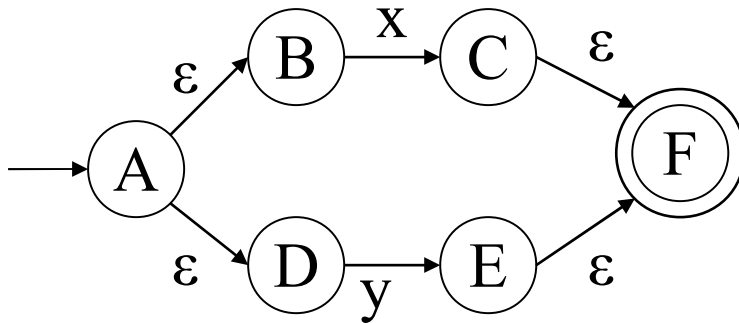
- New start state S ϵ -transitions to the start states of E1 and E2
- ϵ -transitions from the final/accepting states of E1 and E2 to the new final state F



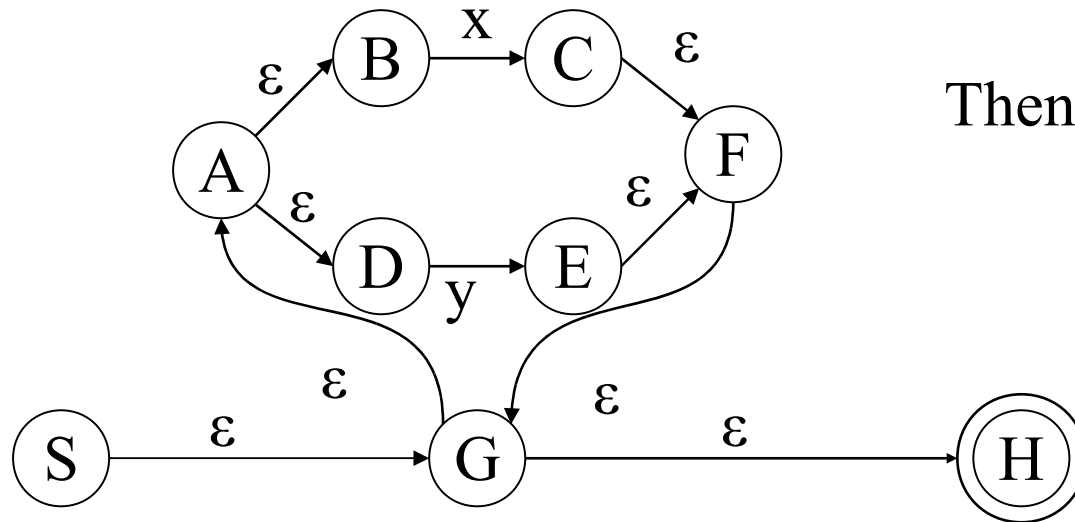
Closure: (E^*)

