40-414 Compiler Design

Implementation of Lexical Analysis

Lecture 3

Notation

- There is variation in regular expression notation

- At least one: $A^+ \equiv AA^*$
- Union: $A \mid B \equiv A + B$
- Option: $A + \varepsilon \equiv A?$
- Range: 'a'+'b'+…+'z' ≡ [a-z]
- Excluded range:

  complement of [a-z] ≡ [^a-z]

Regular Expressions in Lexical Specification

- Last Lecture: a specification for the predicate

$$s \in \underbrace{L(R)}_{\text{Set of strings}}$$

- But a yes/no answer is not enough!
- Instead: partition the input into tokens

$$c_1c_2c_3 \mid c_4c_5c_6c_7 \mid \ldots$$

- We adapt regular expressions to this goal

Regular Expressions => Lexical Spec. (1)

1. Write a rexp for the lexemes of each token
   - Number = digit +
   - Keyword = 'if' + 'else' + …
   - Identifier = letter (letter + digit)*
   - OpenPar = '('
   - …

Regular Expressions => Lexical Spec. (2)

2. Construct R, matching all lexemes for all tokens

   R = Keyword + Identifier + Number + ...

   $= R_1 + R_2 + \ldots$

Regular Expressions => Lexical Spec. (3)

3. Let input be $x_1 \ldots x_n$

   For $1 \leq i \leq n$ check

   $$x_1 \ldots x_i \in L(R)$$

4. If success, then we know that

   $x_1 \ldots x_i \in L(R_j)$ for some j

5. Remove $x_1 \ldots x_i$ from input and go to (3)

Ambiguities (1)

- There are ambiguities in the algorithm

- How much input is used? What if
  - $x_1 \ldots x_i \in L(R)$ and also
  - $x_1 \ldots x_K \in L(R)$

    $k \neq i$

- Rule: Pick longest possible string in $L(R)$
  - The "maximal munch"

Ambiguities (2)

- Which token is used? What if
  - $x_1 \ldots x_i \in L(R_j)$ and also
  - $x_1 \ldots x_i \in L(R_k)$

    $k \neq i$

$$R = R_1 + R_2 + R_3 + \ldots$$

Keyword = 'if' + 'else' + …

Identifier = letter (letter + digit)*

- Rule: use rule listed first (j if $j < k$)
  - Treats "if" as a keyword, not an identifier

Error Handling

- What if
  No rule matches a prefix of input ?
  $x_1 \ldots x_i \notin L(R_j)$

- Problem: Can't just get stuck …

- Solution:
  - Write a rule matching all "bad" strings
  - Put it last (lowest priority)

Summary

- Regular expressions provide a concise notation for string patterns

- Use in lexical analysis requires small extensions
  - To resolve ambiguities
  - To handle errors

- Good algorithms known
  - Require only single pass over the input
  - Few operations per character (table lookup)

Finite Automata

- Regular expressions = specification
- Finite automata = implementation

- A finite automaton consists of
  - An input alphabet Σ
  - A finite set of states S
  - A start state n
  - A set of accepting states $F \subseteq S$
  - A set of transitions state $\rightarrow^{\text{input}}$ state

Finite Automata

- Transition

$$s_1 \to^a s_2$$

- Is read

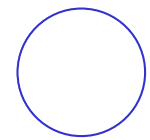
  In state s_1 on input "a" go to state s_2

- If end of input and in accepting state => accept

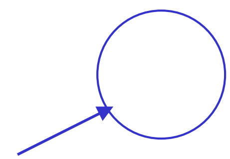
- Otherwise => reject
  - Terminates in a state s that is NOT an accepting state ($s \notin F$)
  - Gets stuck

Finite Automata State Graphs

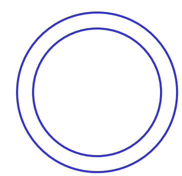
- A state



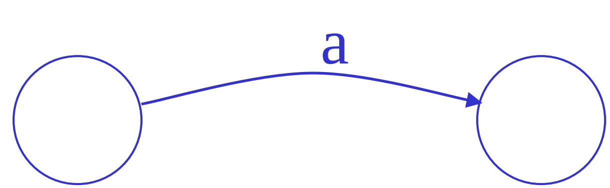
- The start state



- An accepting state

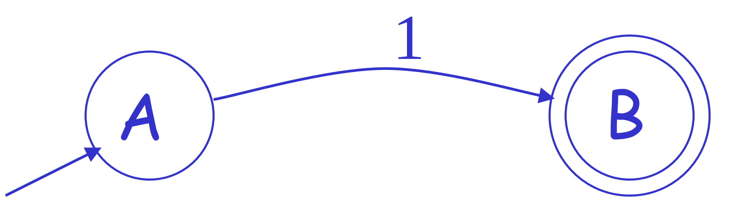


- A transition



A Simple Example

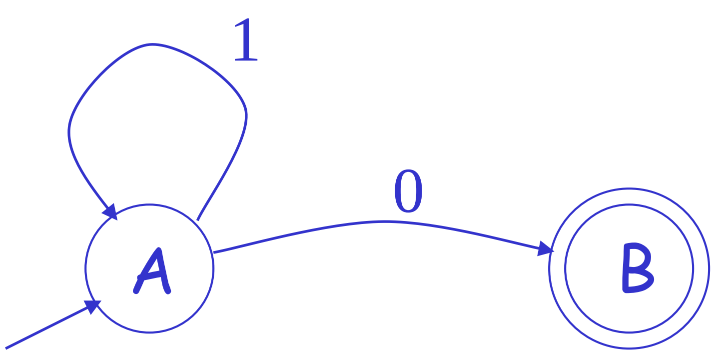
- A finite automaton that accepts only "1"



- Accepts '1' : $\uparrow 1$, $1 \uparrow$
- Rejects '0' : $\uparrow 0$
- Rejects '10' : $\uparrow 1$, $1 \uparrow 0$

Another Simple Example

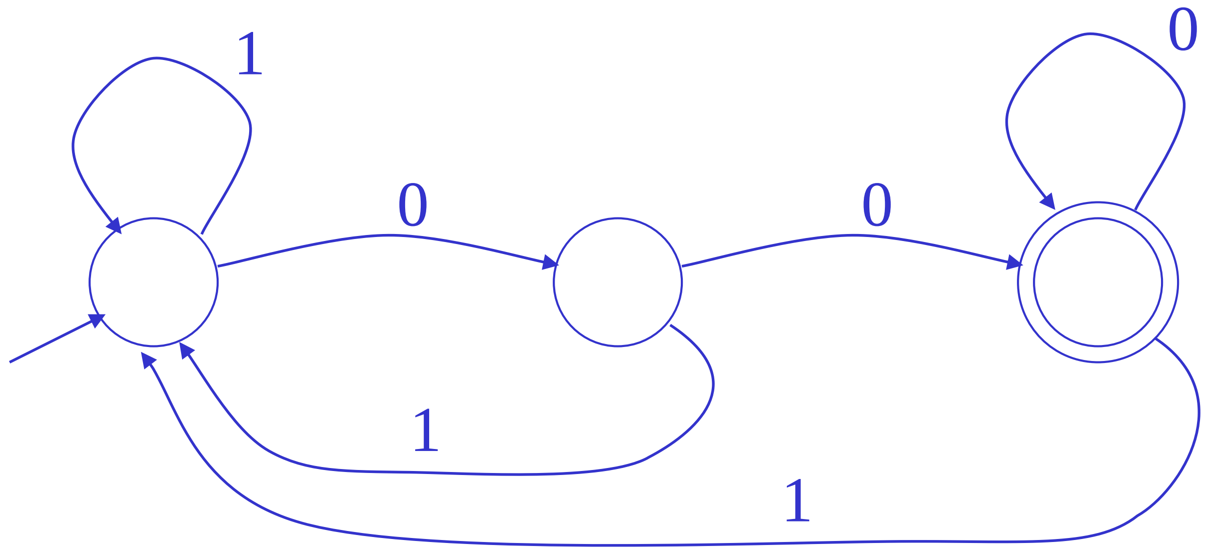
- A finite automaton accepting any number of 1's followed by a single 0
- Alphabet: {0,1}



- Accepts '110': ↑110, 1↑10, 11↑0, 110↑
- Rejects '100' : ↑100, 1↑00, 10↑0

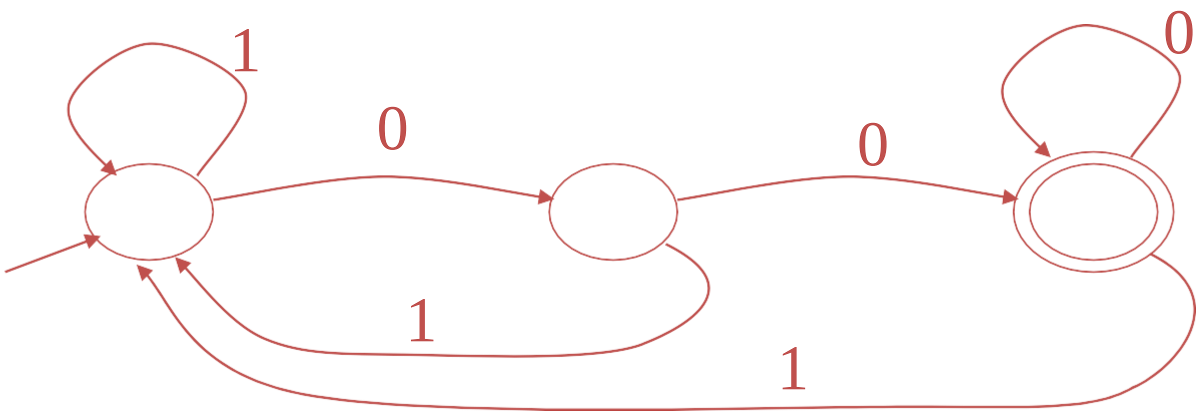
And Another Example

- Alphabet {0,1}
- What language does this recognize?



And Another Example

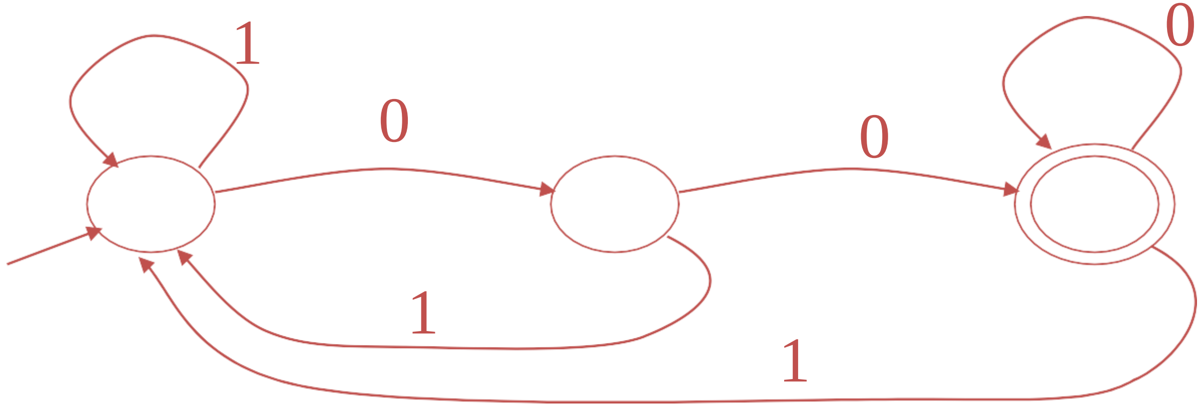
Select the regular language that denotes the same language as this finite automaton



- $(0 + 1)^*$
- $(1^* + 0)(1 + 0)$
- $1^* + (01)^* + (001)^* + (000^*1)^*$
- $(0 + 1)^*00$

And Another Example

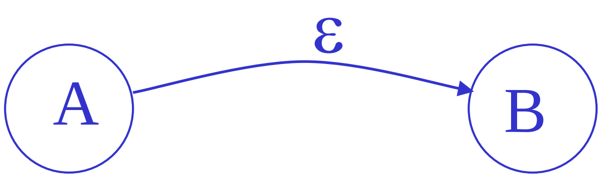
Select the regular language that denotes the same language as this finite automaton



- (0 + 1)*
- (1* + 0)(1 + 0)
- 1* + (01)* + (001)* + (000*1)*
- (0 + 1)*00

Epsilon Moves

- Another kind of transition: ε-moves



- Machine can move from state A to state B without reading input

Deterministic and Nondeterministic Automata

- Deterministic Finite Automata (DFA)
  - One transition per input per state
  - No ε-moves

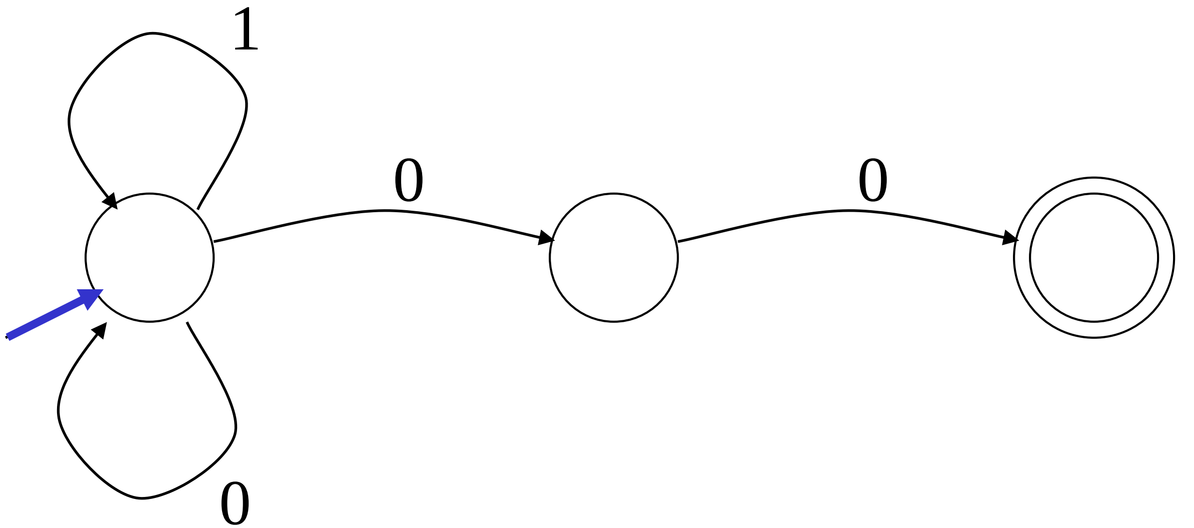
- Nondeterministic Finite Automata (NFA)
  - Can have multiple transitions for one input in a given state
  - Can have ε-moves

