LEXICAL ANALYSIS

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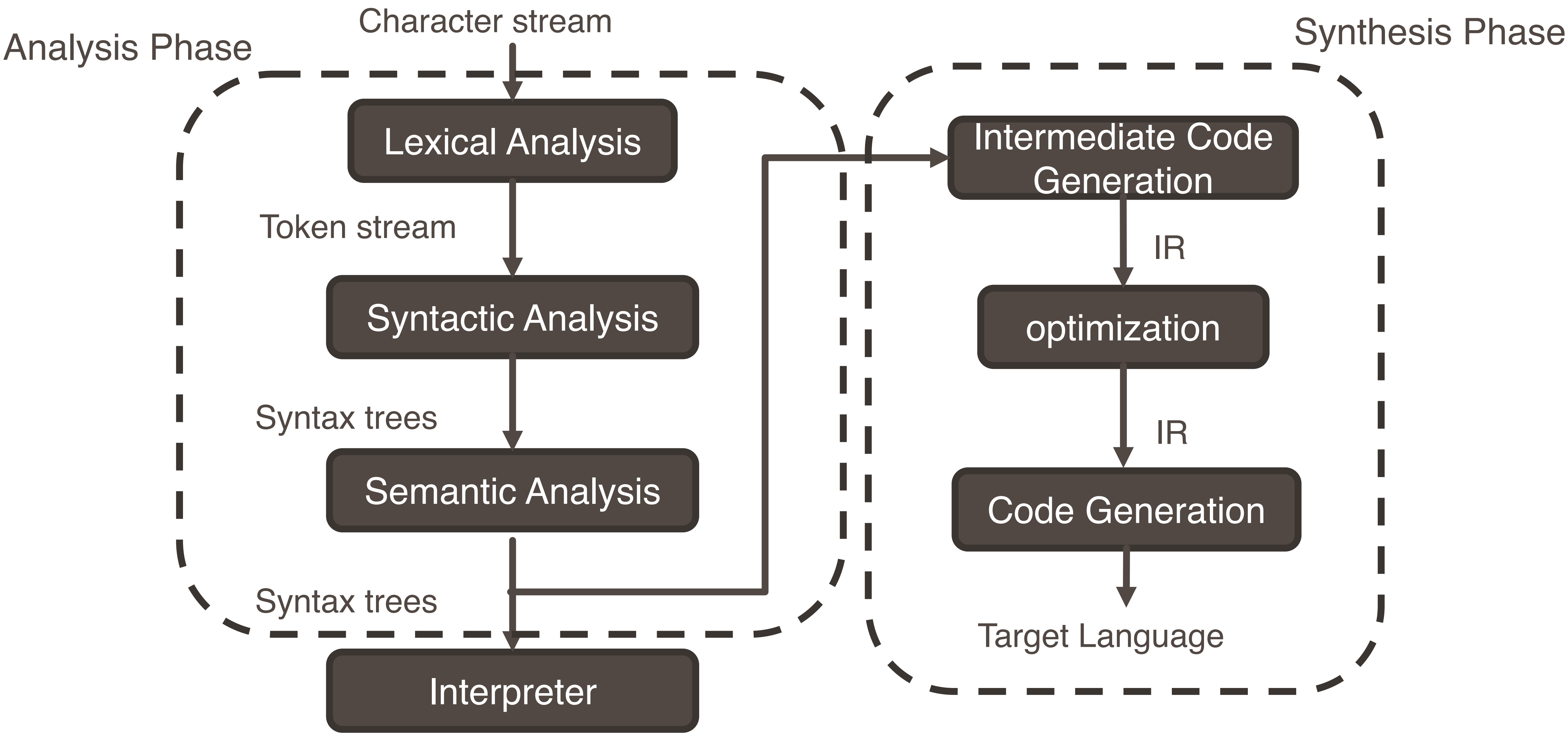
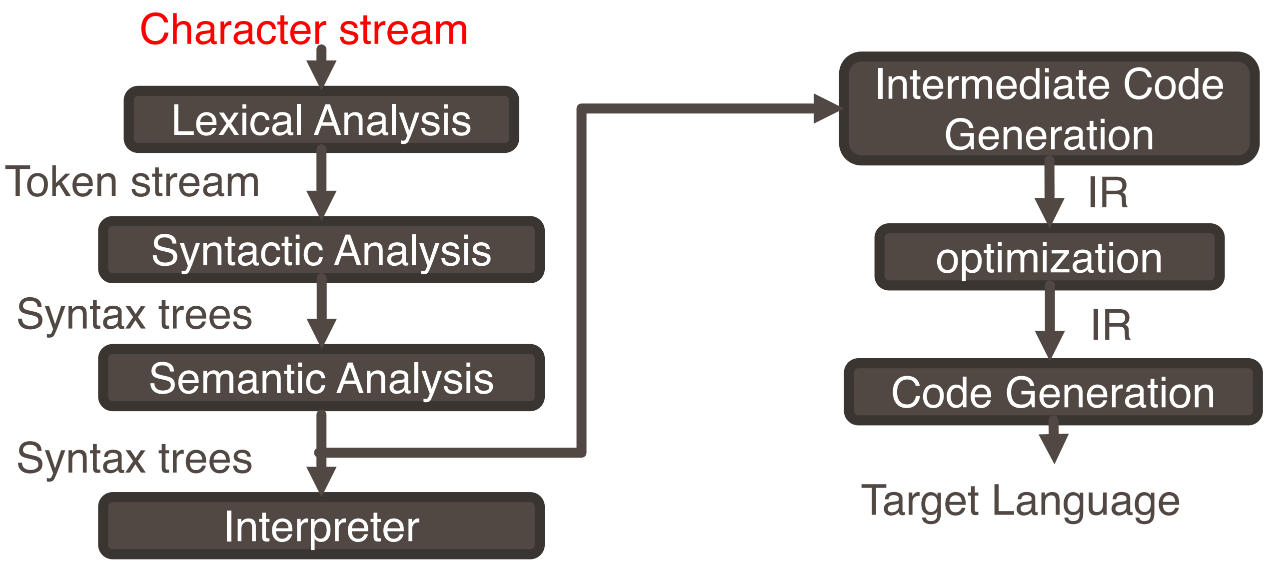
These slides are motivated from Prof. Alex Aiken: Compilers (Stanford)

Structure of a Typical Compiler



Input to Compiler




```
/*simple example*/
if(i == j)
  z = 0;
else
  z = 1;
```

```
/ * s i m p l e  e x a m p l e * /
if ( i = = j )\n\t z = 0 ; \n else\n\t  z = 1 ;
```

Lexical Analysis

```
/*simple exampl
if(i == j)
 z = 0;
else
 z = 1;
```

```
/ * s i m p l e   e x a m p l e * /
if ( i = = j )\n\t z = 0 ; \n else\n\t  z = 1 ;
```

1. Remove comments

```
if ( i = = j )\n\t z = 0 ; \n else\n\t  z = 1 ;
```

2.1. Identify substrings

```
'if' '(' 'i' '==' 'j' ')' '\n' '\t' 'z' '=' '0' ';'
'\n' 'else' '\n' '\t' 'z' '=' '1' ';'
```

2.2. Identify token classes

```
keyword<if> LPAR identifier<i> op<==> identifier<j> RPAR
whitespaces identifier<z> op<=> number<0> <;> whitespaces
keyword<else> identifier<z> op<=> number<1> ';'
```

Token Class

```
keyword<if> LPAR identifier<i> op<==> identifier<j> RPAR
whitespaces identifier<z> op<=> number<0> <;> whitespaces
keyword<else> identifier<z> op<=> number<1> ';'
```

- keywords, identifiers, LPAR, RPAR, number, etc.