Thompson Construction - Example

Develop an NFA for the RE: $(x | y)^*$



First create NFA for $(x | y)$



Then add in the closure operator

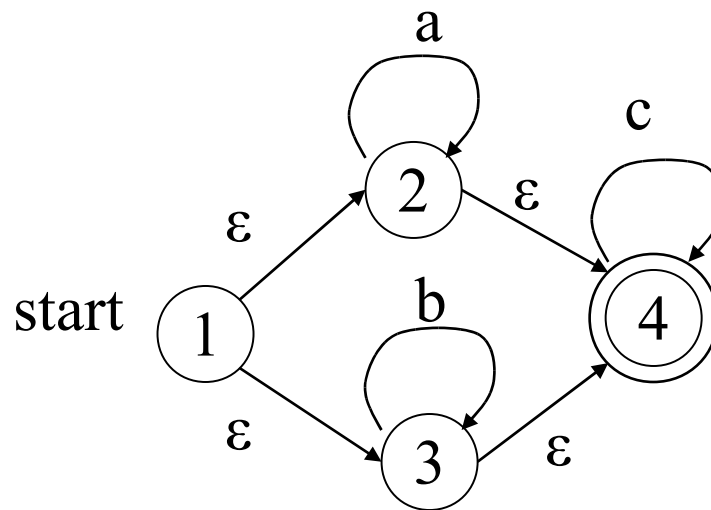
Class Problem

Develop an NFA for the RE: $(\backslash+? | -?) d+$

NFA to DFA

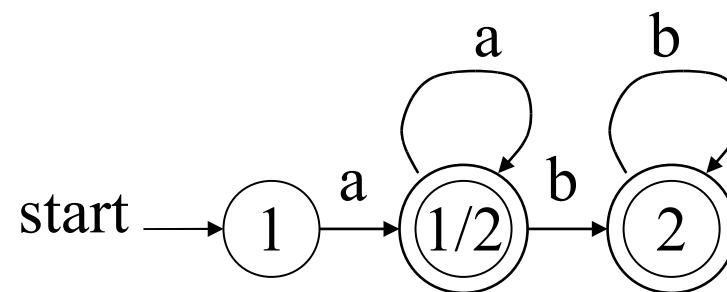
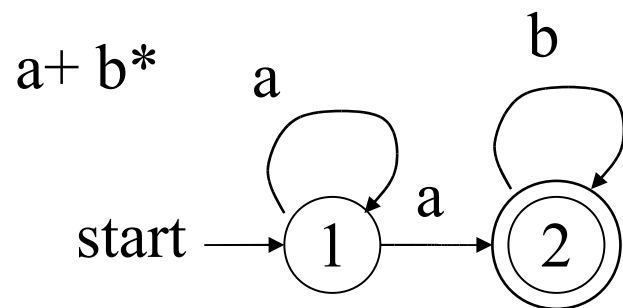
- Remove the non-determinism
- 2 problems
 - States with multiple outgoing edges due to same input
 - ϵ transitions

$(a^* | b^*) c^*$



NFA to DFA

- Problem 1: Multiple transitions
 - Solve by subset construction
 - Build new DFA based upon the power set of states on the NFA
 - Move (S,a) is relabeled to target a new state whenever single input goes to multiple states



$(1,a) \rightarrow 1$ or 2 , create new state $1/2$

$(1/2,a) \rightarrow 1/2$

$(1/2,b) \rightarrow 2$

$(2,a) \rightarrow \text{ERROR}$

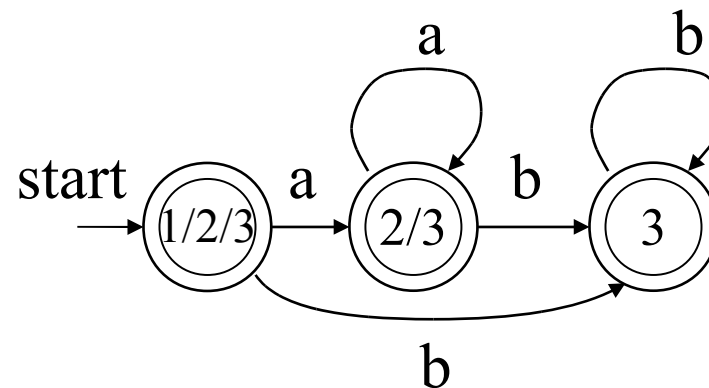
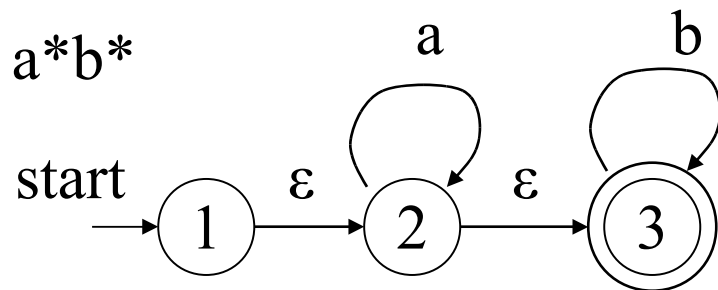
$(2,b) \rightarrow 2$