Execution of Finite Automata

- A DFA can take only one path through the state graph
  - Completely determined by input
- NFAs can choose
  - Whether to make ε-moves
  - Which of multiple transitions for a single input to take

Acceptance of NFAs

- An NFA can get into multiple states

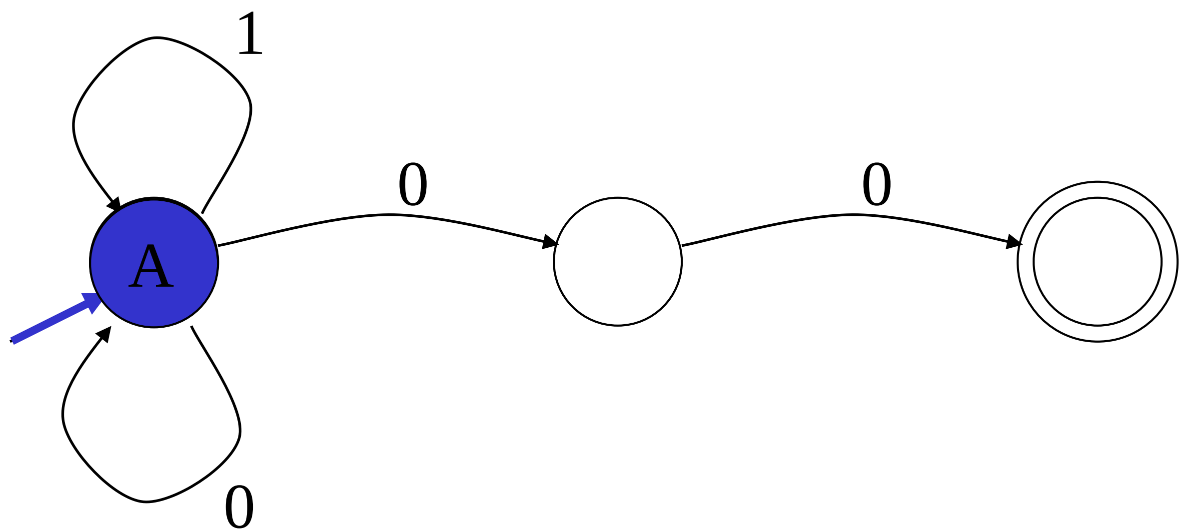


- Input:
- Possible States:

Rule: NFA accepts if it can get to a final state

Acceptance of NFAs

- An NFA can get into multiple states

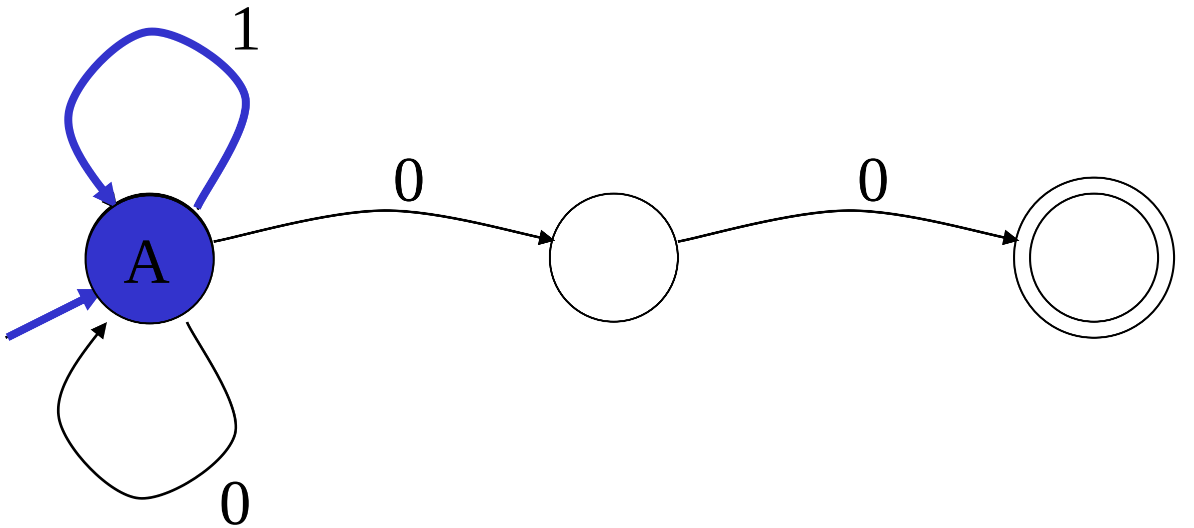


- Input: 1
- Possible States:

Rule: NFA accepts if it <u>can</u> get to a final state

Acceptance of NFAs

- An NFA can get into multiple states

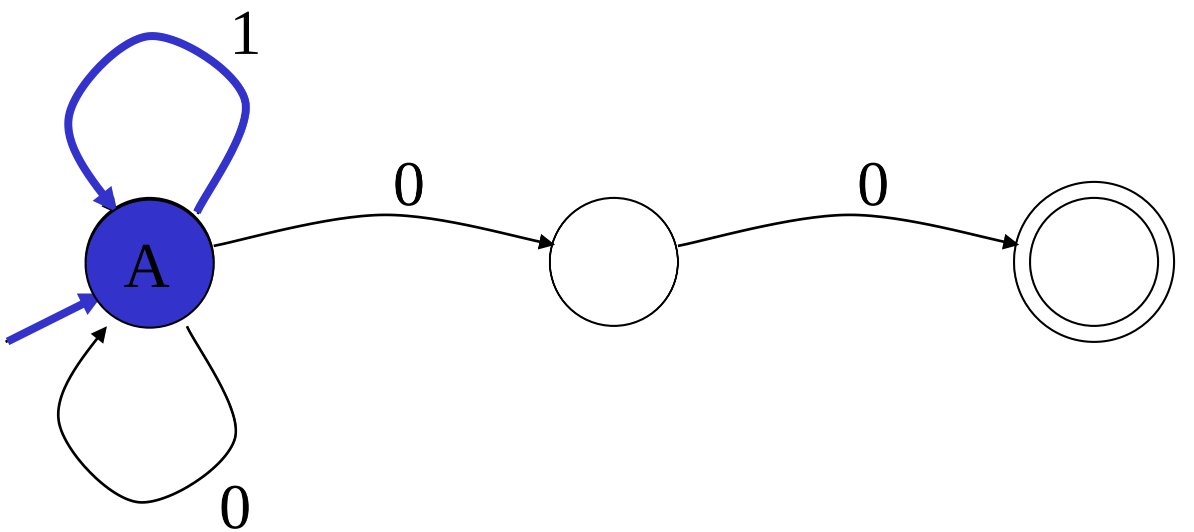


- Input: 1
- Possible States: {A}

Rule: NFA accepts if it <u>can</u> get to a final state

Acceptance of NFAs

- An NFA can get into multiple states

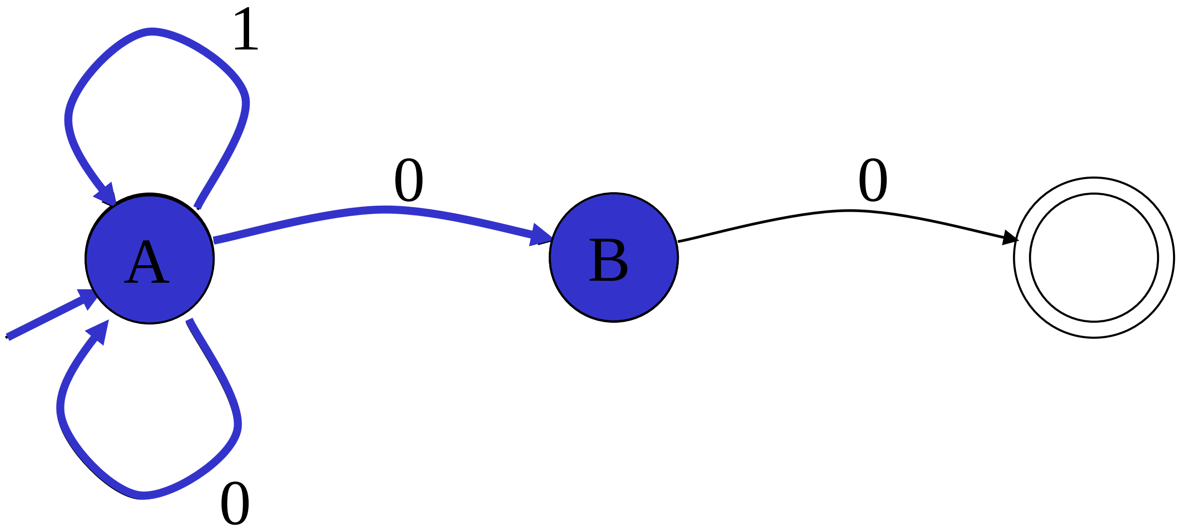


- Input: 1 0
- Possible States: {A}

Rule: NFA accepts if it <u>can</u> get to a final state

Acceptance of NFAs

- An NFA can get into multiple states

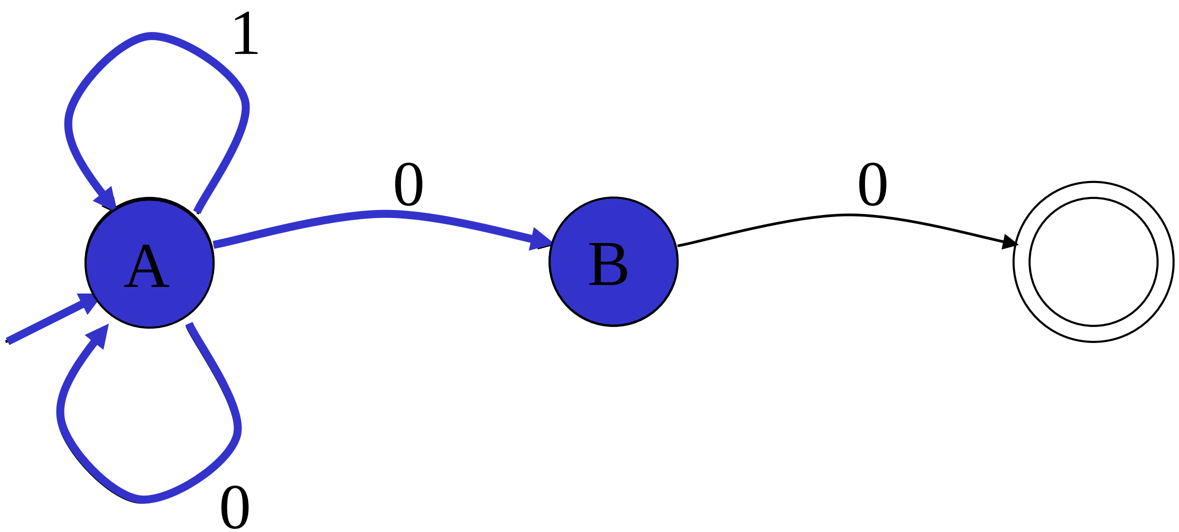


- Input: 1 0
- Possible States: {A} {A, B}

Rule: NFA accepts if it <u>can</u> get to a final state

Acceptance of NFAs

- An NFA can get into multiple states

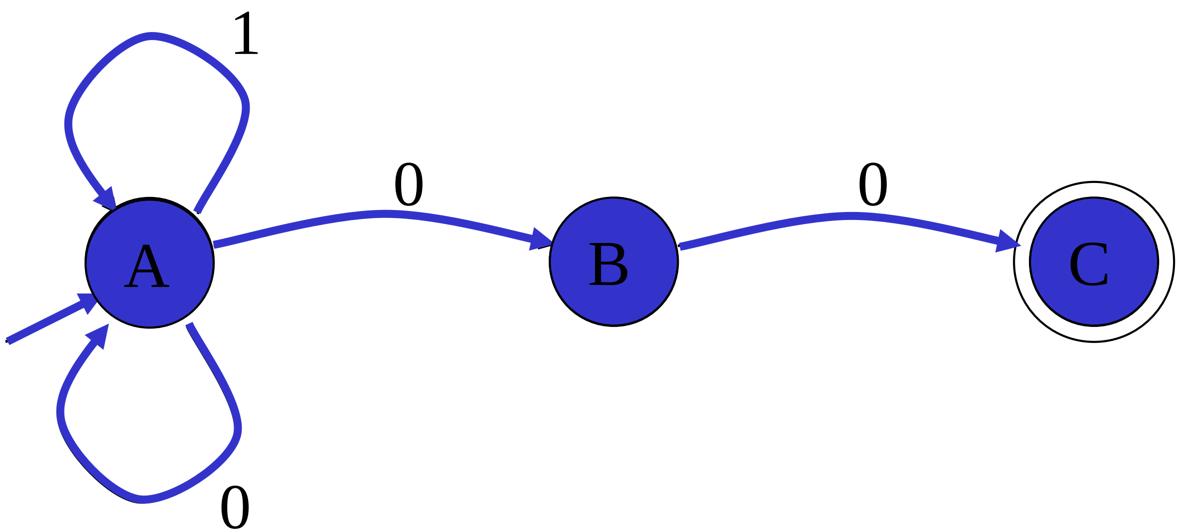


- Input: 1 0 0
- Possible States: {A} {A, B}

Rule: NFA accepts if it <u>can</u> get to a final state

Acceptance of NFAs

- An NFA can get into multiple states



- Input: 1 0 0
- Possible States: {A} {A, B} {A, B, C}

Rule: NFA accepts if it <u>can</u> get to a final state

NFA vs. DFA (1)

- NFAs and DFAs recognize the same set of languages (regular languages)