Token Class

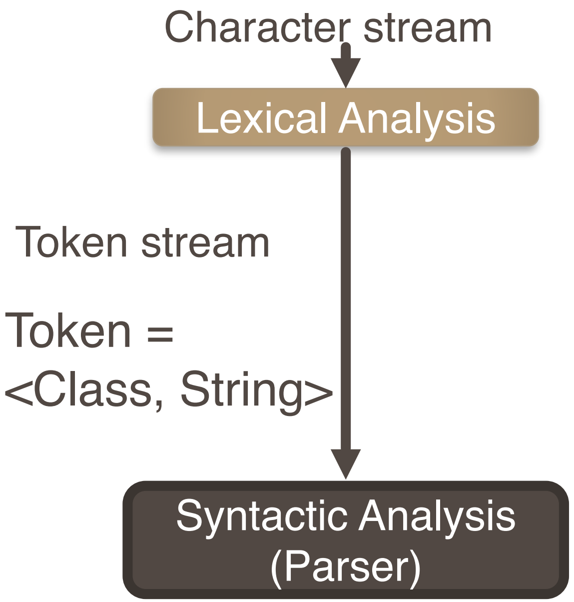
- Each class corresponds to a set of strings
- Identifier
  - Strings are letters or digits, starting with a letter
  - Eg:
- Numbers:
  - A non-empty strings of digits
  - Eg:
- Keywords
  - A fixed set of reserved words
  - Eg:
- Whitespace
  - A non-empty sequence of blanks, newlines, and tabs

Different Language can treat same symbol differently

- WhiteSpace in Python:
  - Except at the beginning of a logical line or in string literals, the whitespace characters space and tab can be used interchangeably to separate tokens.
  - Whitespace is needed between two tokens only if their concatenation could otherwise be interpreted as a different token (e.g., ab is one token, but a b is two tokens).
- Whitespace in C Like Language:
  - Blanks, horizontal and vertical tabs, newlines formfeeds, and comments as described below (collectively, "white space") are ignored except as they separate tokens.

Lexical Analysis (Example)

- Classify program substrings according to roles (token class)
- Communicate tokens to parser



Z = 1

- <Id, “Z”>
- <Op, “=”>
- <Numbers, “1”>

“Z”, “=”, “1” are called lexemes (an instance of the corr. token class)

Lexical Analysis: HTML Examples

```
Here is a photo of <b> my house </b>
```

<text, "Here is a photo of">
<nodestart, b>
<text, "my house">
<nodeend, b>

Exercise

```
x = p;
while ( x < 100 ) { x++ ; }
```

Exercise

```
if(i == j)
  z = 0;
else
  z = 1;
```

==/=?

Keyword/Identifier?

Lookahead

- Lexical analysis tries to partition the input string into the logical units of the language. This is implemented by reading left to right. “scanning”, recognizing one token at a time.
- “Lookahead” is required to decide where one token ends and the next token begins.

```
if(i == j)
 z = 0;
else
 z = 1;
```

==/=?

Keyword/Identifier?

Lookahead: Examples

- Usually, given the pattern describing the lexemes of a token, it is relatively simple to recognize matching lexemes when they occur on the input.
- However, in some languages, it is not immediately apparent when we have seen an instance of a lexeme corresponding to a token.

```
FORTRAN RULE: White Space is insignificant: VA R1 == VAR1

DO 5 I = 1,25

DO 5 I = 1.25
```

- Lexical analysis may require to “look ahead” to resolve ambiguity.
  - Look ahead complicates the design of lexical analysis
  - Minimize the amount of look ahead

Lexical Analysis: Examples

- C++ template Syntax:
  - Foo<Bar>
- C++ stream Syntax:
  - cin >> var
- Ambiguity
  - Foo<Bar<Bar>>
  - cin >> var

Lexical Errors

- A lexical error is any input that can be rejected by the lexer.
- When a token cannot be recognized by the rules defined token class
  - Example: '@' is rejected as a lexical error for identifiers in Java (it's reserved).

- Recovery
  - Panic Mode: delete successive characters until a valid token is found
  - Delete one character from remaining inputs
  - Insert one character in the remaining input
  - Replace / transpose

Lexical Errors

```
fi(a==f(x))
```

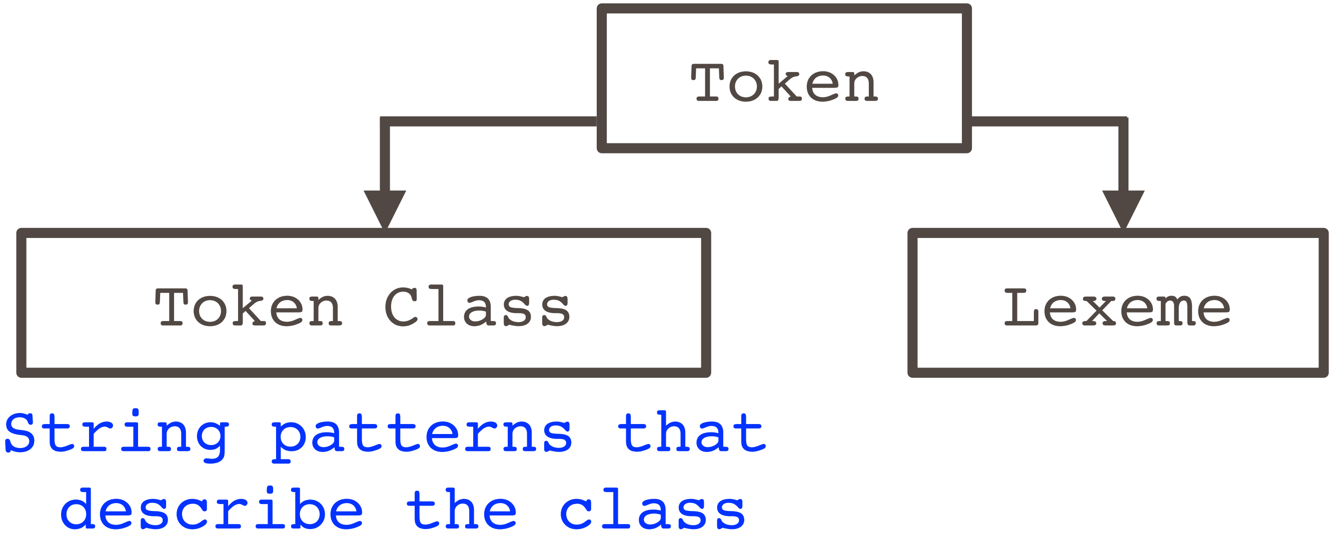
- Is fi lexical error?
  - It can be a function identifier
  - It is quite difficult for a lexical analyzer to decide whether fi is an error without further information

Summary So Far

- The goal of Lexical Analysis
  - Partition the input string to lexeme
  - Identify the token class of each lexeme

- Left-to-right scan => look ahead may require
  - In reality, lookahead is always needed
  - Our goal is to minimize thee amount of lookahead

Recognizing Token Class



- How to describe the string patterns?
  - i.e., which set of strings belongs to which token class?
  - Use regular languages

- Use Regular Expressions to define Regular Languages.

REGULAR LANGUAGES

Regular Expressions

- Single character
  - ‘c’ = {“c”}
- Epsilon
  - ε = {“”}
- Union
  - A + B = {a | a ϵ A} $\cup$ {b | b ϵ B}
- Concatenation
  - AB = {ab | a ϵ A ^ b ϵ B}
- Iteration (Kleene closure)
  - $A* = \bigcup_{i>=0} A^i = A^0 A^1 \ldots . A^i$ = A…..A (i times)
  - $A^+ = \bigcup_{i>0} A^i$ (no empty string is allowed)

Regular Expressions

- Def: The regular expressions over Σ are the smallest set of expressions including

R = ε

| 'c', 'c' ϵ Σ

| R + R

| RR

| R*

Regular Expression Example

- Σ = {p,q}
  - q*
  - (p+q)q
  - p*+q*
  - (p+q)*

- There can be many ways to write an expression

Exercise

Choose the regular languages that are equivalent to the given regular language: $(p + q)^*q(p + q)^*$

A. $(pq + qq)^*(p + q)^*$

B. $(p + q)^*(qp + qq + q)(p + q)^*$

C. $(q + p)^*q(q + p)^*$

D. $(p + q)^*(p + q)(p + q)^*$

Formal Languages

- Def: Let Σ be a set of character (alphabet). A language over Σ is a set of strings of characters drawn from Σ.
  - Regular languages is a formal language
- Alphabet = English character, Language = English Language
  - Is it formal language?
- Alphabet = ASCII, Language = C Language

Formal Language

$'c' = \{``c"\}$

$\varepsilon = \{``"\}$

$A + B = \{a \mid a \in A\} \cup \{b \mid b \in B\}$

$AB = \{ab \mid a \in A \wedge b \in B\}$

$$\underbrace{A^*}_{\text{expression}} = \underbrace{\bigcup_{i>=0} A^i}_{\text{Set}}$$

Formal Language

$L(\text{‘c’}) = \{\text{“c”}\}$

$L(\varepsilon) = \{\text{“”}\}$

$L(A + B) = \{a \mid a \in L(A)\} \cup \{b \mid b \in L(B)\}$

$L(AB) = \{ab \mid a \in L(A) \wedge b \in L(B)\}$

$$\underbrace{L(A^*)}_{\text{expression}} = \underbrace{\bigcup_{i>=0} L(A^i)}_{\text{Set}}$$

L: Expressions -> Set of strings

- Meaning function L maps syntax to semantics
- Mapping is many to one
- Q: One to Many?