Any state with "2" in name is a final state

NFA to DFA

- Problem 2: ϵ transitions

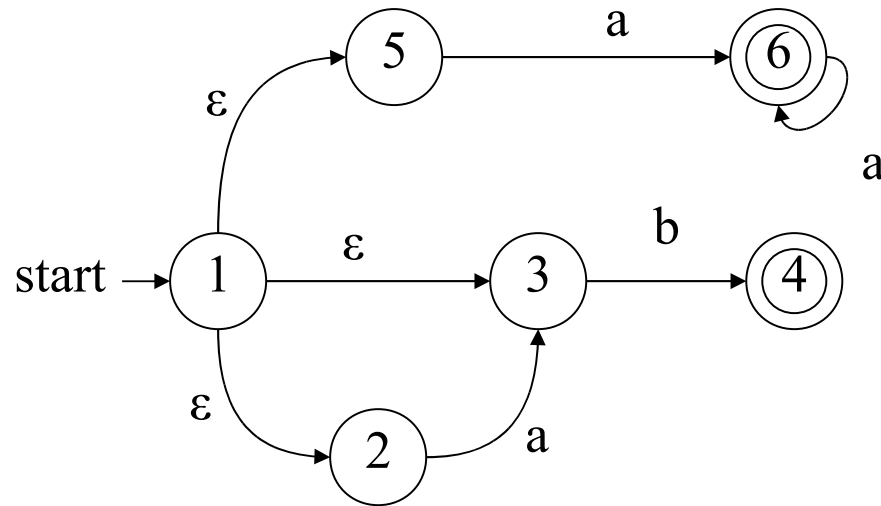
- Any state reachable by an ϵ transition is “part of the state”
- ϵ -closure - Any state reachable from S by ϵ transitions is in the ϵ -closure; treat ϵ -closure as 1 big state, always include ϵ -closure as part of the state



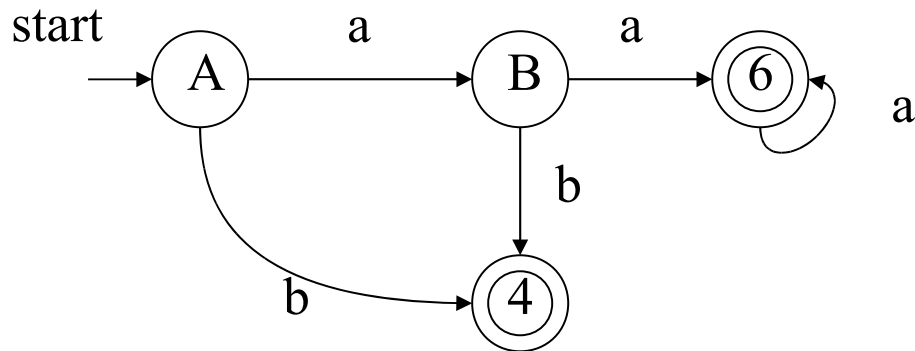
ϵ -closure(1) = {1,2,3}
 ϵ -closure(2) = {2,3}
 create new state 1/2/3
 create new state 2/3

$(1/2/3, a) \rightarrow 2/3$
 $(1/2/3, b) \rightarrow 3$
 $(2/3, a) \rightarrow 2/3$
 $(2/3, b) \rightarrow 3$