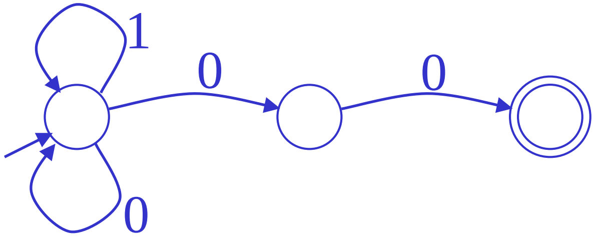
- DFAs are faster to execute
  - There are no choices to consider

- NFAs are, in general, smaller
  - Sometimes exponentially smaller

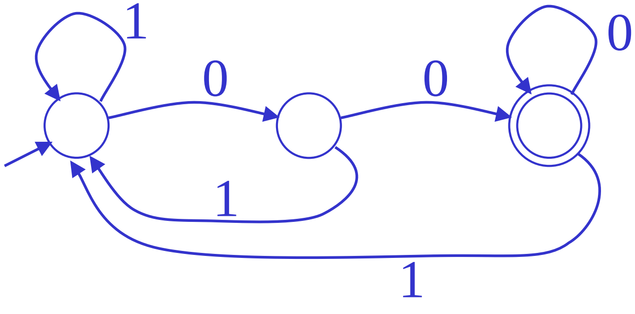
NFA vs. DFA (2)

- For a given language NFA can be simpler than DFA

NFA



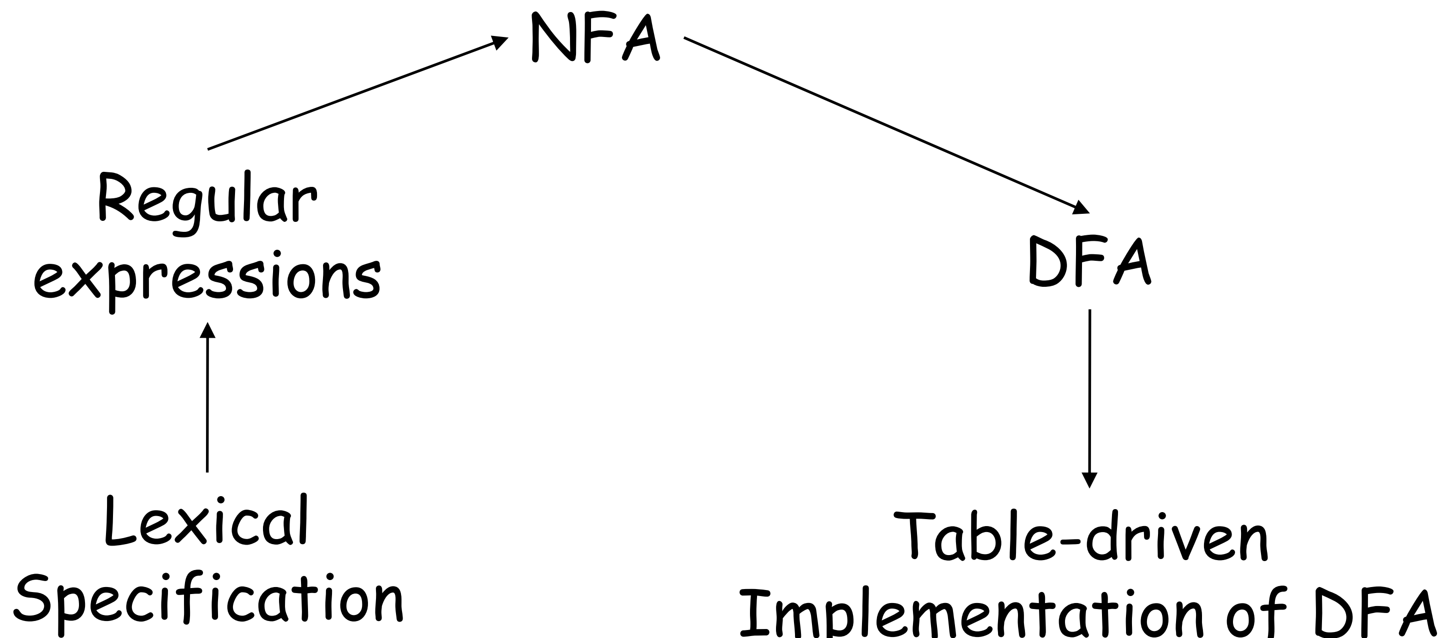
DFA



- DFA can be exponentially larger than NFA

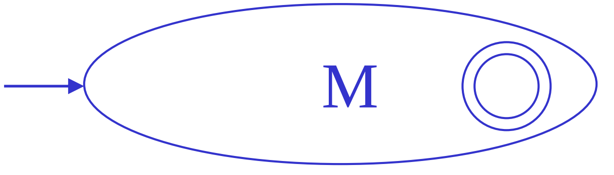
Regular Expressions to Finite Automata

- High-level sketch

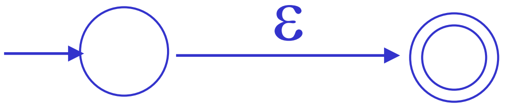


Regular Expressions to NFA (1)

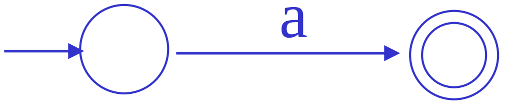
- For each kind of rexp, define an NFA
  - Notation: NFA for rexp M



- For ε

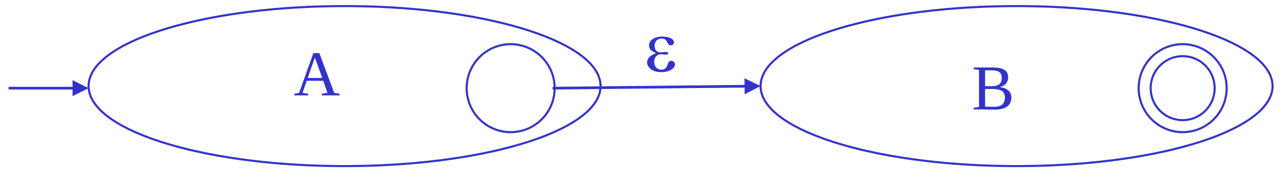


- For input a

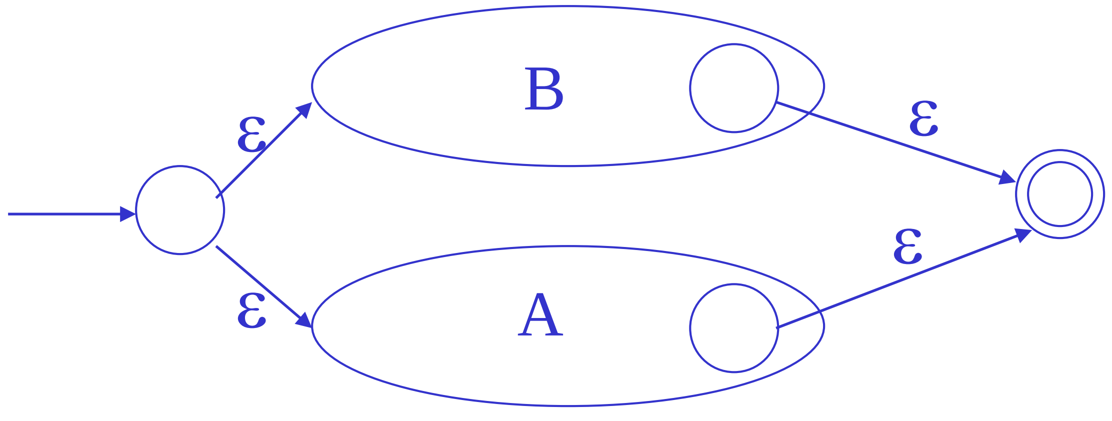


Regular Expressions to NFA (2)

- For AB

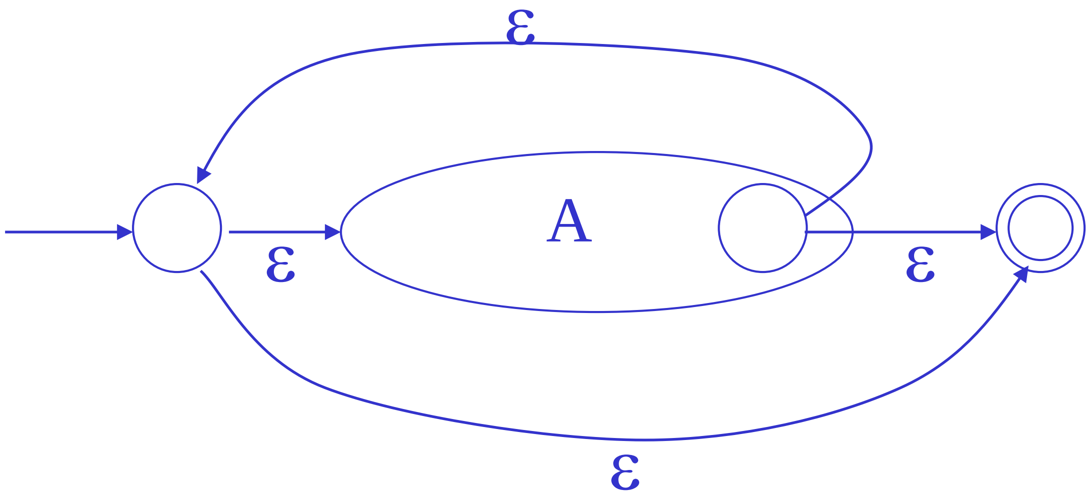


- For A + B



Regular Expressions to NFA (3)

- For *A**

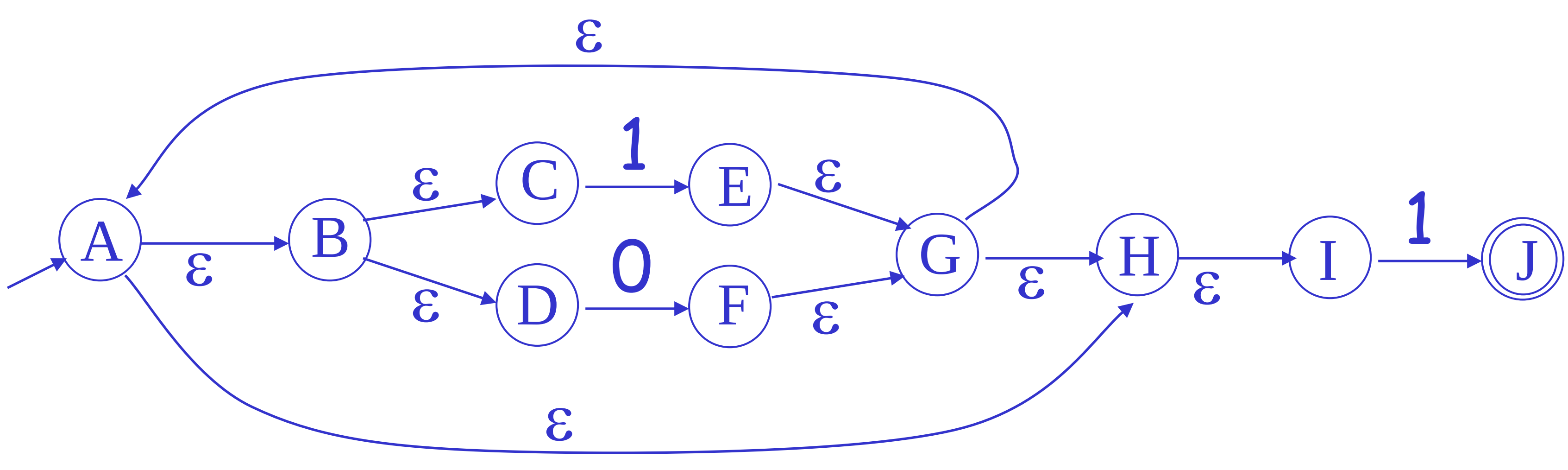


Example of RegExp -> NFA conversion

- Consider the regular expression

  $(1+0)^*1$

- The NFA is



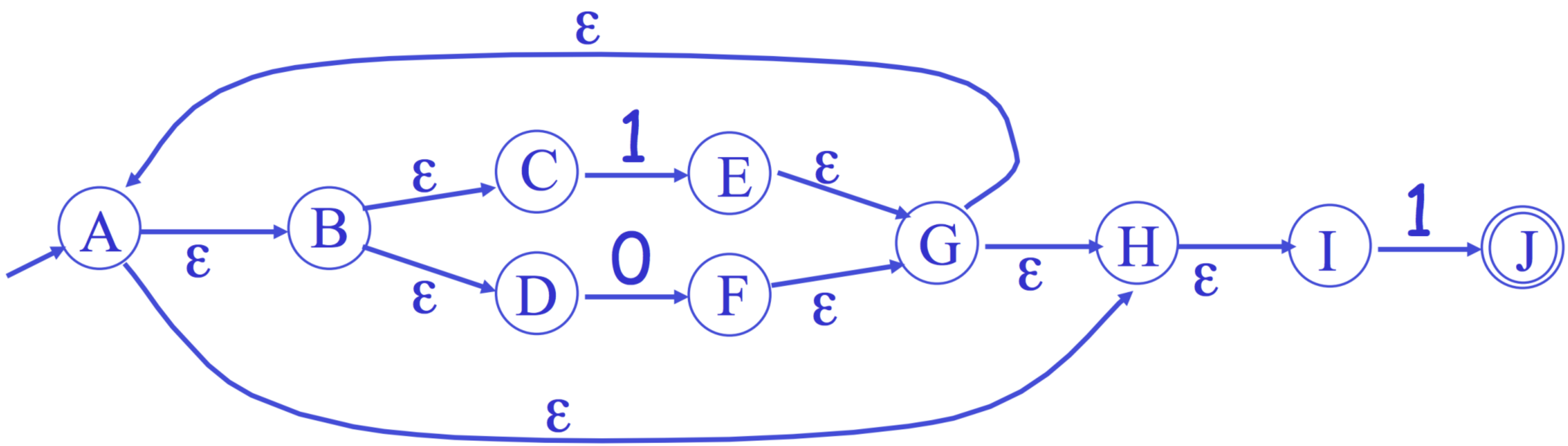
NFA to DFA: *The Trick*

- Simulate the NFA
- Each state of DFA
  = a non-empty subset of states of the NFA
- Start state
  = ε-closure of the start state of NFA
- Add a transition $S \rightarrow^{a} S'$ to DFA iff
  - S' is the set of NFA states reachable from any state in S after seeing the input a, considering ε-moves as well
- Final states
  - Subsets that include at least one final state of NFA