Formal Language

$L(\text{‘c’}) = \{\text{“c”}\}$

$L(\varepsilon) = \{\text{“”}\}$

$L(A + B) = \{a \mid a \in L(A)\} \cup \{b \mid b \in L(B)\}$

$L(AB) = \{ab \mid a \in L(A) \wedge b \in L(B)\}$

$$\underbrace{L(A^*)}_{\text{expression}} = \underbrace{\bigcup_{i>=0} L(A^i)}_{\text{Set}}$$

L: Expressions -> Set of strings

- Meaning function L maps syntax to semantics
- Mapping is many to one
- Never one to many

Lexical Specifications

- Keywords: “if” or “else” or “then” or “for” ….
  - Regular expression = ‘i’ ‘f’ + ‘e’ ‘l’ ‘s’ ‘e’
    = ‘if’ + ‘else’ + ‘then’

- Numbers: a non-empty string of digits
  - digit = ‘1’+’0’+’2’+’3’+’4’+’5’+’6’+’7’+’8’+’9’
  - digit*
  - How to enforce non-empty string?
    - digit digit* = digit$^+$

Lexical Specifications

- Identifier: strings of letters or digits, starting with a letter
  - letter = ‘a’ + ‘b’ + ‘c’ + …. + ‘z’ + ‘A’ + ‘B’ + …. + ‘Z’
    = [a-zA-Z]
  - letter (letter + digit)*
- Whitespace: a non-empty sequence of blanks, newline, and tabs
  - $(\text{‘ ’} + \text{‘\textbackslash n’} + \text{‘\textbackslash t’})^+$

PASCAL Lexical Specification

- digit = ‘0’+‘1’+‘2’+‘3’+‘4’+‘5’+‘6’+‘7’+‘8’+‘9’
- digits = digit^{+}
- opt_fraction = (‘.’ digits) + ε = (‘.’ digits)?
- opt_exponent = (‘E’ (‘+’ + ‘-’ + ε) digits) + ε

  = (‘E’ (‘+’ + ‘-’)? digits)?
- num = digits opt_fraction opt_exponent

Common Regular Expression

- At least one $A^+ \equiv AA^*$
- Union: $A \mid B \equiv A + B$
- Option: $A? \equiv A + \varepsilon$
- Range: $'a' + \ldots + 'z' = [a\text{-}z]$
- Excluded range: complement of $[a\text{-}z] \equiv [\hat{}\,a\text{-}z]$

Summary of Regular Languages

- Regular Expressions specify regular languages

- Five constructs
  - Two base expression
    - Empty and 1-character string

  - Three compound expressions
    - Union, Concatenation, Iteration

Lexical Specification of a language

1. Write a regex for the lexemes of each token class
   - Number = $digit^+$
   - Keywords = ‘if’ + ‘else’ + ‘while’ + ‘for’ + ‘return’…
   - Identifiers = letter (letter + digit)*
   - LPAR = ‘(‘
   - RPAR=‘)’

Lexical Specification of a language

2. Construct R, matching all lexemes for all tokens

   R = Number + Keywords + Identifiers + …

   $= R_1 + R_2 + R_3 + \dots$

3. Let input be $x_q \dots x_n$.

   For $1 \leq i \leq n$, check $x_1 \dots x_i \in L(R)$

4. If successful, then we know that

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

5. Remove $x_1 \dots x_i$ from input and go to step 3.

Lexical Specification of a language

- How much input is used?
  - $x_1 \ldots x_i \in L(R)$
  - $x_1 \ldots x_j \in L(R)$, $i \neq j$
  - Which one do we want? (e.g., == or =)
  - Maximal munch: always choose the longer one

- Which token is used if more than one matches?
  - $x_1 \ldots x_i \in L(R)$ where $R = R_1 + R_2 + .. + R_n$
  - $x_1 \ldots x_i \in L(R_m)$
  - $x_1 \ldots x_i \in L(R_n)$, $m \neq n$
  - Eg: Keywords = 'if', Identifier = letter (letter + digit)*, if matches both
  - Keyword has higher priority
  - Rule of Thumb: Choose the one listed first

Lexical Specification of a language

- What if no rule matches?
  - $x_1 \ldots x_i \notin L(R)$ … compiler typically tries to avoid this scenario
  - Error = [all strings not in the lexical spec]
  - Put it in last in priority

Summary so far

- Regular Expressions are concise notations for the string patterns

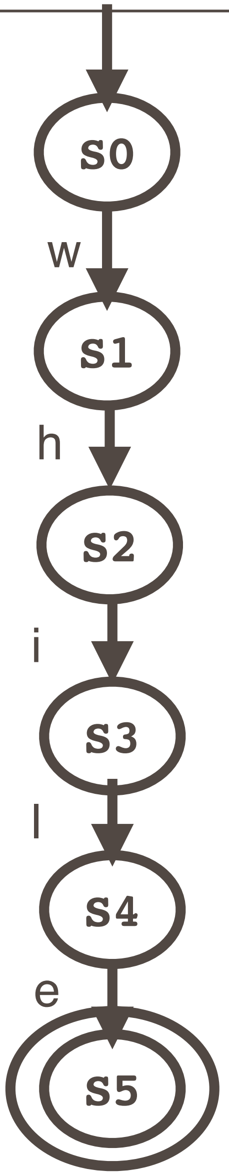
- Use in lexical analysis with some extensions
  - To resolve ambiguities
  - To handle errors

- Implementation?
  - We will study next

Recognizing Lexemes:
a simple character by character formulation

Recognize word while

```
c=NextChar();
if(c!='w') { /*do something*/}
else {
  c=NextChar();
  if(c!='h') { /*do something*/}
  else {
    c=NextChar();
    if(c!='i'){ /*do something*/}
    else {
      c=NextChar();
      if(c!='l'){ /*do something*/}
      else{
        c=NextChar();
        if(c!='e'){ /*do something*/}
        else{
          /*report success*/
        }}}}
```

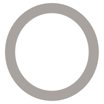
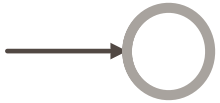
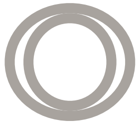


Si s are all abstract states of computation

Recognizing Lexemes

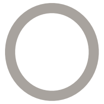
- x = 1

A Formalism of Recognizer

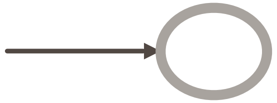
- A finite automaton consists of
  - An input Alphabet: Σ
  - A finite set of states: S 
  - A start state: 
  - A set of accepting states: F $\subseteq$ S 
  - A set of transitions state: state1 $\xrightarrow{input}$ state2

A Formalism of Recognizer

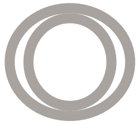
- A finite automaton consists of
  - An input Alphabet: Σ
  - A finite set of states: S



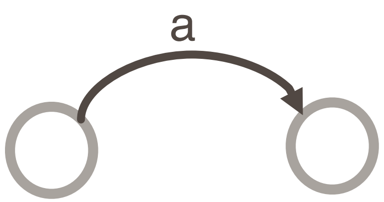
  - A start state: S0



  - A set of accepting states: F $\subseteq$ S



  - A set of transitions state δ: state1 $\xrightarrow{input}$ state2



S=$\{S_0, S_1, S_2, S_3\}$

Σ = {x,=,1}

$\delta = \{S_0 \xrightarrow{x} S_1, S_0 \xrightarrow{=} S_2, S_0 \xrightarrow{1} S_3\}$

$S_0 = S_0$

$F = \{S_1, S_2, S_3\}$

A simple parser for x=1

```
c=NextChar();
state=S_0
while(c!='eof' and state!=S_err) {
   state=δ(state, c)
   c=NextChar();
}

if(state ∈ F)
   /* report acceptance */
else
   /* report failure */
```

S=$\{S_0, S_1, S_2, S_3\}$

Σ = {x,=,1}

$\delta = \{S_0 \xrightarrow{x} S_1, S_0 \xrightarrow{+} S_2, S_0 \xrightarrow{1} S_3\}$