NFA to DFA - Example

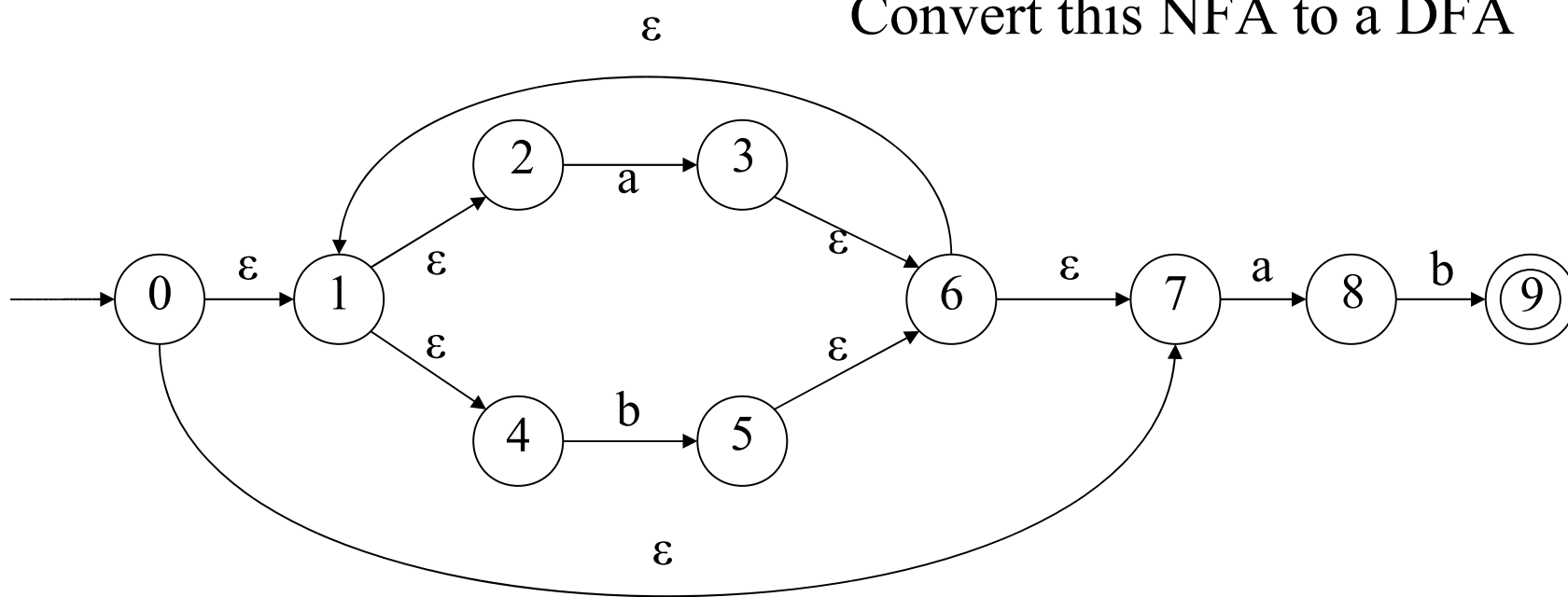


- ϵ -closure(1) = {1, 2, 3, 5}
- Create a new state A = {1, 2, 3, 5} and examine transitions out of it
- $\text{move}(A, a) = \{3, 6\}$
- Call this a new subset state = B = {3, 6}
- $\text{move}(A, b) = \{4\}$
- $\text{move}(B, a) = \{6\}$
- $\text{move}(B, b) = \{4\}$
- Complete by checking $\text{move}(4, a)$; $\text{move}(4, b)$; $\text{move}(6, a)$; $\text{move}(6, b)$



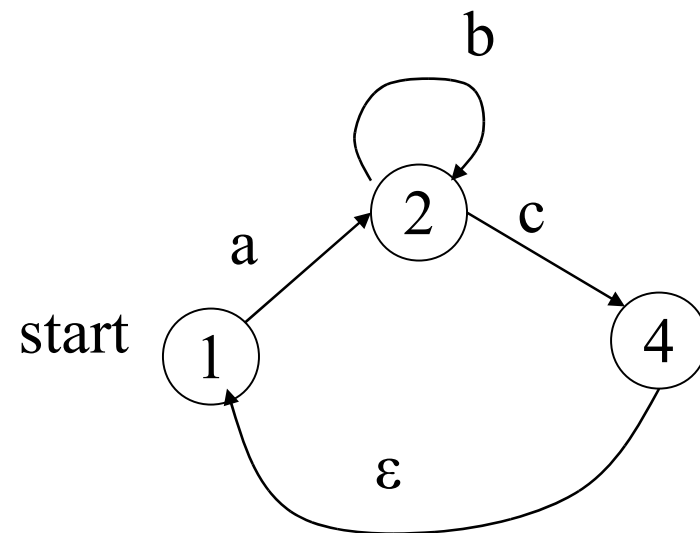
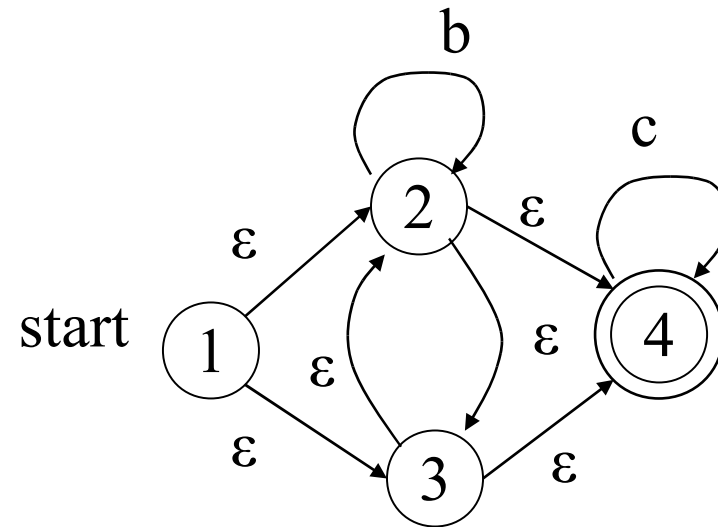
Class Problem