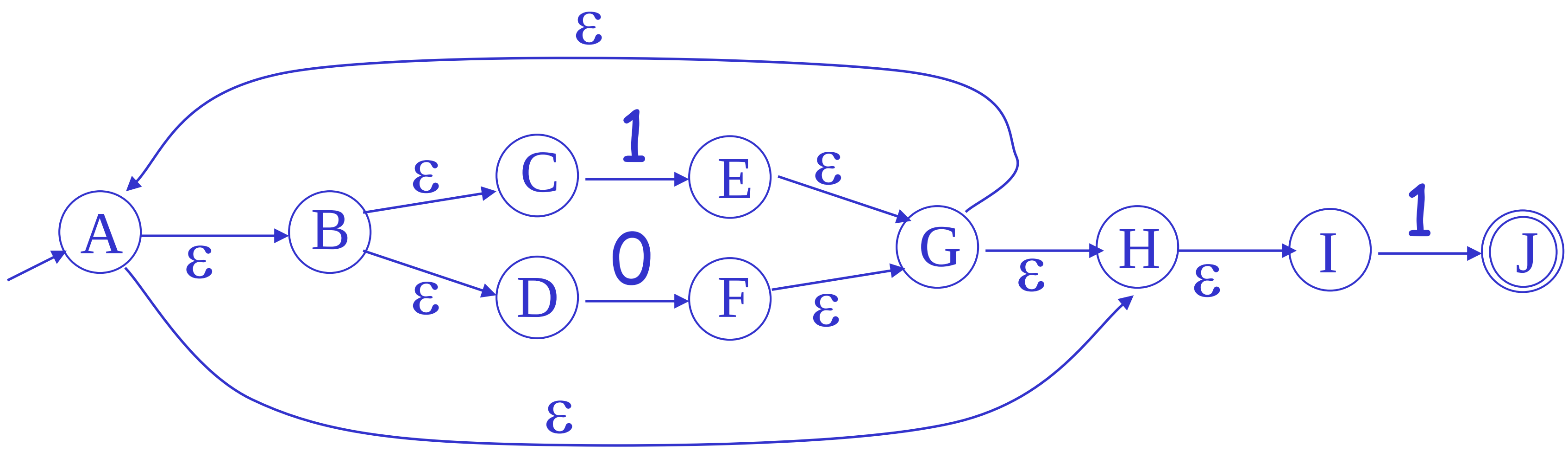
ε-closure of a state

ε-closure(B)= {B,C,D}

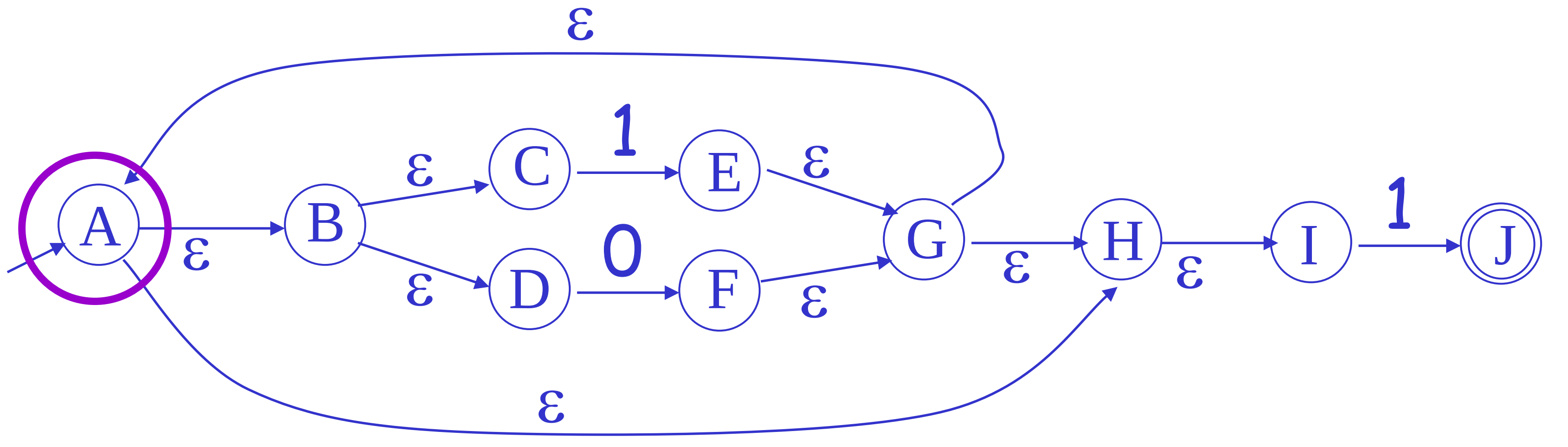
ε-closure(G)= {A,B,C,D,G,H,I}



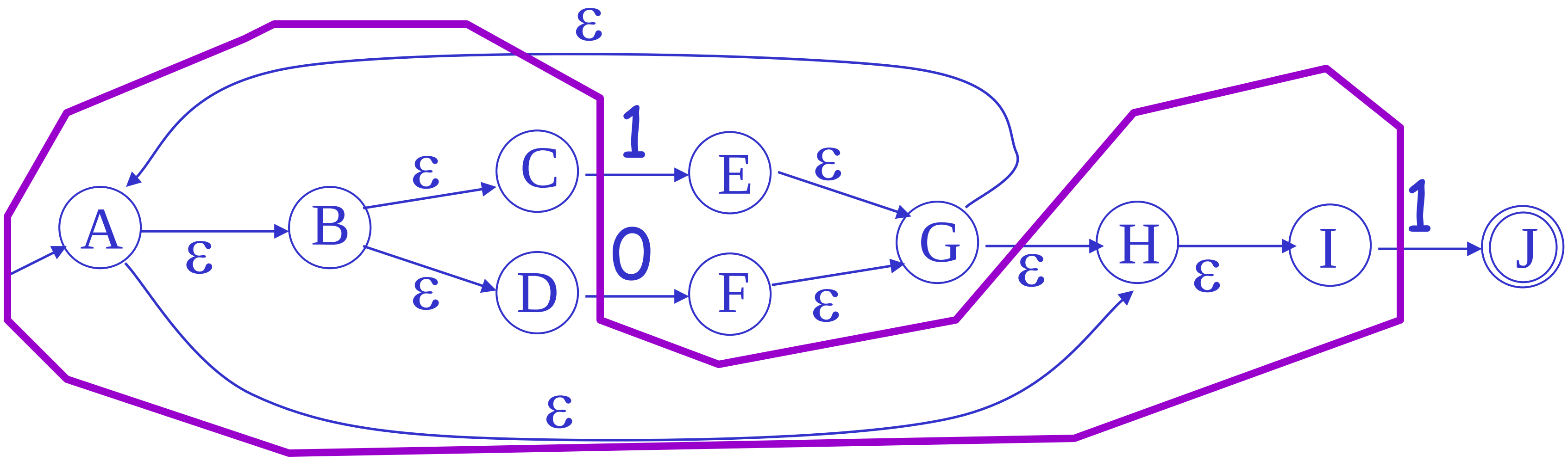
NFA -> DFA Example



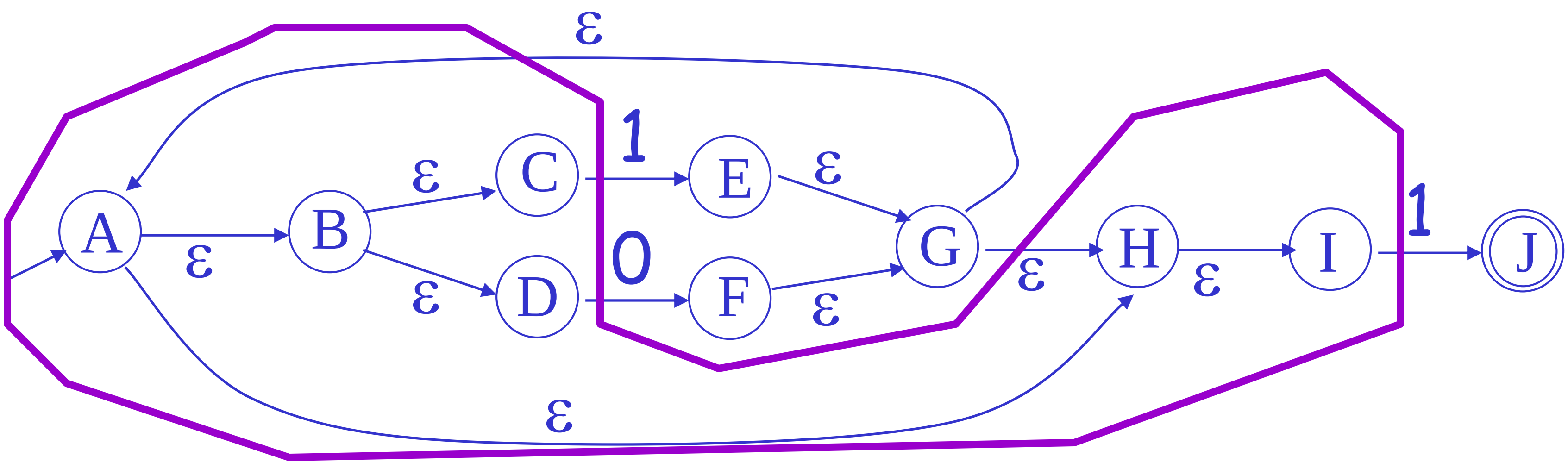
NFA -> DFA Example



NFA -> DFA Example



NFA -> DFA Example



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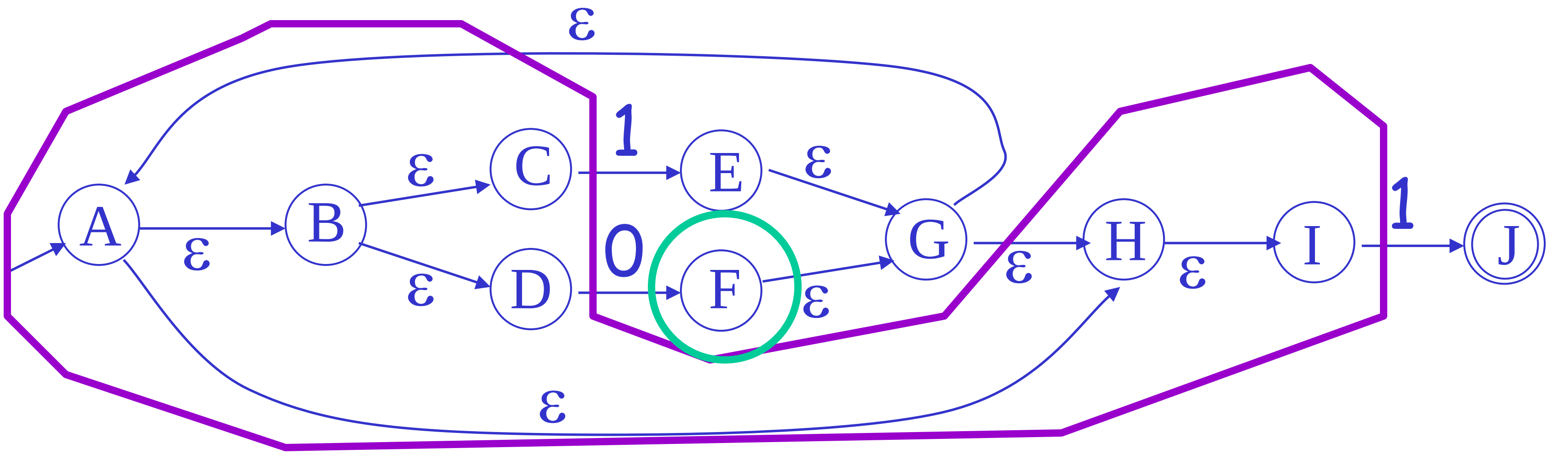

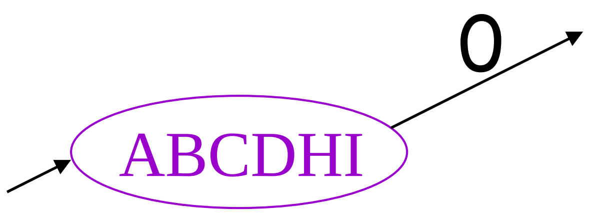

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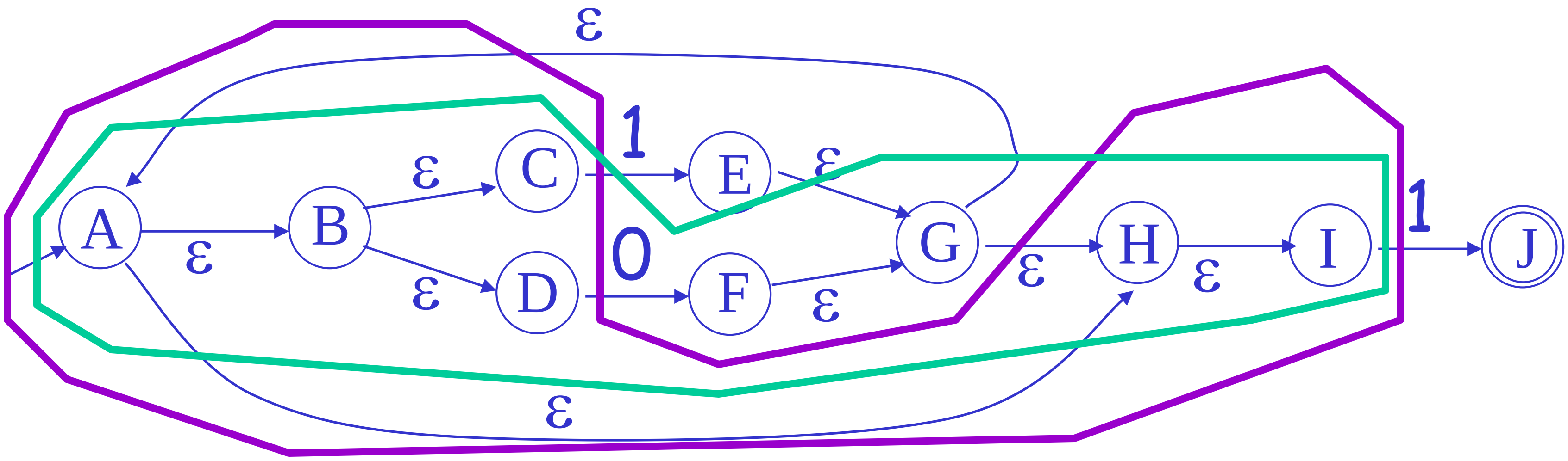