$S_0 = S_0$

$F = \{S_1, S_2, S_3\}$

Example: Lexeme Recognition

- Show simple state transition of : e = m * c ** 2

S=$\{S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$

Σ = {e,m,c,*,**,2,=}

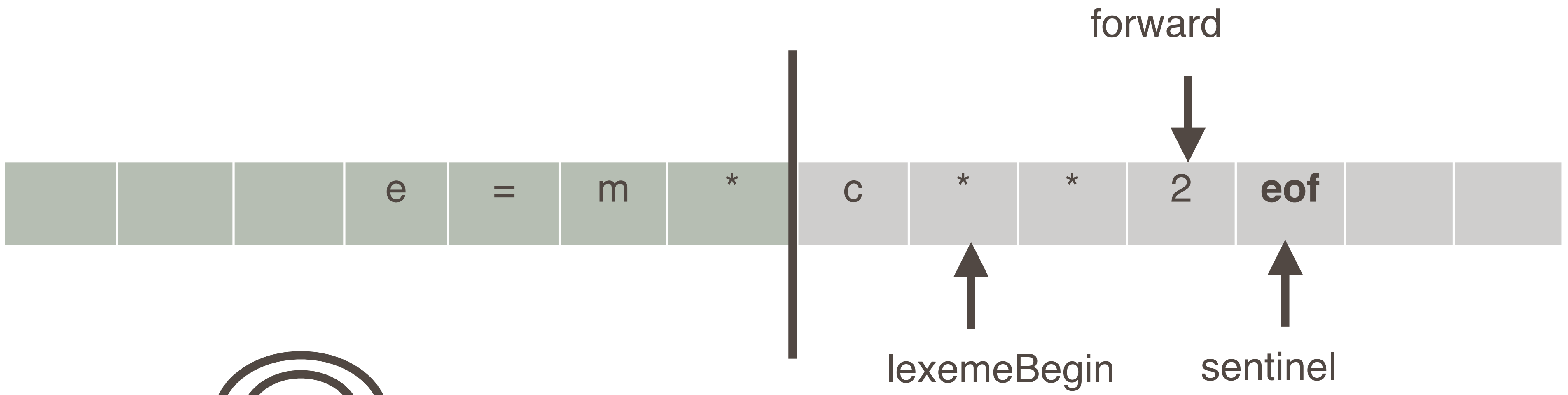
$$\delta = \{S_0 \xrightarrow{\text{e}} S_1, S_0 \xrightarrow{=} S_2, S_0 \xrightarrow{\text{m}} S_3, S_0 \xrightarrow{*} S_4, S_4 \xrightarrow{*} S_5, S_0 \xrightarrow{\text{c}} S_6, S_0 \xrightarrow{2} S_7\}$$

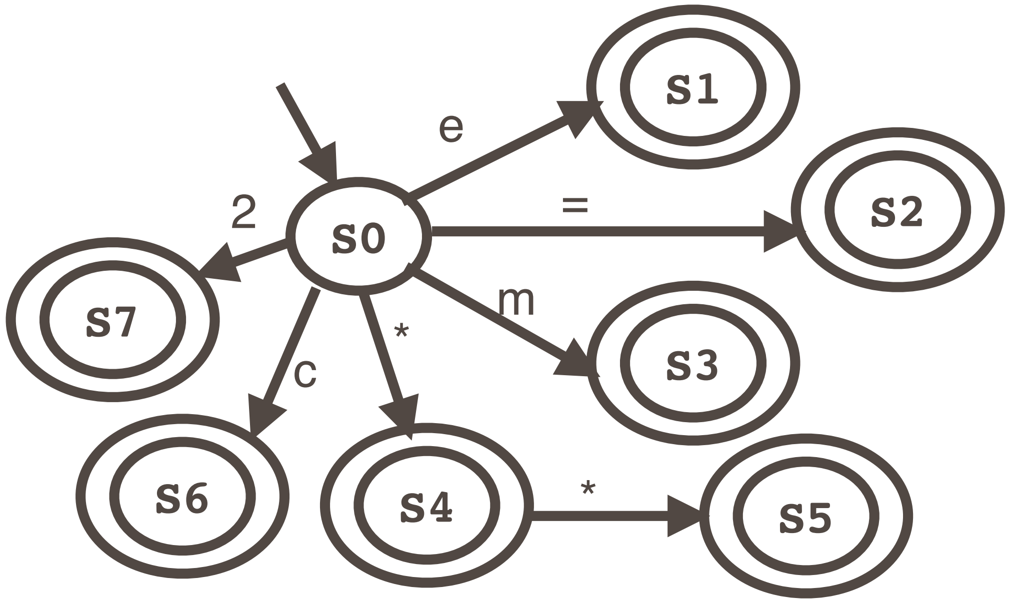
$$S_0 = S_0$$

$$F = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$$

Input Buffering

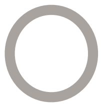
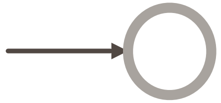
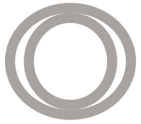
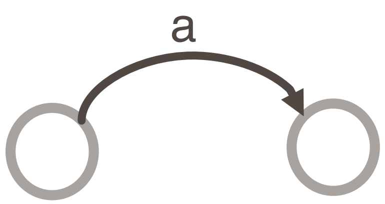
- e = m * c ** 2m





Finite Automata

- Regular Expression = 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: state1 $\xrightarrow{input}$ state2 

Transition

- s1 $\xrightarrow{a}$ s2 (state s1 on input a goes to state s2)
- If end of the input and in final state, the input is accepted
- Otherwise reject

- Language of FA = set of strings accepted by that FA

Example Automata

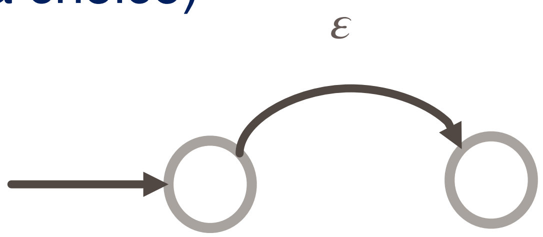
- a finite automaton that accepts only "1"

Example Automata

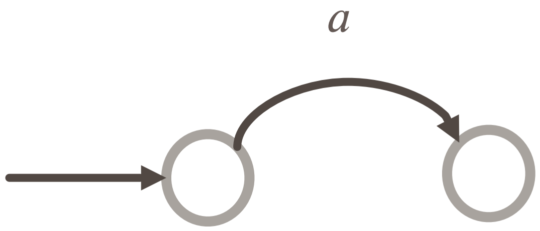
- A finite automaton that accepting any number of “1” followed by “0”

Regular Expression to NFA

- For ε (it's a choice)



- For input a



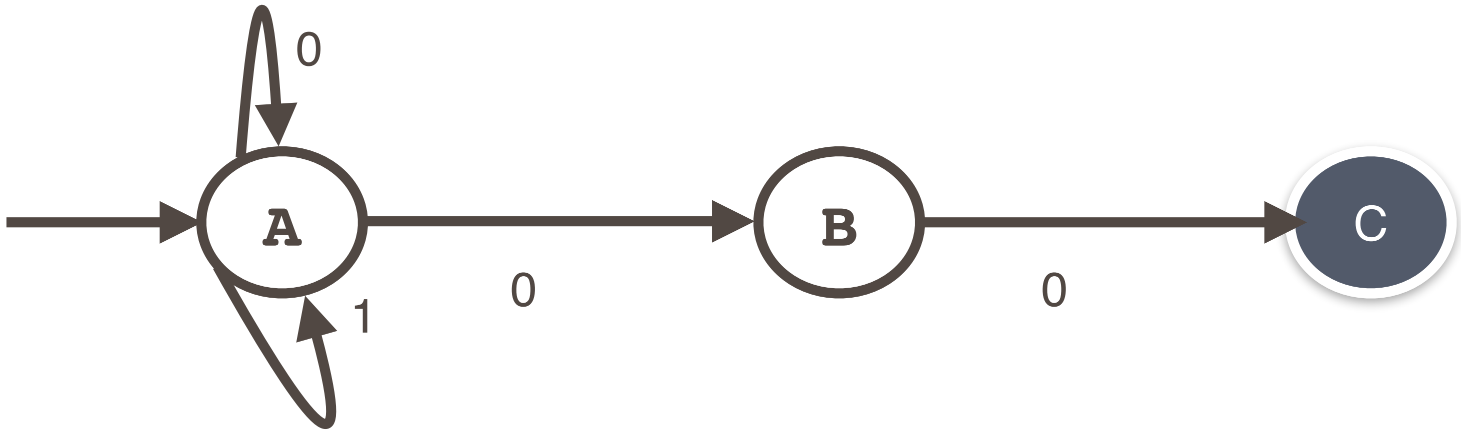
Finite Automata

- Deterministic Finite Automata (DFA)
    - One transition per input per state
    - No ε-moves
    - Takes only one path through the state graph

- Nondeterministic Finite Automata (NFA)
    - Can have multiple transitions for one input in a given state
    - Can have ε-moves
    - Can choose which path to take
        - An NFA accepts if some of these paths lead to accepting state at the end of input.