Convert this NFA to a DFA



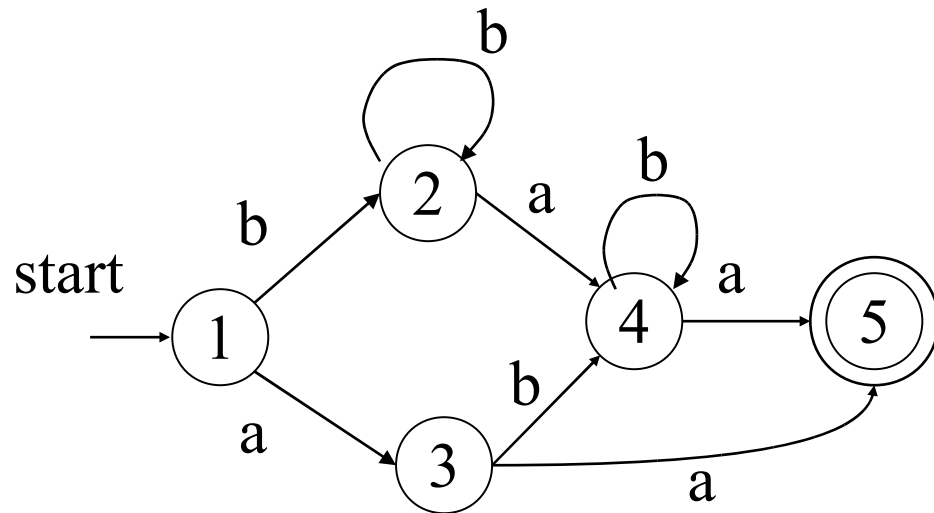
NFA to DFA Optimizations

- Prior to NFA to DFA conversion:
- Empty cycle removal
 - Combine nodes that comprise cycle
 - Combine 2 and 3
- Empty transition removal
 - Remove state 4, change transition 2-4 to 2-1