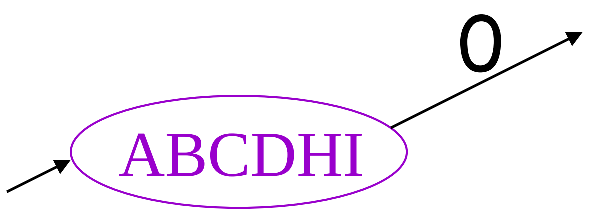

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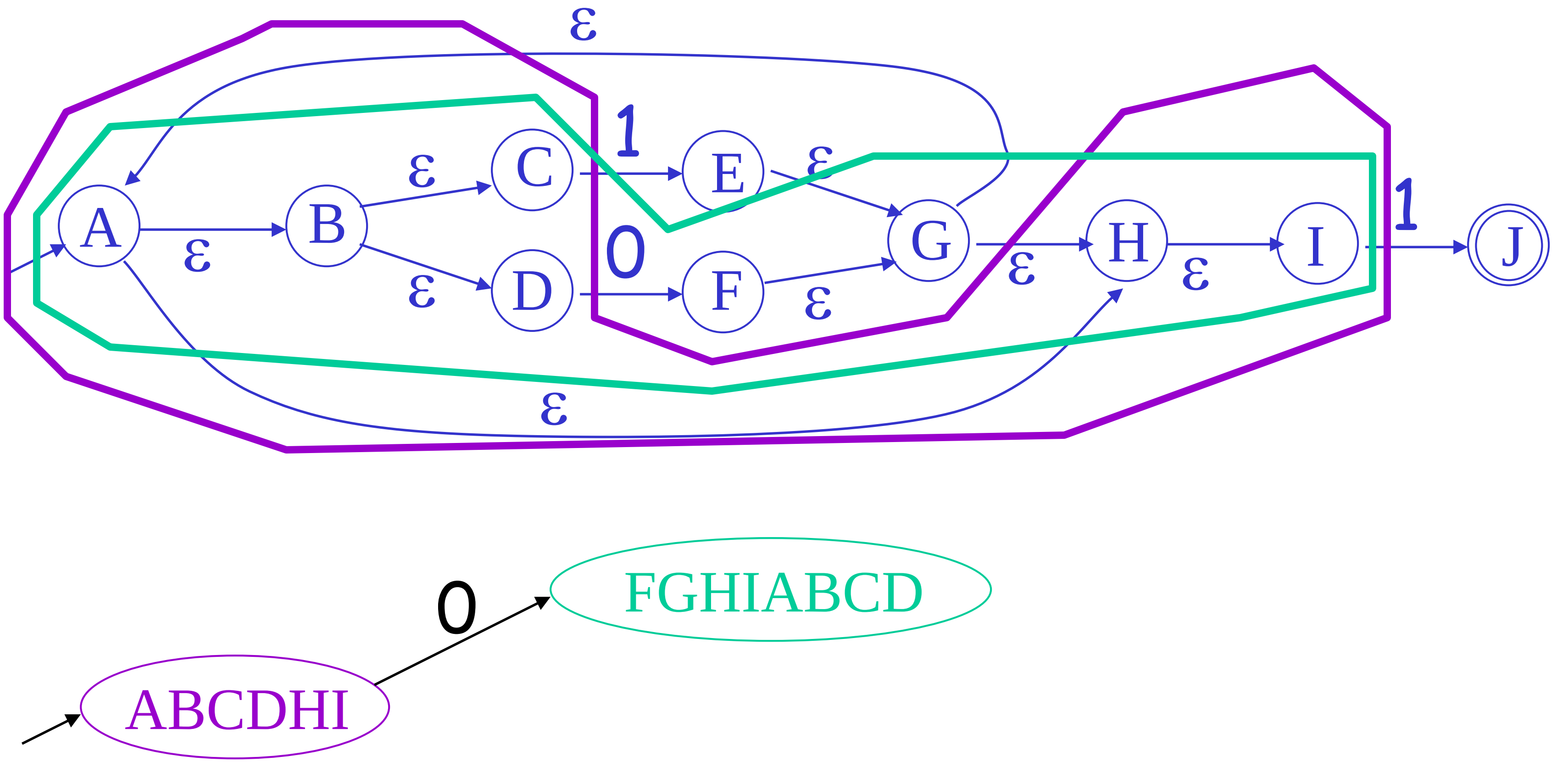

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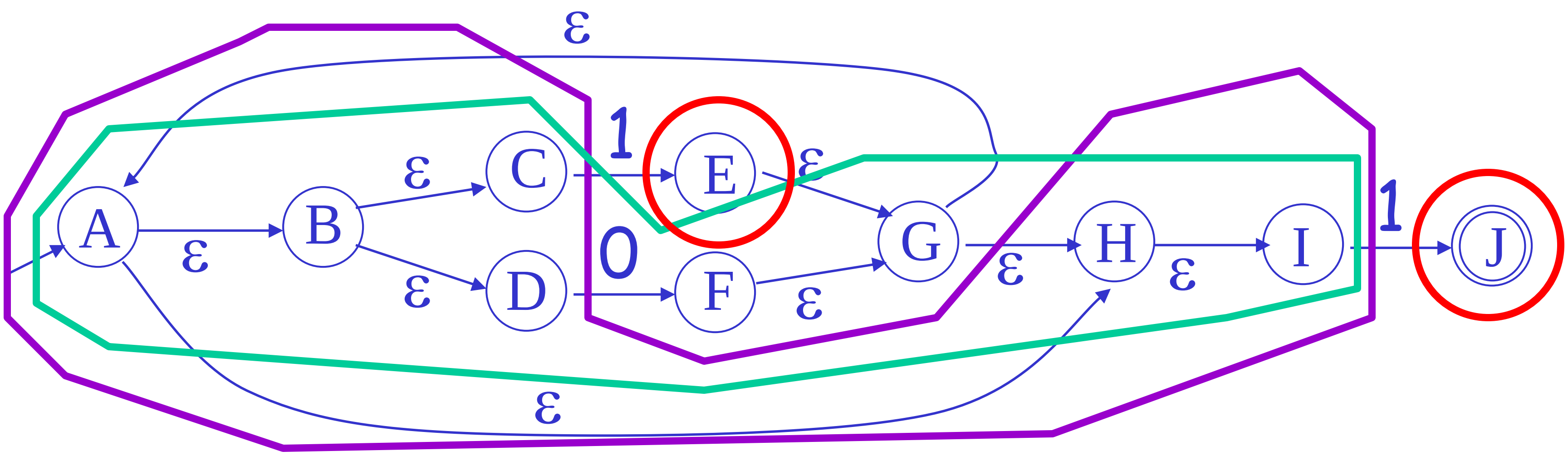
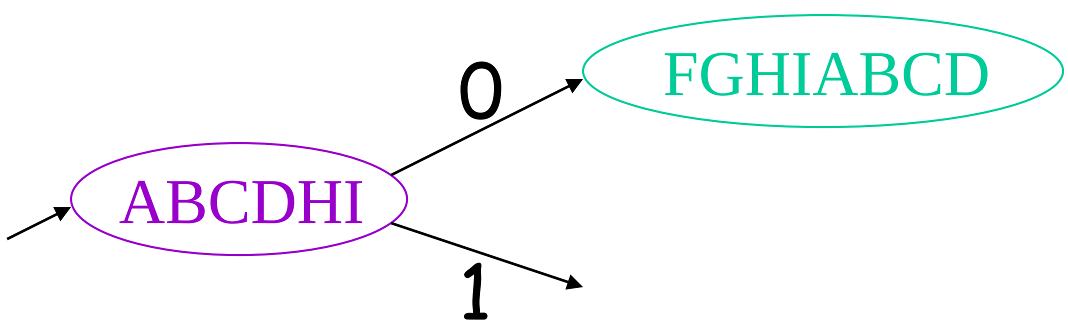
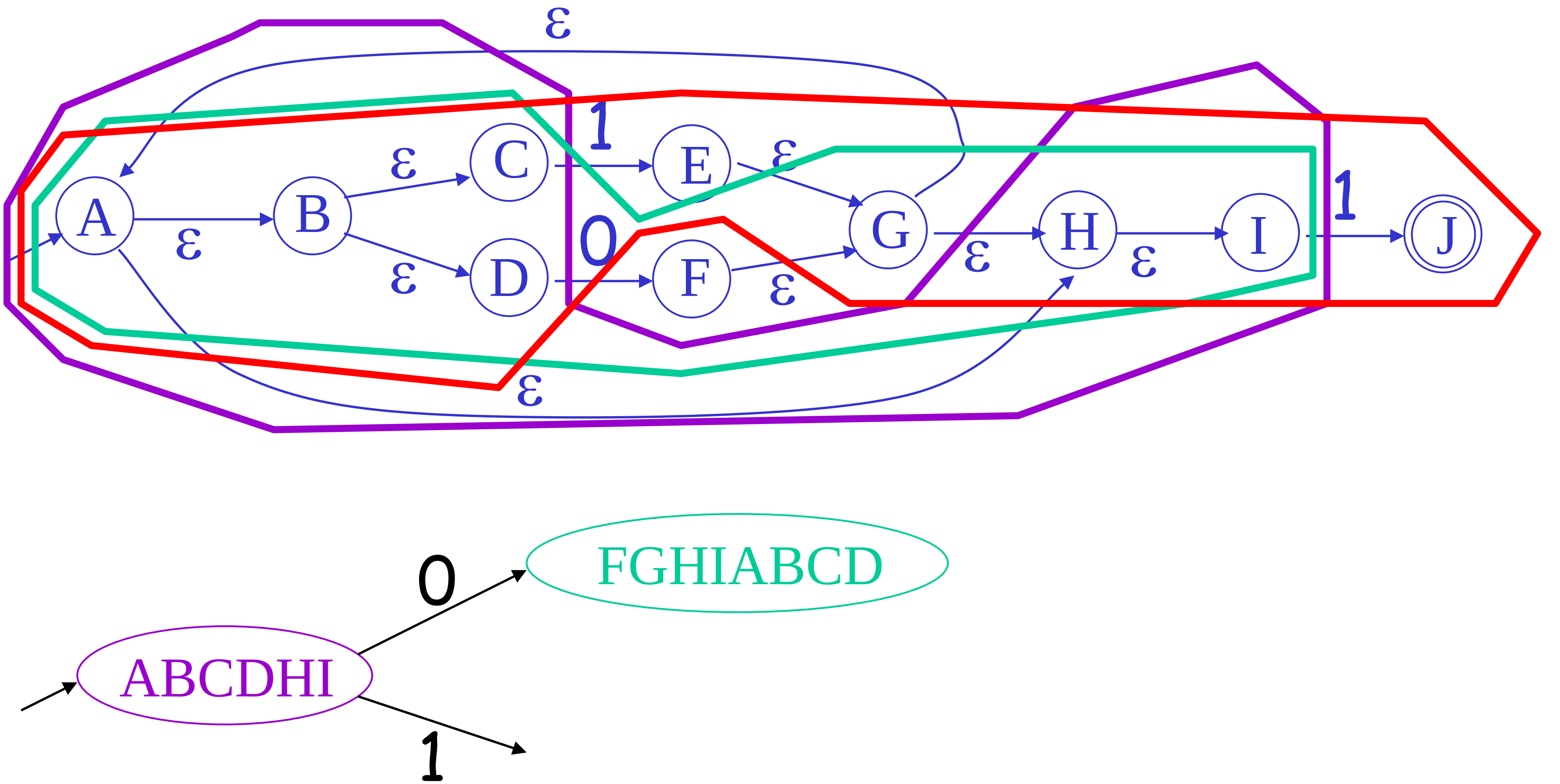