Finite Automata

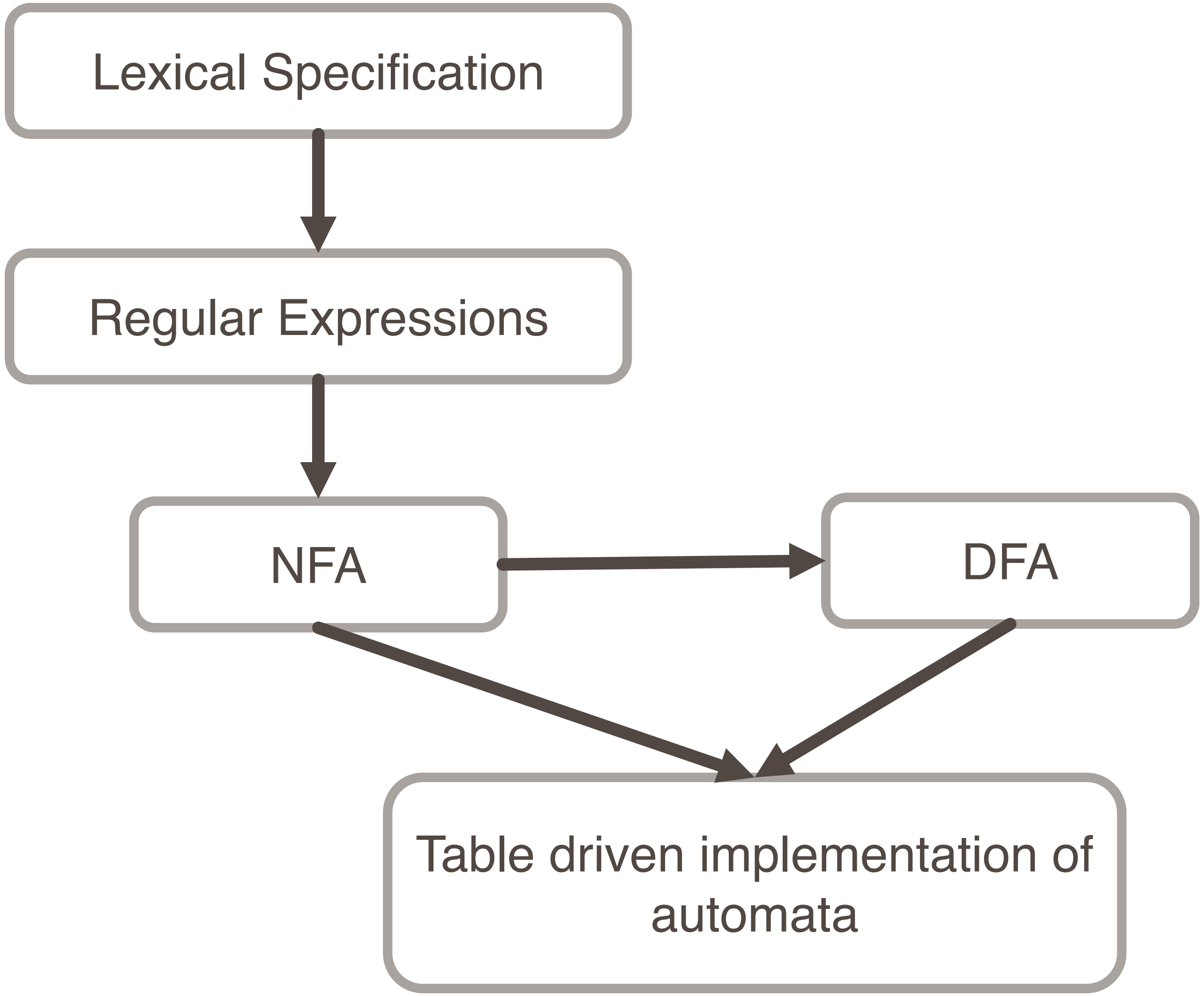
- An NFA can get into multiple states

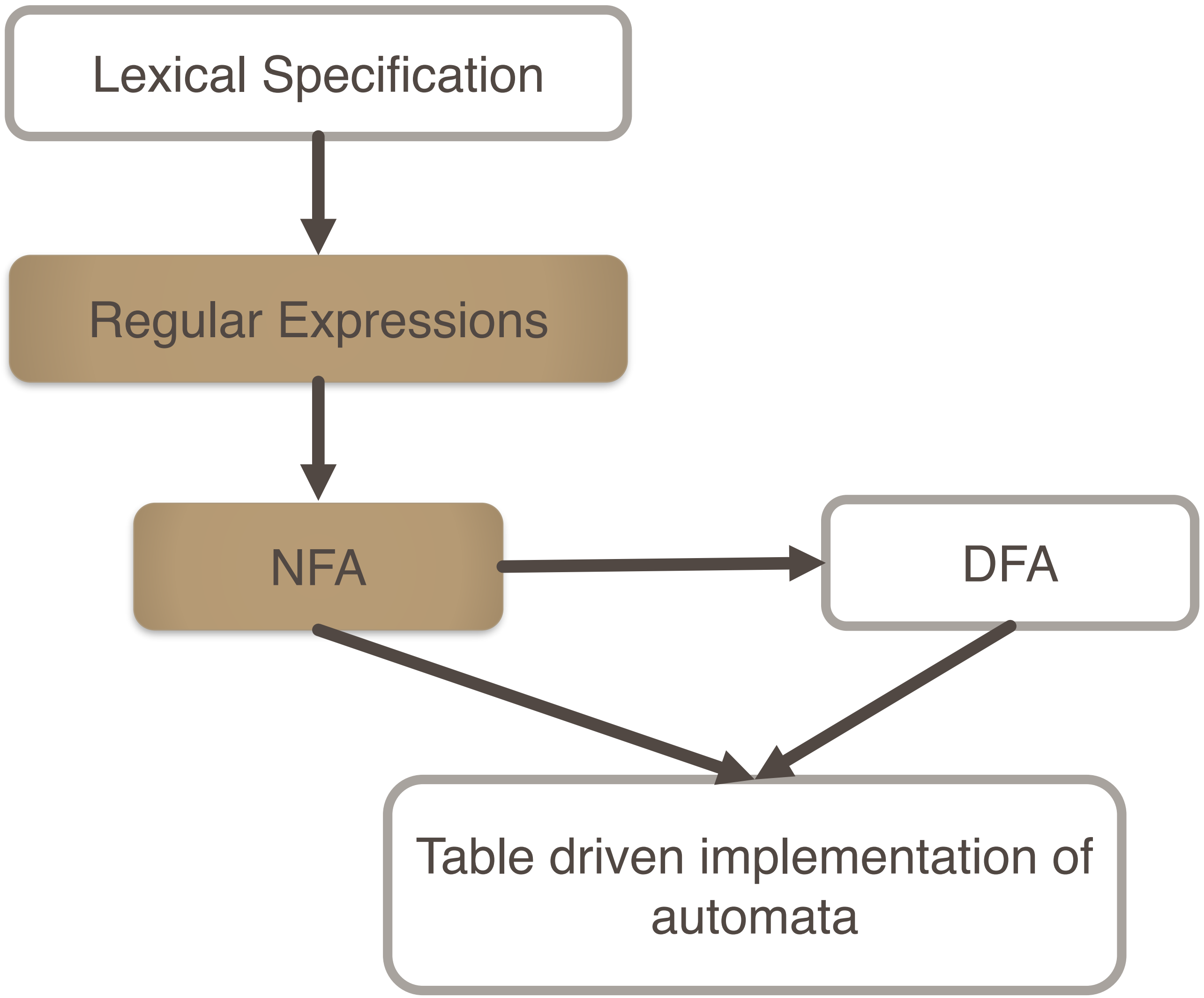


- Input: 1 0 0
- Output: {A}. {A,B} {A,B,C}

NFA vs. DFA

- NFAs and DFAs recognize the same set of regular languages
- DFAs are faster to execute
  - No choices to consider
- NFAs are, in general, small