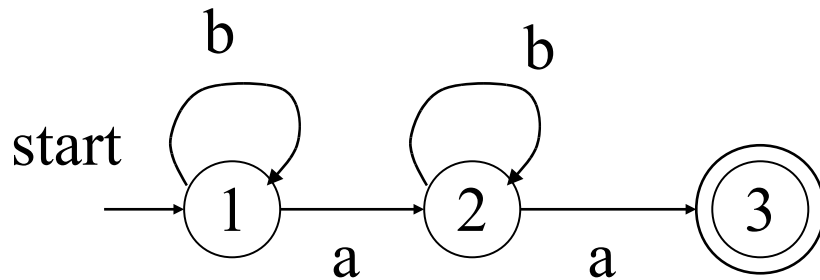


State Minimization

- Resulting DFA can be quite large
 - Contains redundant or equivalent states

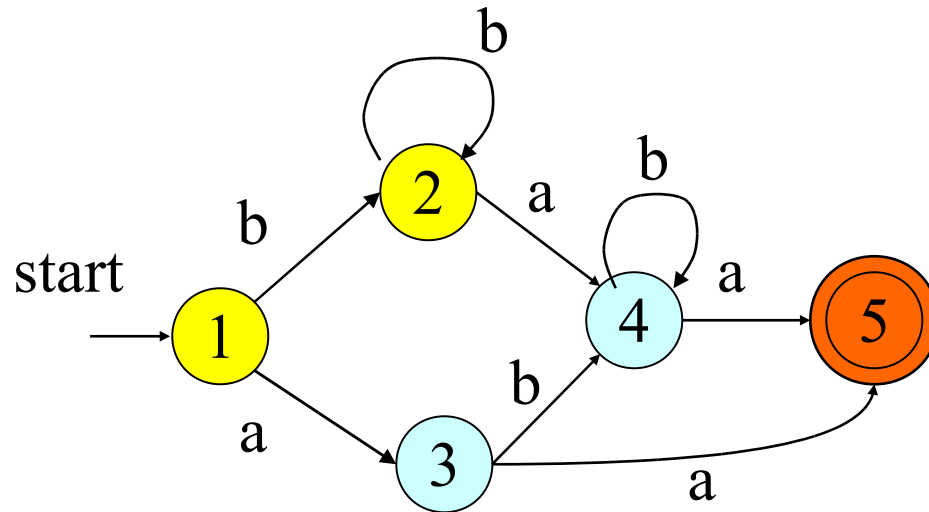


Both DFAs accept
 b^*ab^*a



State Minimization

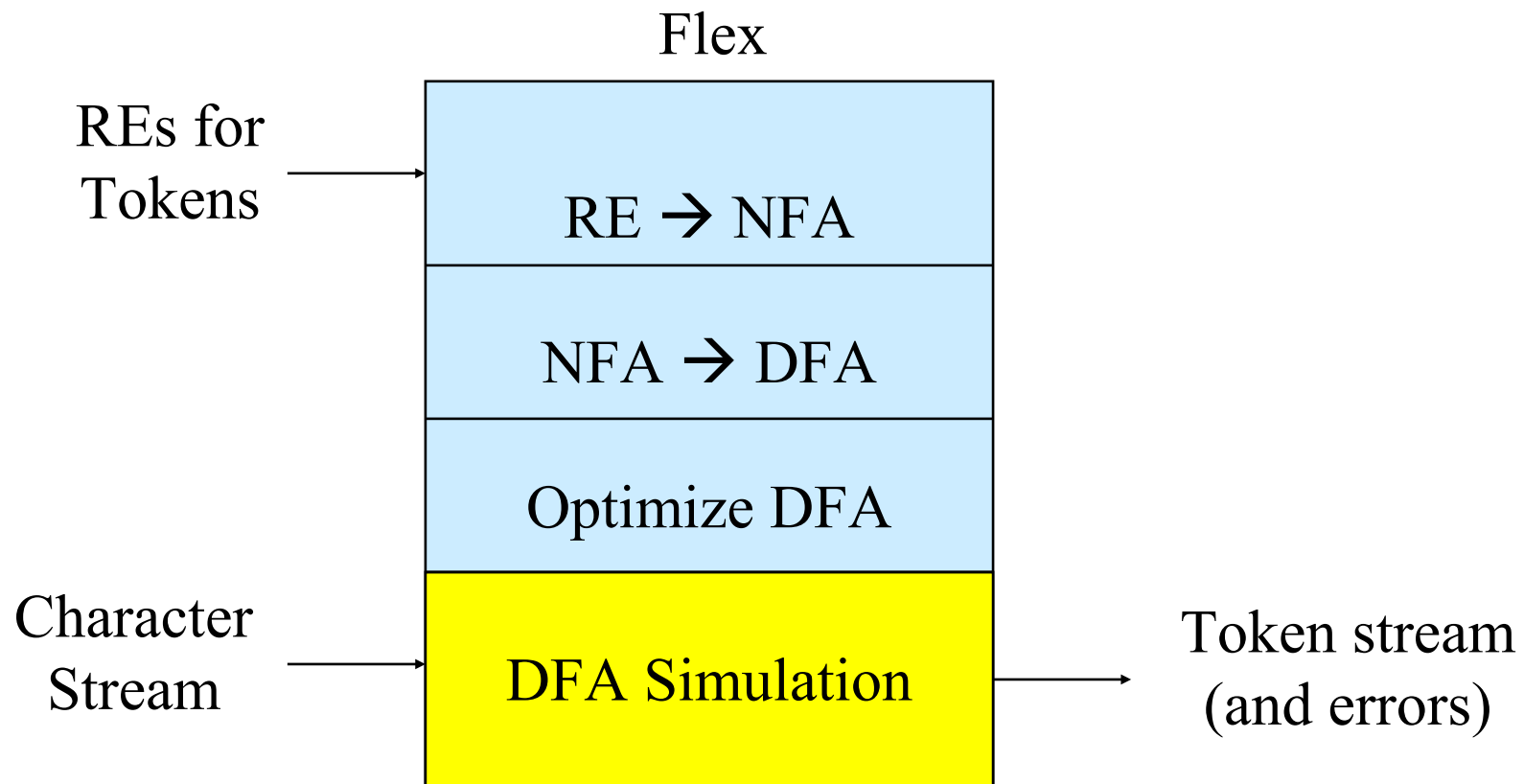
- Idea – find groups of equivalent states and merge them
 - All transitions from states in group G1 go to states in another group G2
 - Construct minimized DFA such that there is 1 state for each group of states