NFA -> DFA Example



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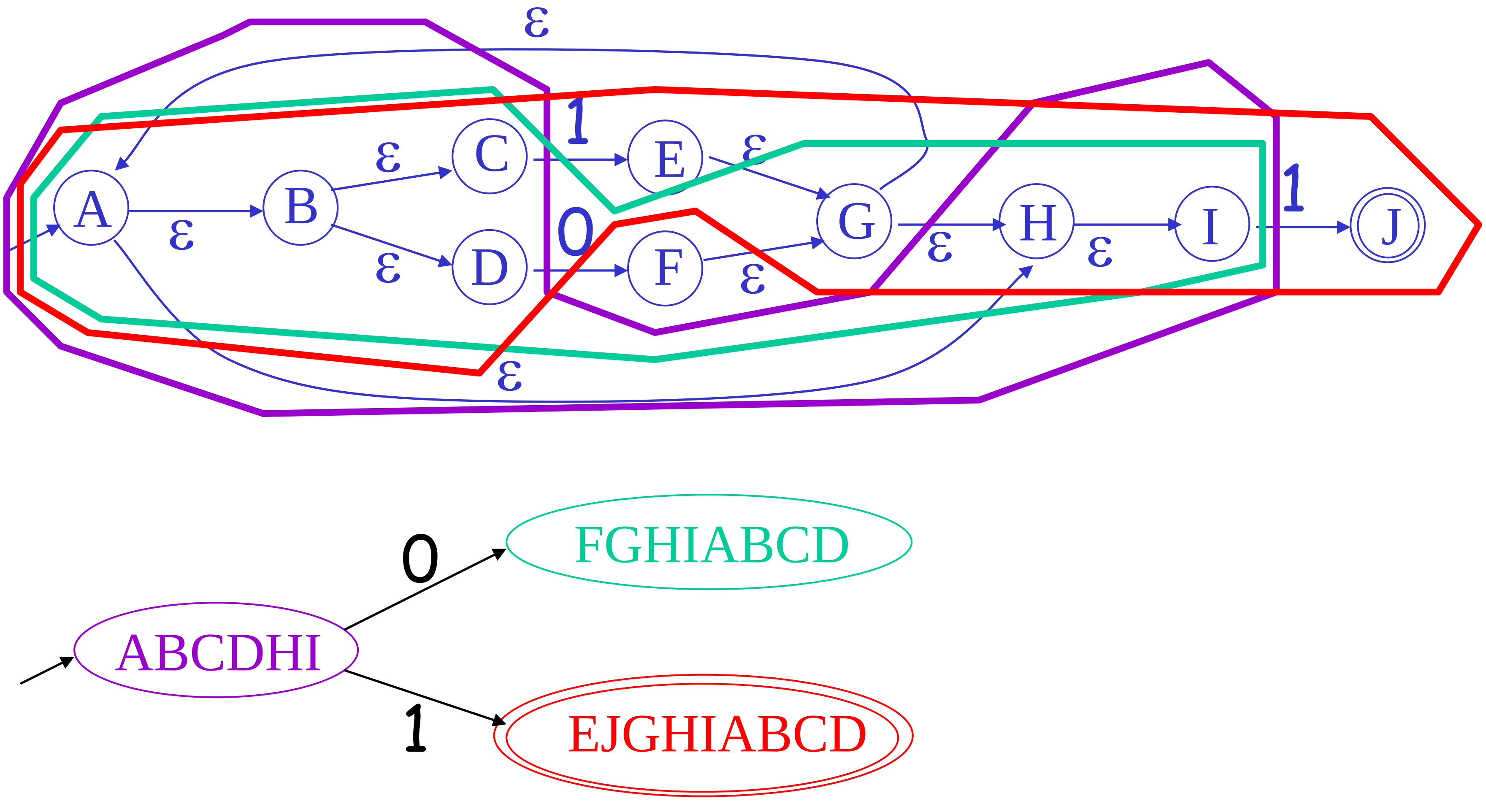

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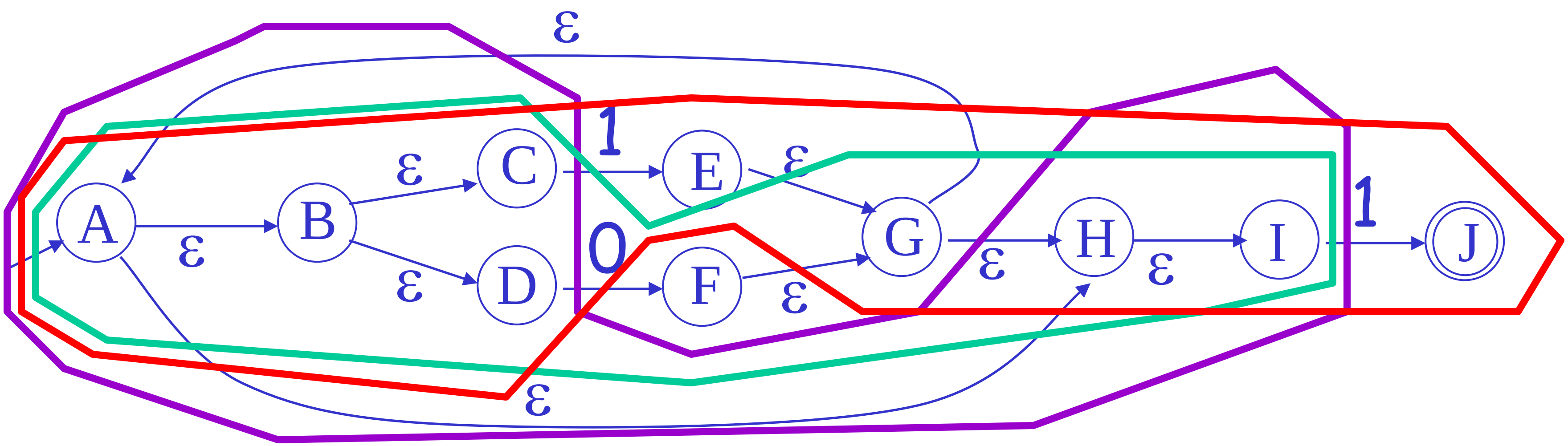
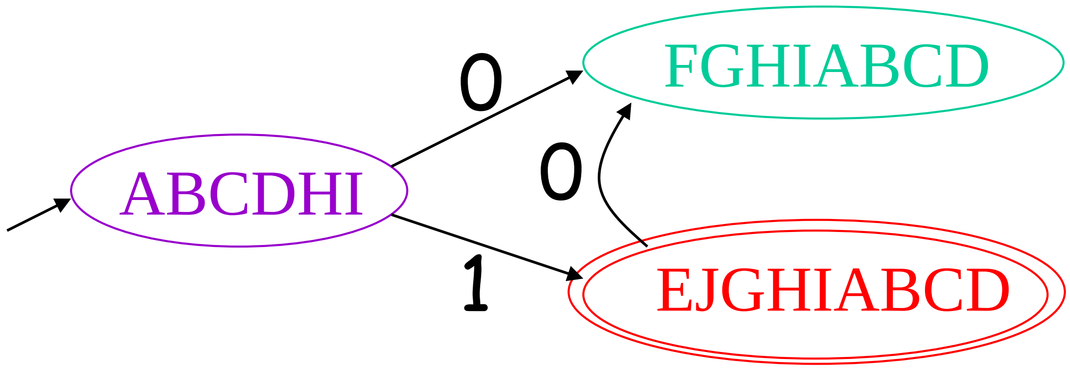
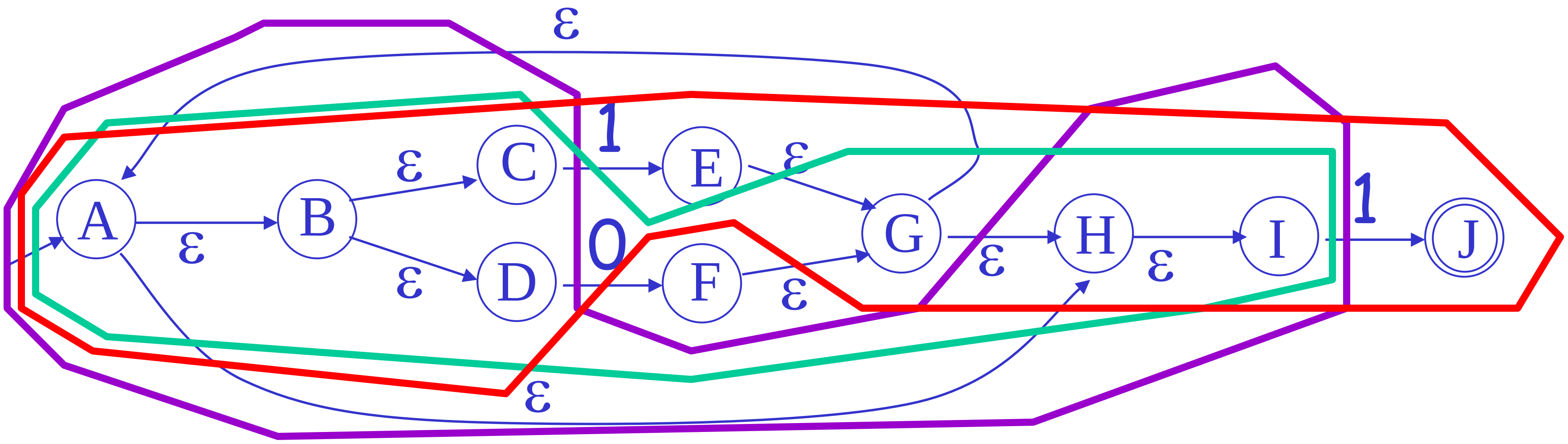
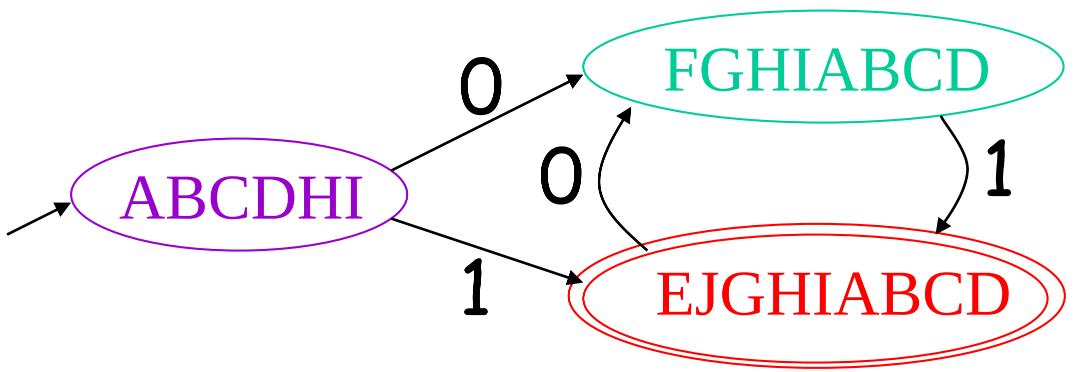