Lexical Specification
Regular Expressions
NFA
DFA
Table driven implementation of automata


Lexical Specification
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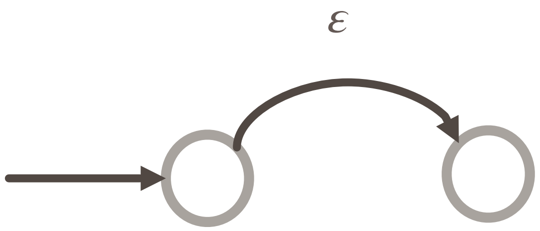
NFA
DFA
Table driven implementation of automata

Finite Automata

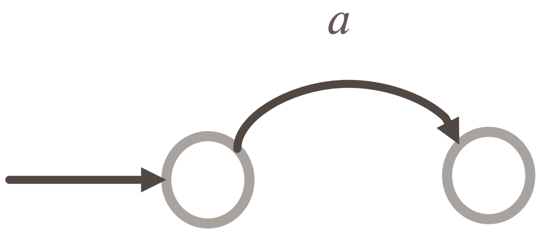
- For each kind of regex, define an equivalent NFA
  - Notation: NFA for regex M

Regular Expression to NFA

- For ε

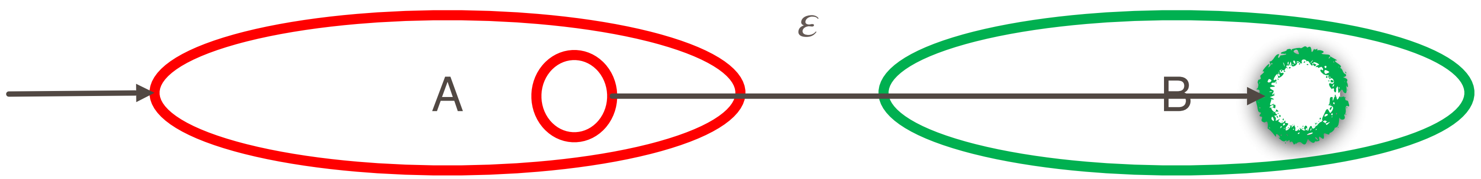


- For input a

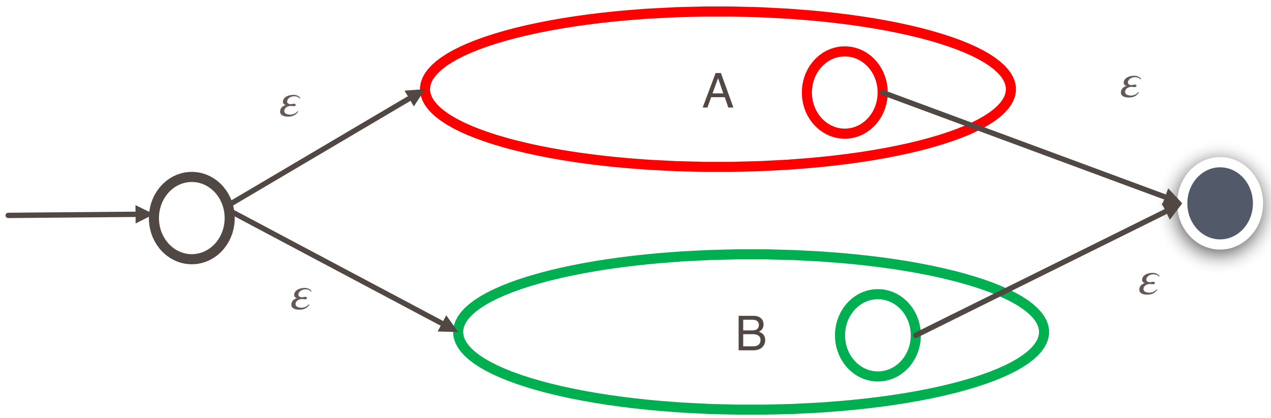


Regular Expression to NFA

- For AB

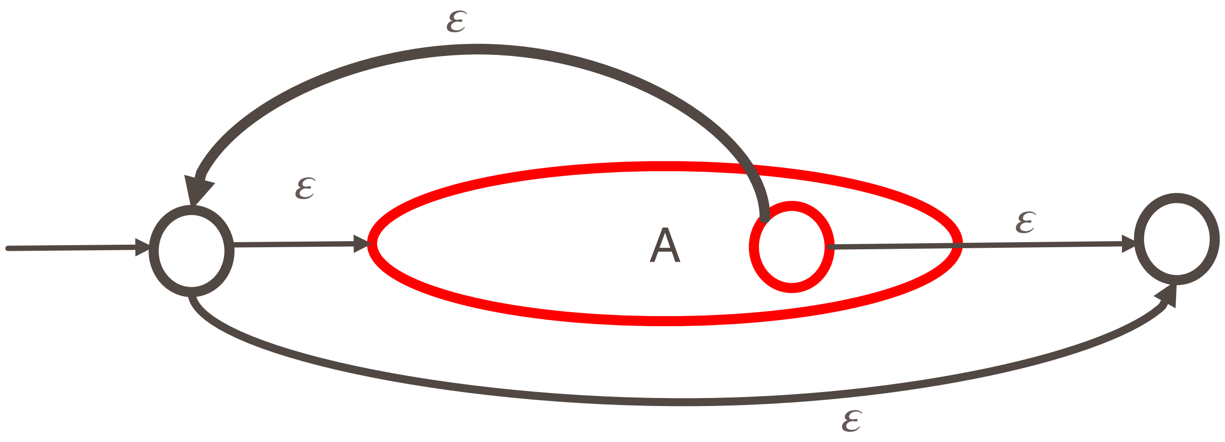


- For A + B



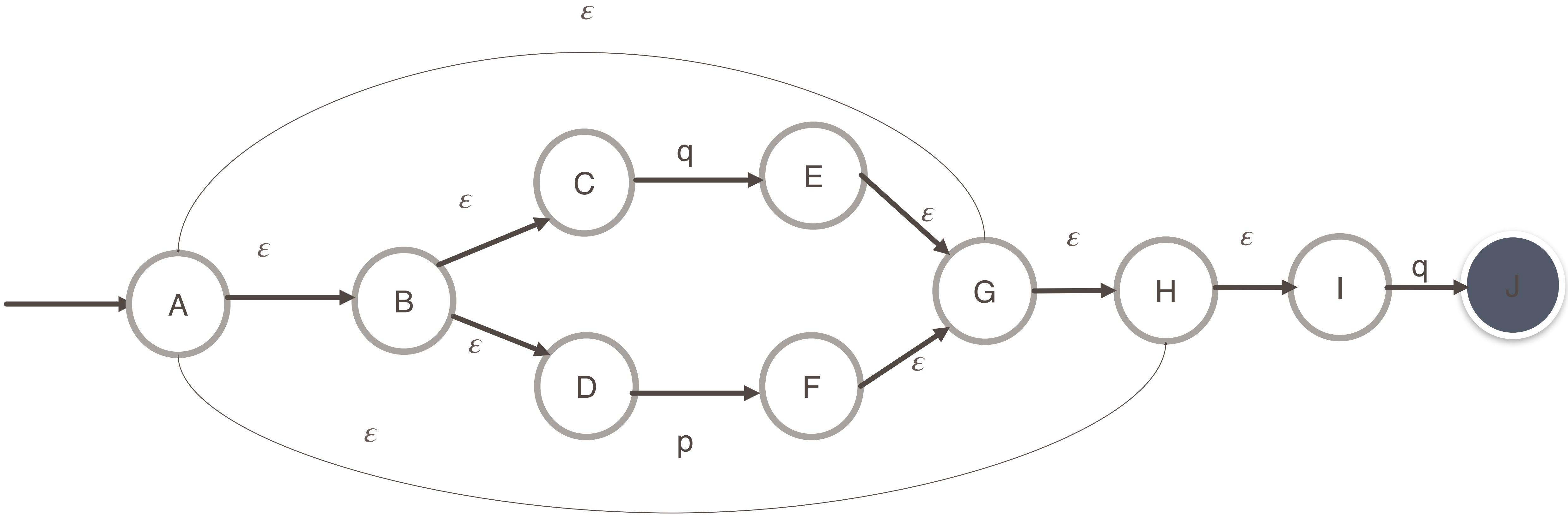
Regular Expression to NFA

- For A*



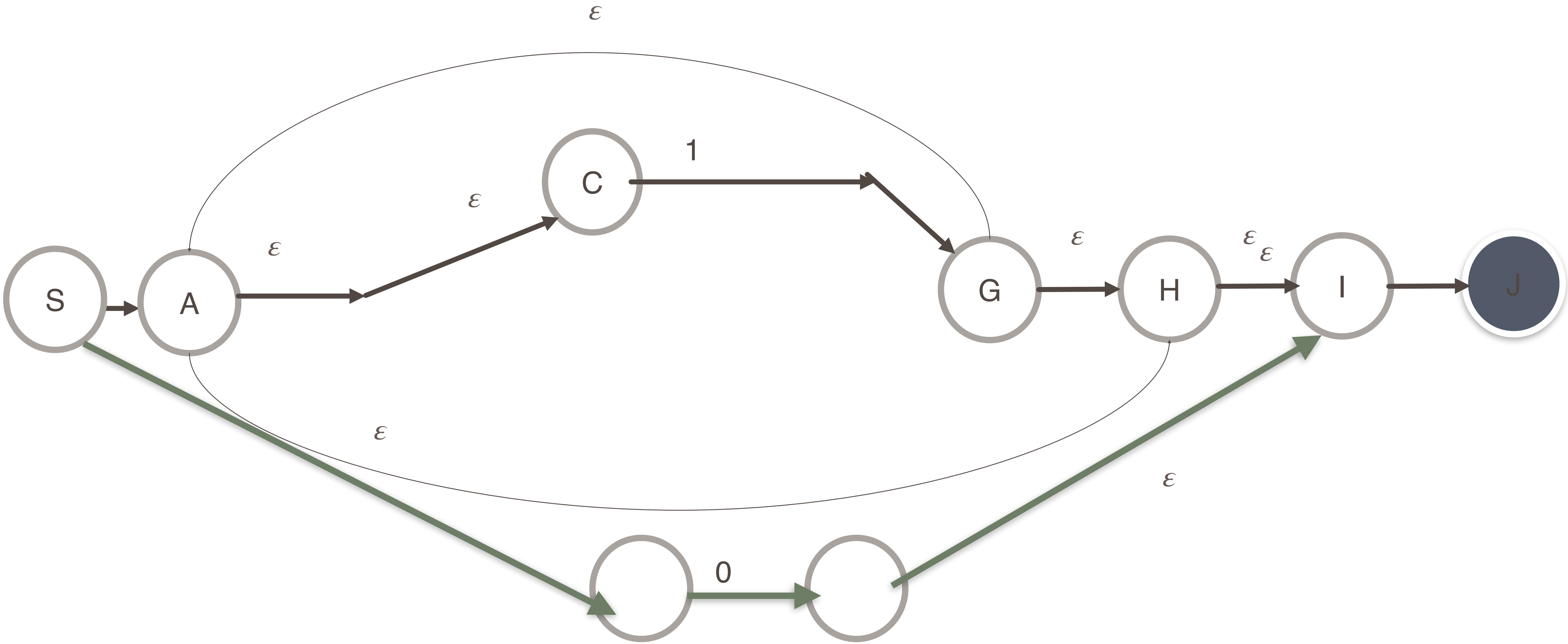
Example

- (q+p)*q



Example

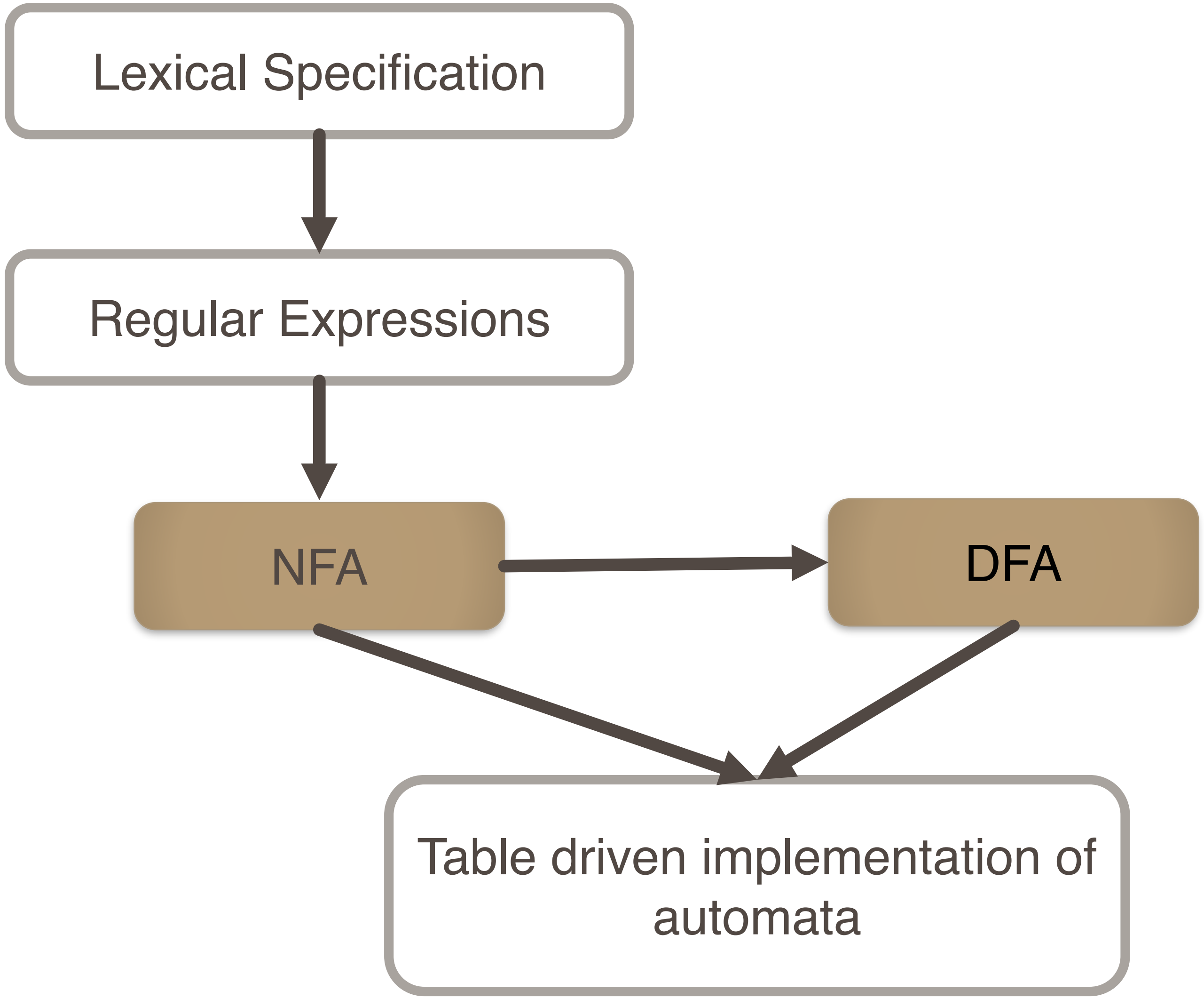
- 1* + 0



Example

Choose the NFA that accepts the regular expression: 1* + 0.