Basic strategy: identify distinguishing transitions

Putting It All Together

- Remaining issues: how to Simulate, multiple REs, producing a token stream, longest match, rule priority



Simulating the DFA

- Straight-forward translation of DFA to C program
- Transitions from each state/input can be represented as table
 - Table lookup tells where to go based on current

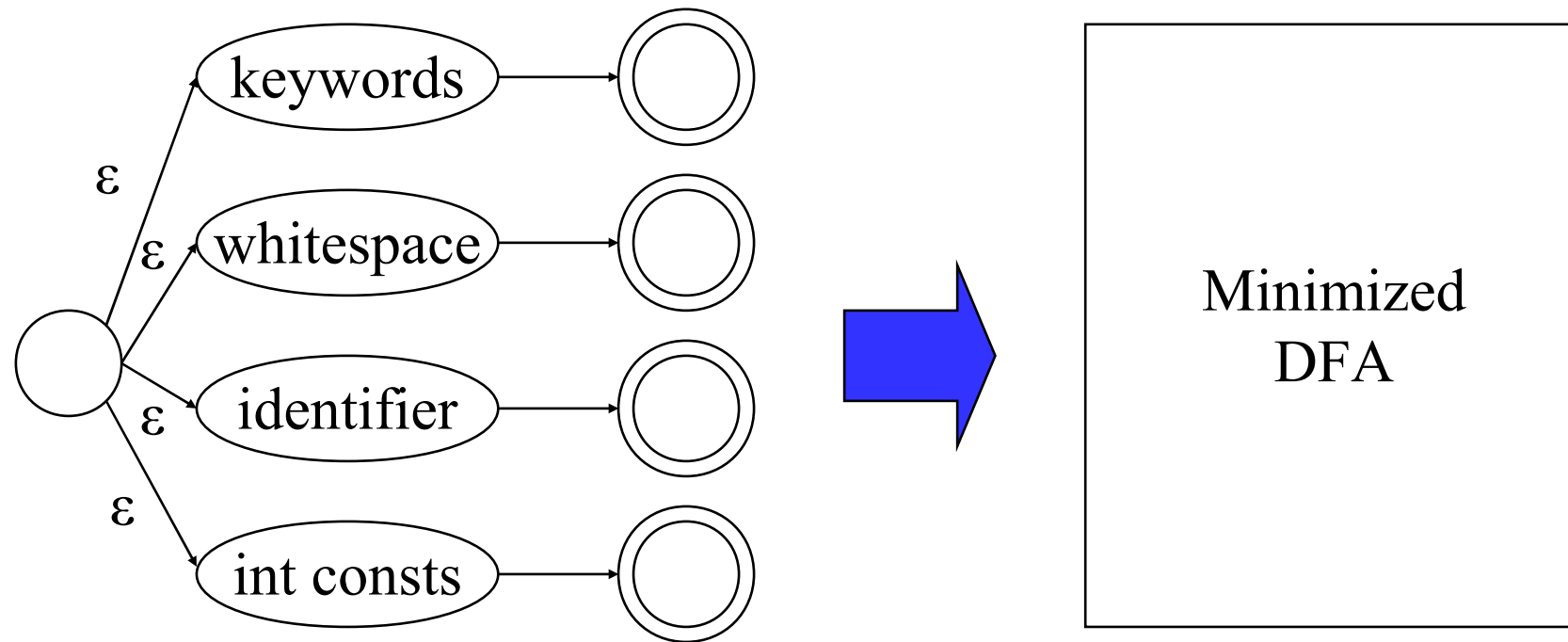
```
trans_table[NSTATES][NINPUTS];
accept_states[NSTATES];
state = INITIAL;

while (state != ERROR) {
    c = input.read();
    if (c == EOF) break;
    state = trans_table[state][c];
}
return accept_states[state];
```

Not quite
this simple
but close!

Handling Multiple REs

- Combine the NFAs of all the regular expressions into a single NFA



Remaining Issues

- Token stream at output
 - Associate tokens with final states
 - Output corresponding token when reach final state
- Longest match
 - When in a final state, look if there is a further transition. If no, return the token for the current final state
- Rule priority
 - Same longest matching token when there is a final state corresponding to multiple tokens
 - Associate that final state to the token with highest priority