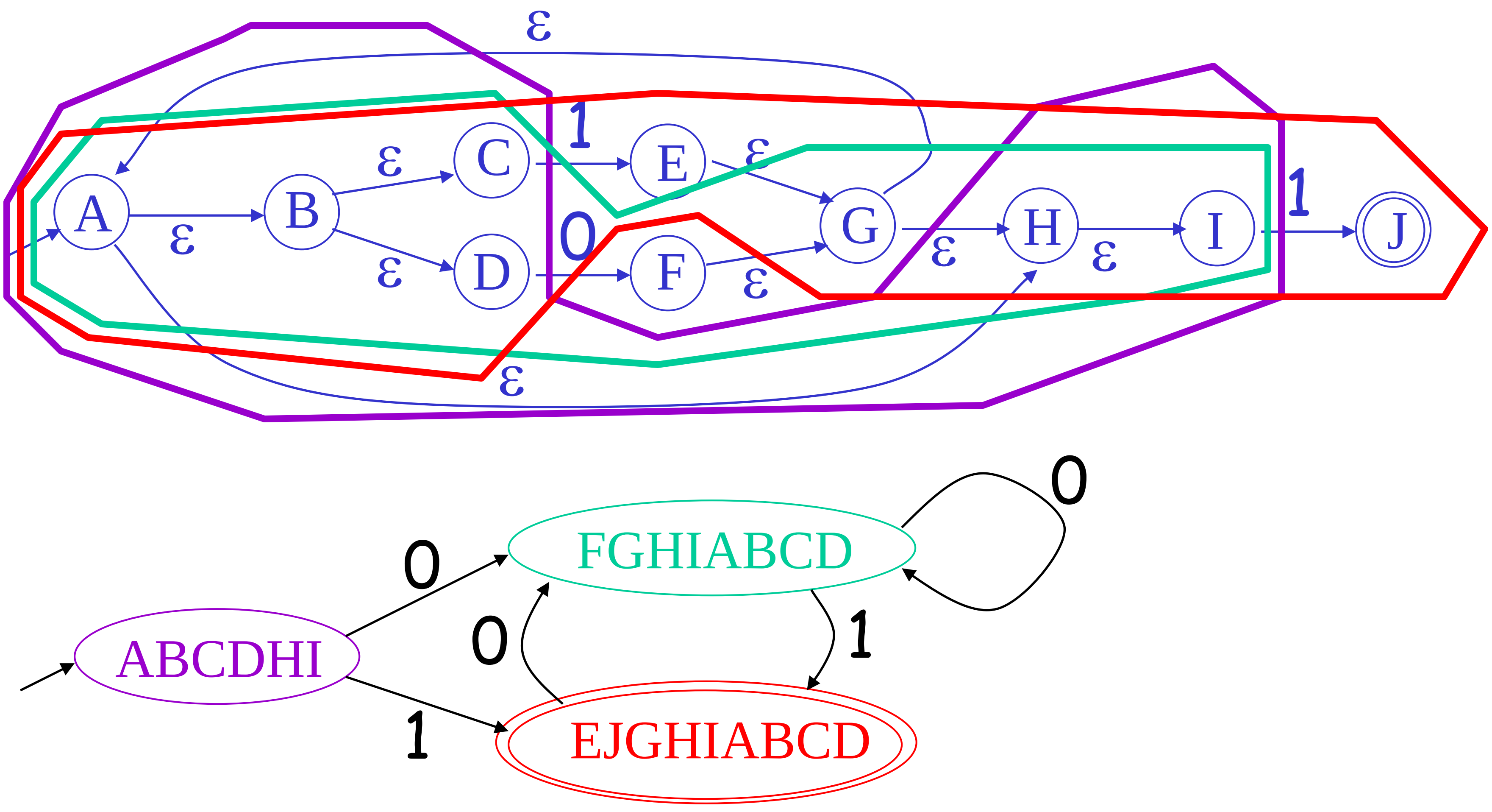


NFA -> DFA Example

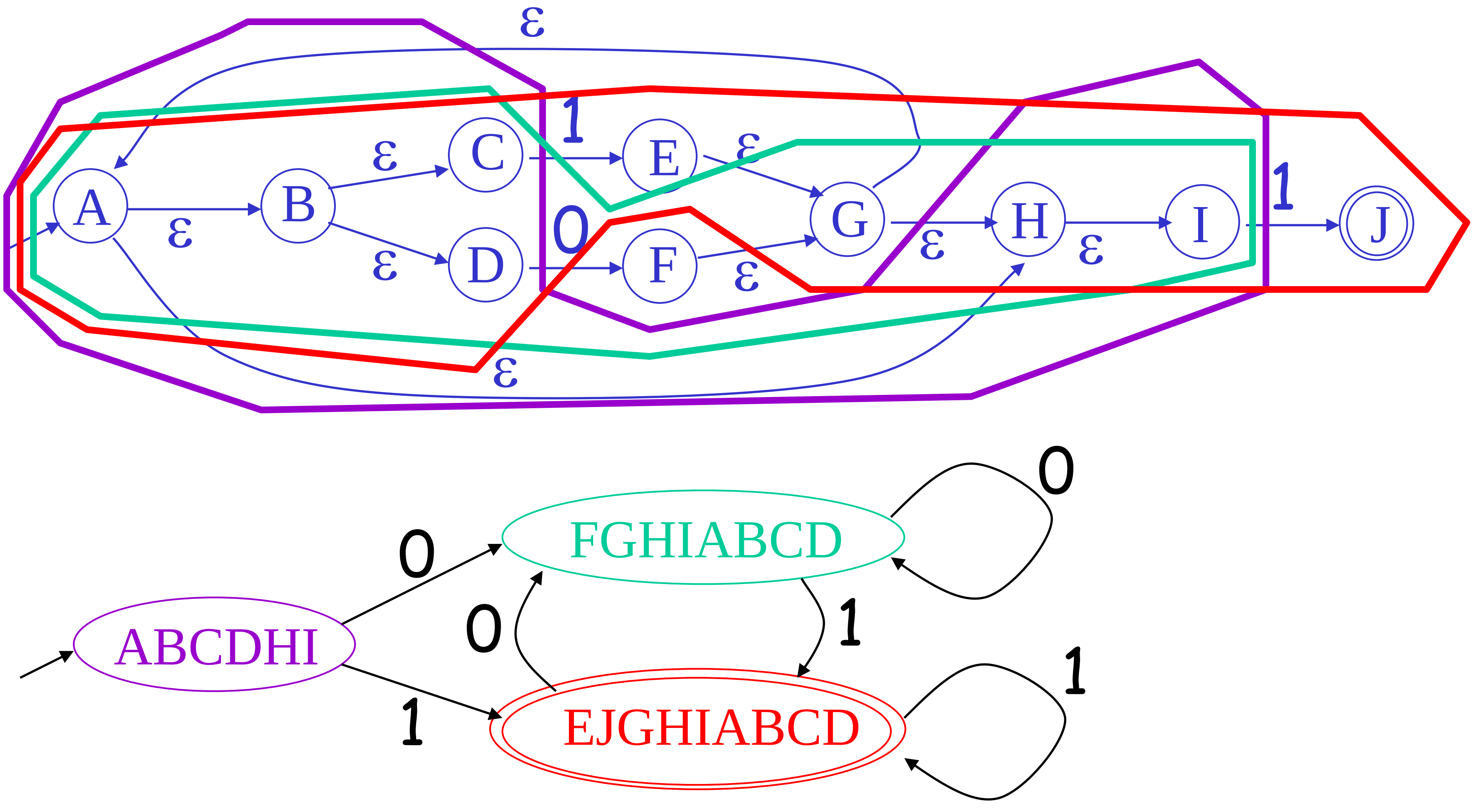




NFA -> DFA Example



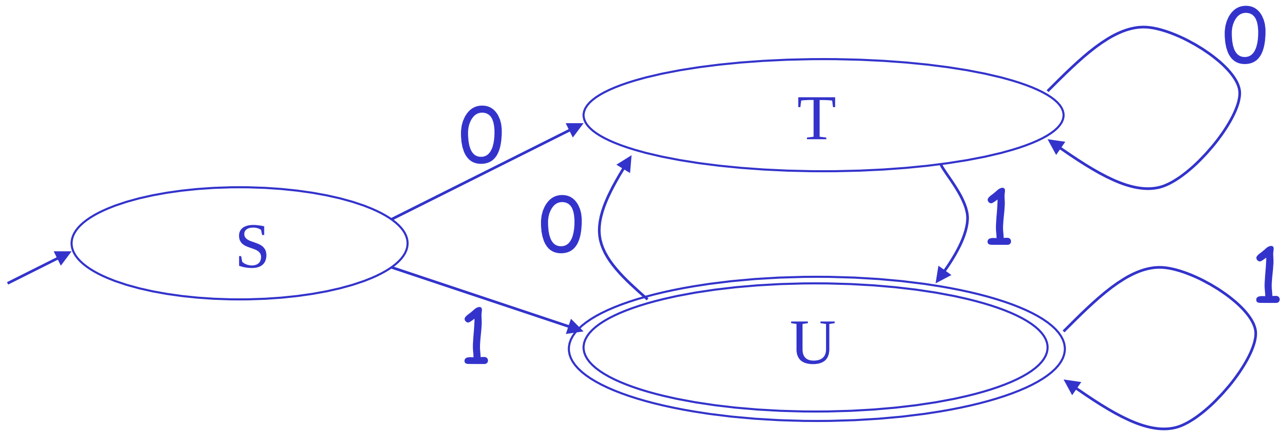
NFA -> DFA Example



Implementation

- A DFA can be implemented by a 2D table T
  - One dimension is "states"
  - Other dimension is "input symbol"
  - For every transition $S_i \rightarrow^a S_k$ define $T[i,a] = k$
- DFA "execution"
  - If in state S_i and input a, read $T[i,a] = k$ and skip to state S_k
  - Very efficient

Table Implementation of a DFA

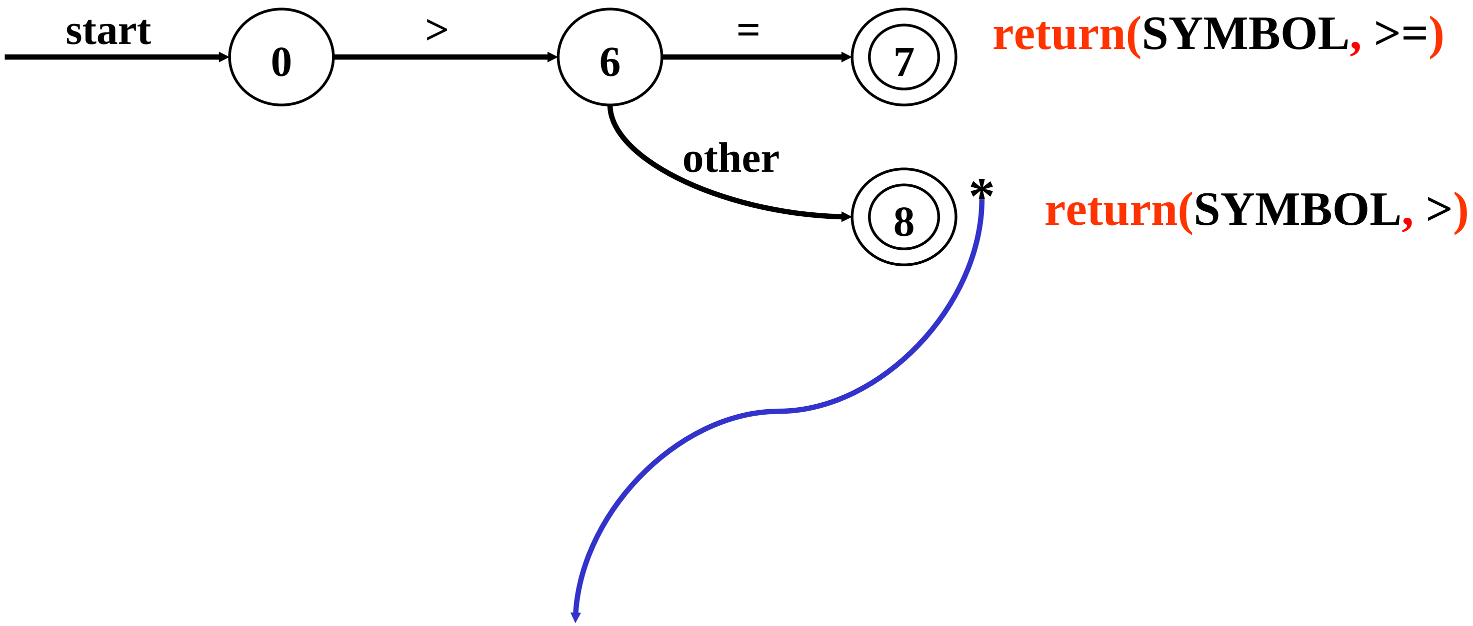


	0	1
S	T	U
T	T	U
U	T	U

Implementation (Cont.)

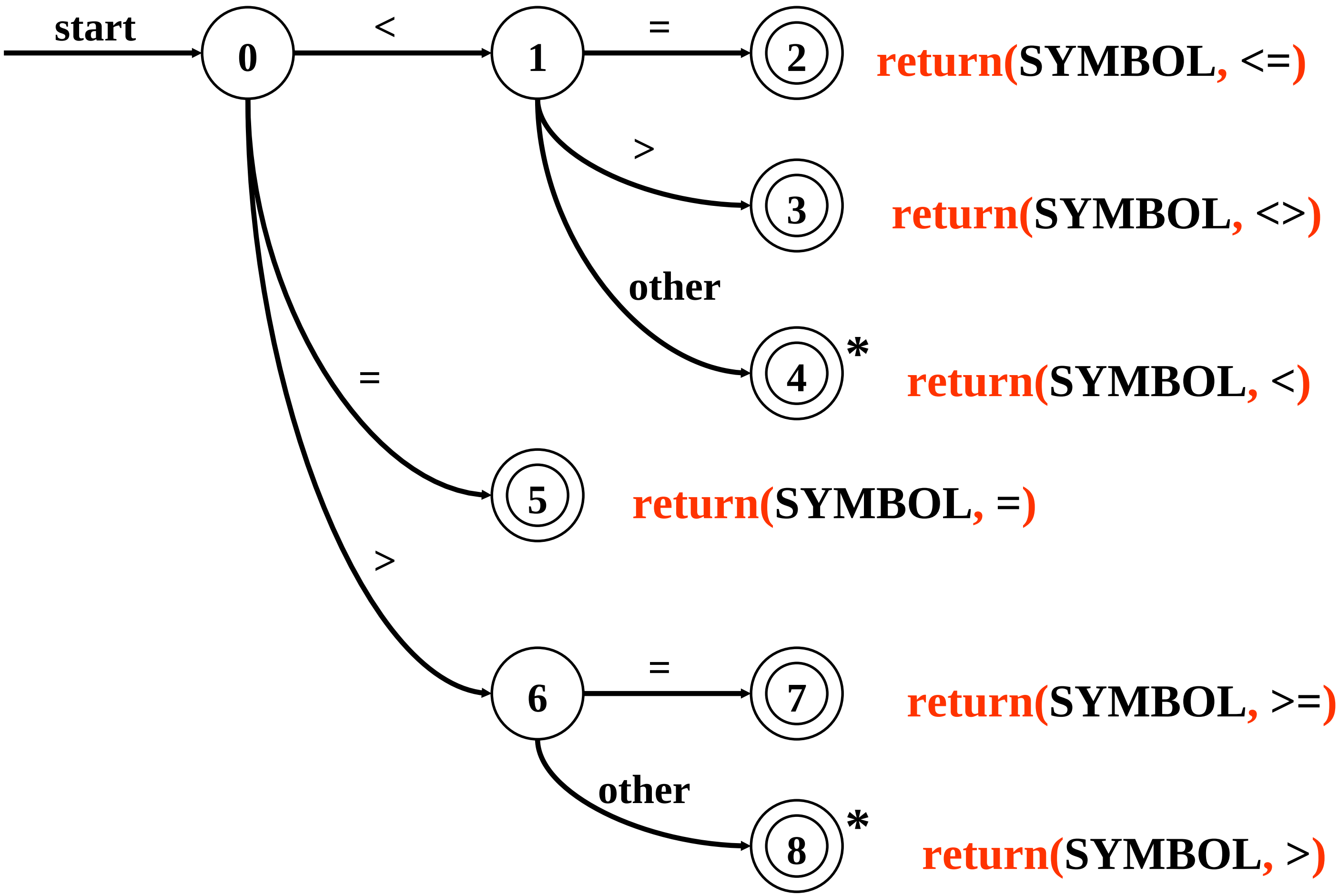
- NFA -> DFA conversion is at the heart of tools such as flex
- But, DFAs can be huge
- In practice, flex-like tools trade off speed for space in the choice of NFA and DFA representations

DFA for recognizing two relational operators

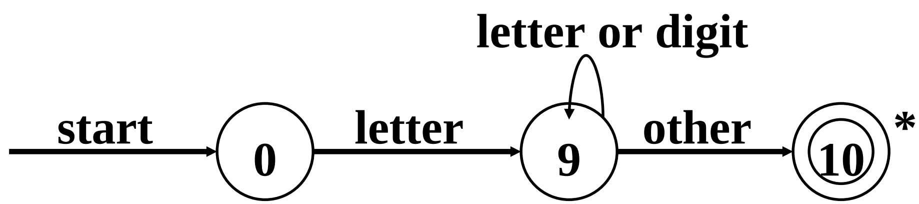


We've accepted ">" and have read "other" character that must be unread. That is moving the input pointer one character back.

DFA of Pascal relational operators



DFA for recognizing id and keyword

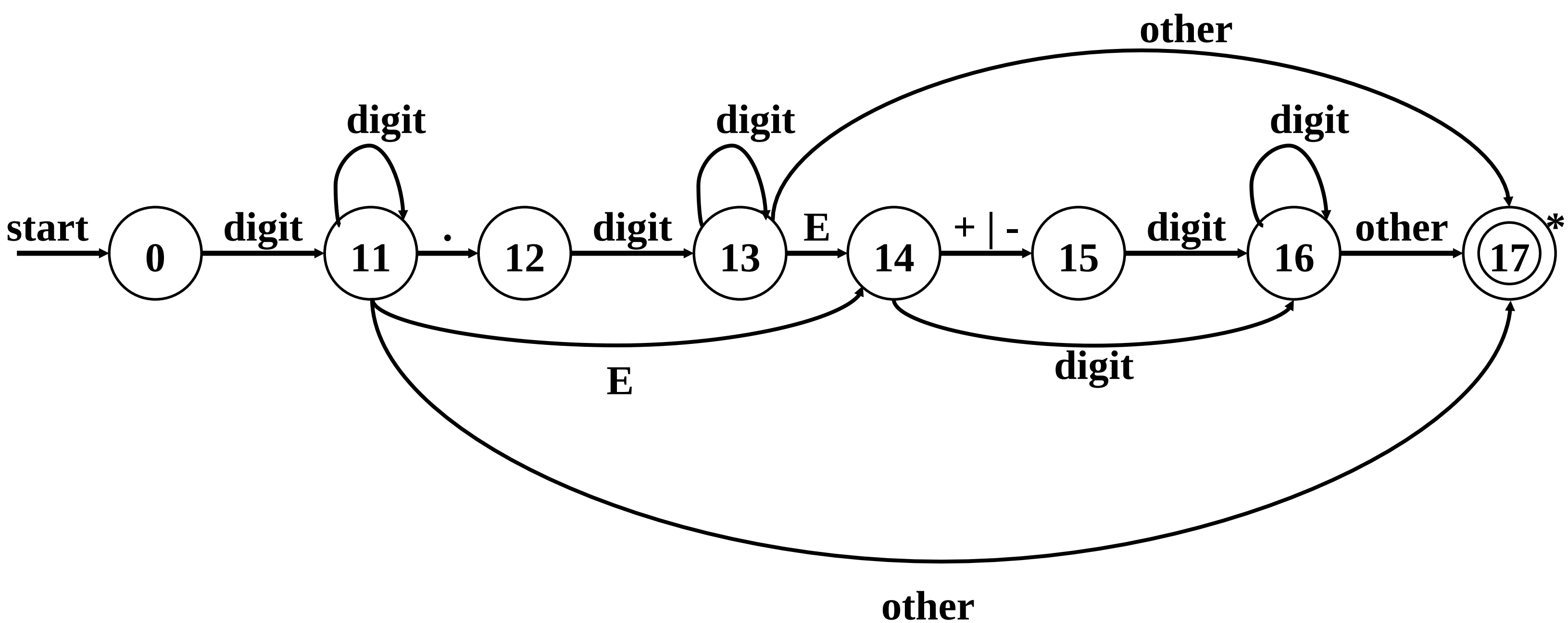


return(get_token(), install_id())

returns either a KEYWORD or ID based on the type of the token

If the token is an ID, its lexeme is inserted into the symbol table (only one record for each lexeme); and lexeme of the token is returned.

DFA of Pascal Unsigned Numbers



return(NUM, lexeme of the number)

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

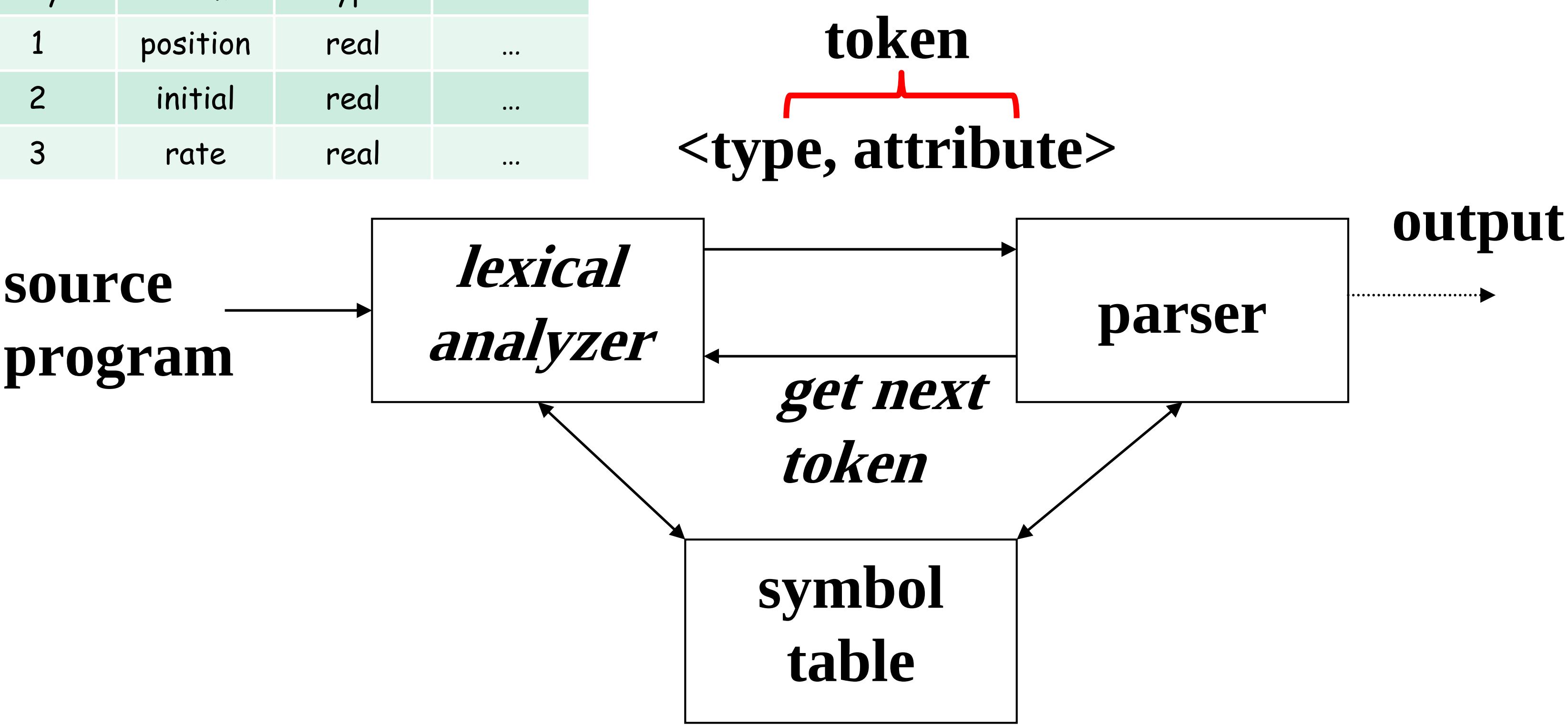
Error recovery

- 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

Lexical Analyzer in Perspective (Revisited)

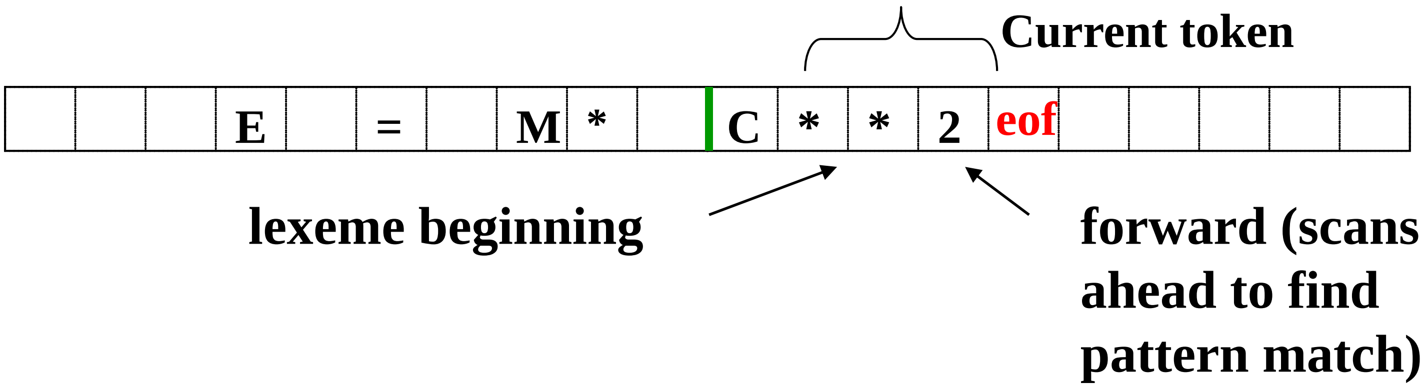
Symbol Table			
key	lexeme	type	…
1	position	real	…
2	initial	real	…
3	rate	real	…



position = initial + rate * 60

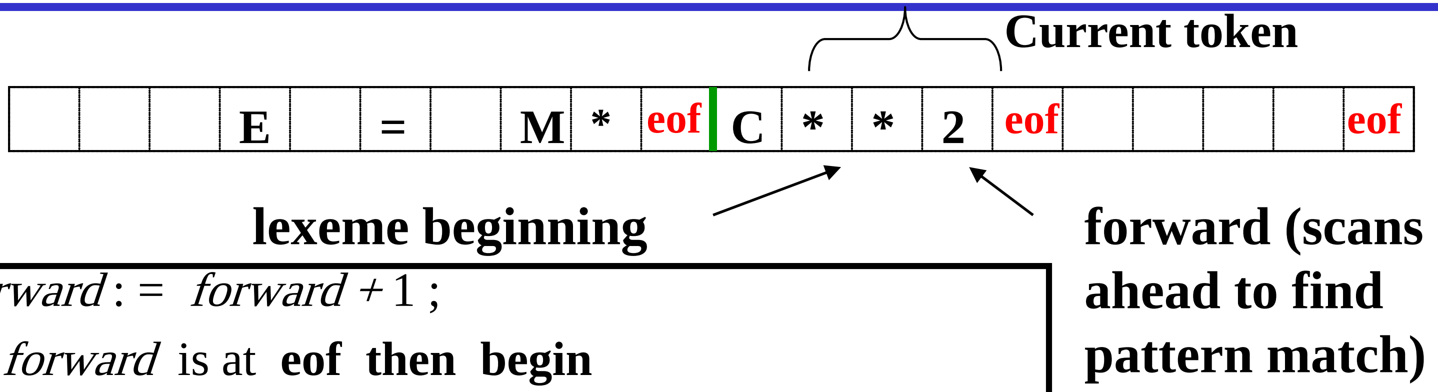
<id, 1> <op, = > <id, 2> <op, + > <id, 3> <op, * > <num, 60 >

Using Buffer 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 biginning of first half
    end
    else  forward : =  forward + 1 ;
```

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 biginning of first half

  end

  else / * **eof** within buffer signifying end of input * /

    terminate lexical analysis

end 2nd **eof** ⇒ no more input !

Question?

Consider the string **abbbaacc** . Which of the following lexical specifications produces the tokenization: ab/bb/a/acc

Choose all that apply

- c*
  b+
  ab
  ac*
- a(b + c*)
  b+
- ab
  b+
  ac*
- b+
  ab*
  ac*

Question?

Using the lexical specification below, how is the string "**dictatorial**" tokenized?

Choose all that apply

dict (1)
dictator (2)
[a-z]* (3)
dictatorial (4)

- 1, 3
- 3
- 4
- 2, 3

Question?

Given the following lexical specification:

a(ba)*
b*(ab)*
abd
d+

Which of the following statements is true?

Choose all that apply

- babad will be tokenized as: bab/a/d
- ababdddd will be tokenized as: abab/dddd
- dddabbabab will be tokenized as: ddd/a/bbabab
- ababddababa will be tokenized as: ab/abd/d/ababa

Question?

Given the following lexical specification:

(00)*
01+
10+

Which strings are NOT successfully processed by this specification?

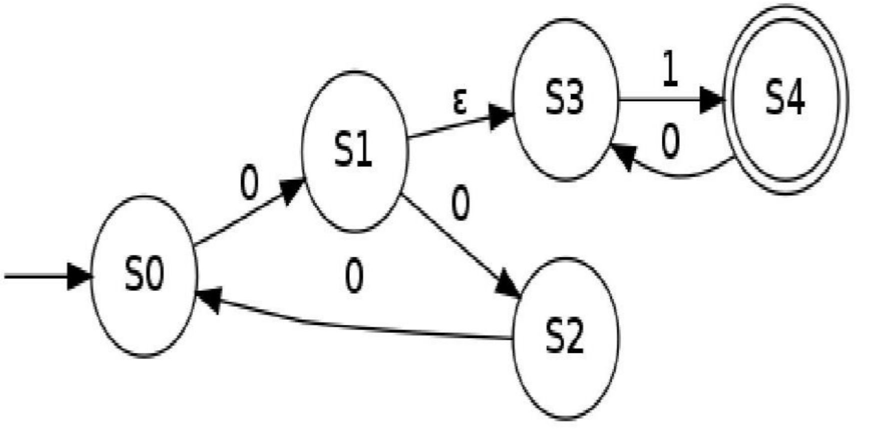
Choose all that apply

- 011110
- 01100100
- 01100110
- 0001101

Question?

Which of the following regular expressions generate the same language as the one recognized by this NFA?

Choose all that apply

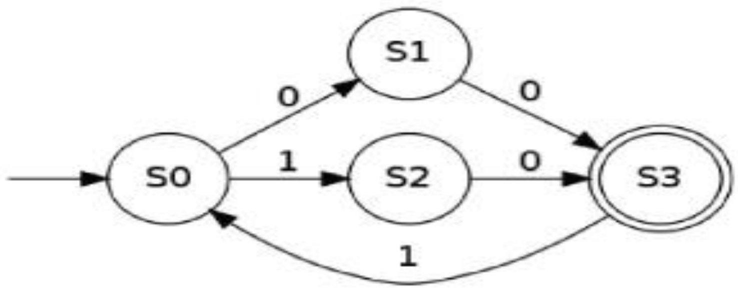


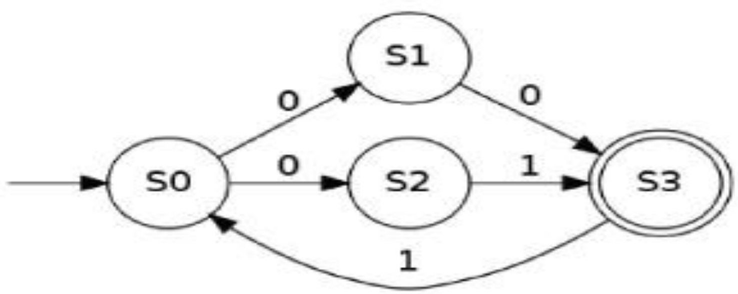
- (000)*(01)+
- 0(000)*1(01)*
- (000)*(10)+
- 0(00)*(10)*
- 0(000)*(01)*

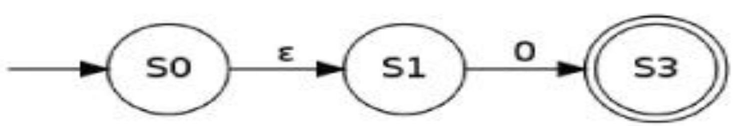
Question?

Which of the following automata are DFA? Choose all that apply

- 

- 

- 

- 

Question?

Which of the following automata are NFA? Choose all that apply