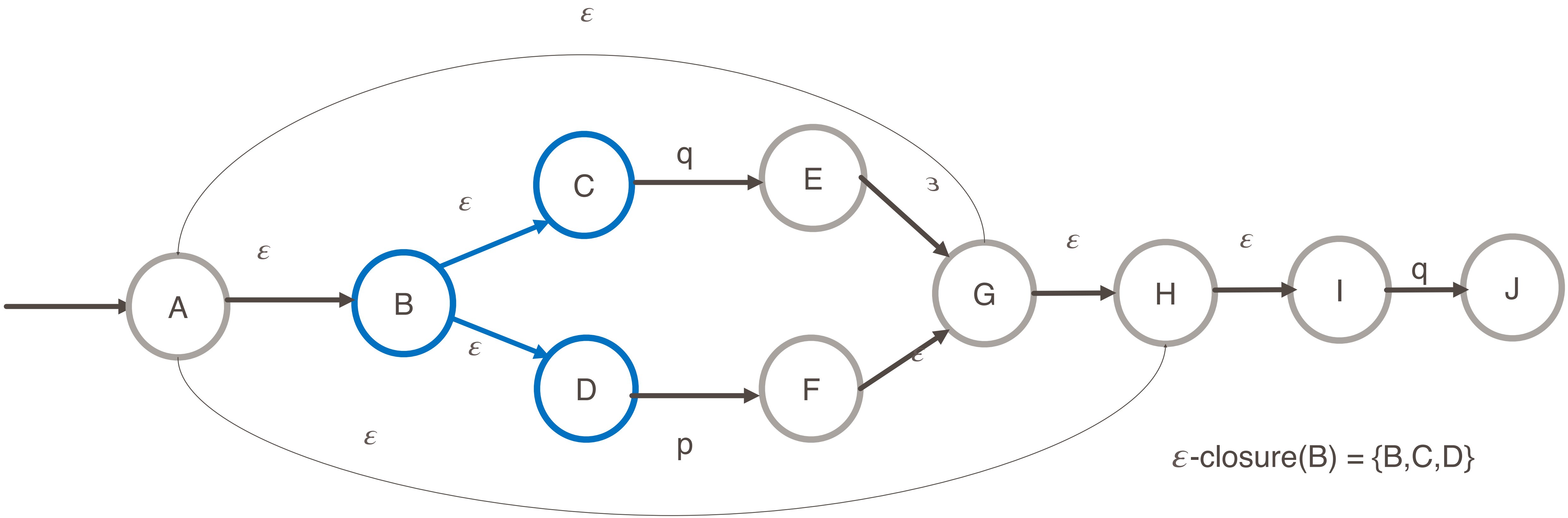
NFA to DFA



Lexical Specification
Regular Expressions
NFA
DFA
Table driven implementation of automata

ε-closure

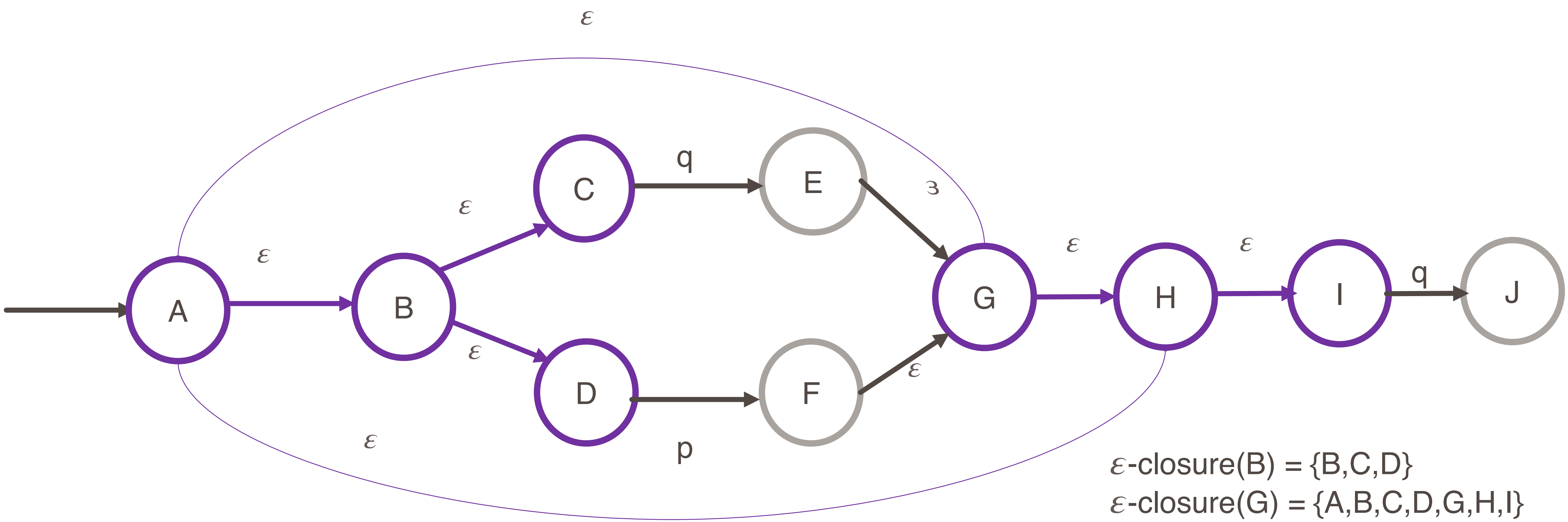
- ε-closure of a state is all the state I can reach following ε move .



ε-closure(B) = {B,C,D}

ε-closure

- ε-closure of a state is all the state I can reach following ε move .



ε-closure(B) = {B,C,D}
ε-closure(G) = {A,B,C,D,G,H,I}

NFA to DFA

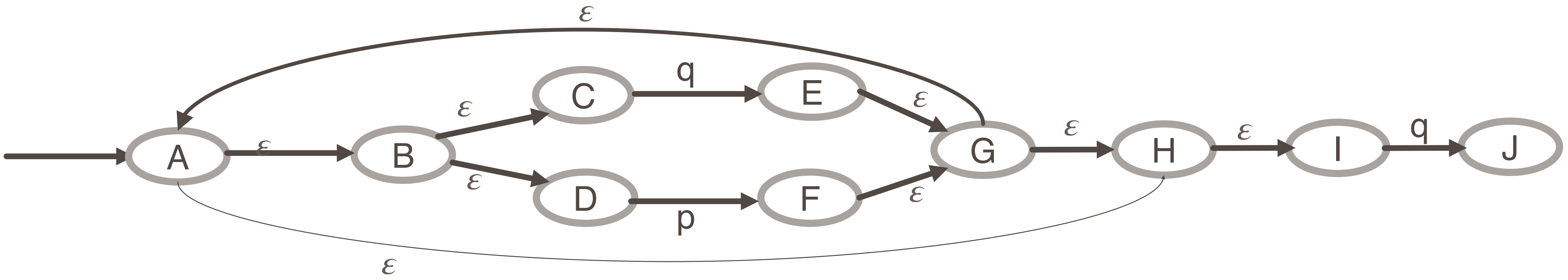
NFA

- States S
- Start s
- Final state F
- Transition state
    - a(X) = {y | x $\in$ X $\bigwedge$ x $\xrightarrow{a}$ y)
- $\varepsilon - closure$

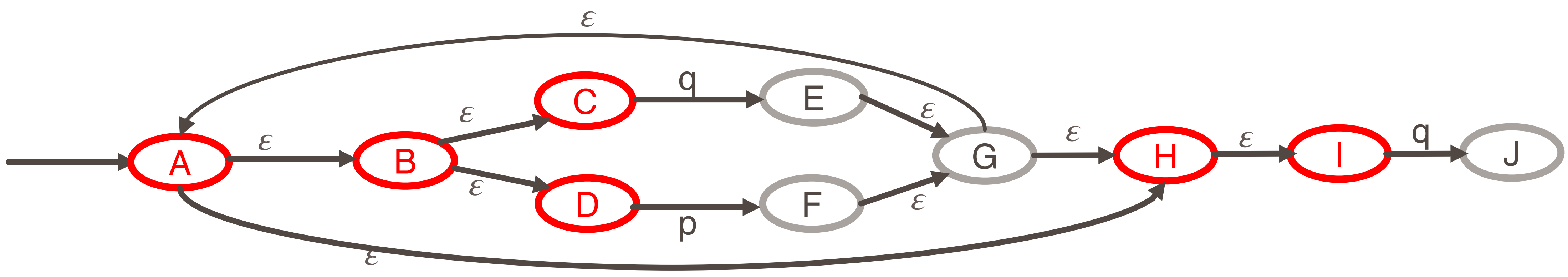
DFA

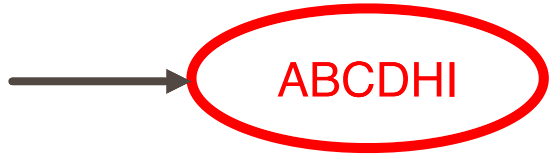
- States will be all possible subset of S except empty set
- Start state = $\varepsilon - closure$(s)
- Final state $\{\mathrm{X} \mid X \cap F \mathrel{!=} \varnothing\}$
- X $\xrightarrow{a}$ Y if
    - Y = $\varepsilon - closure(a(X))$

NFA to DFA

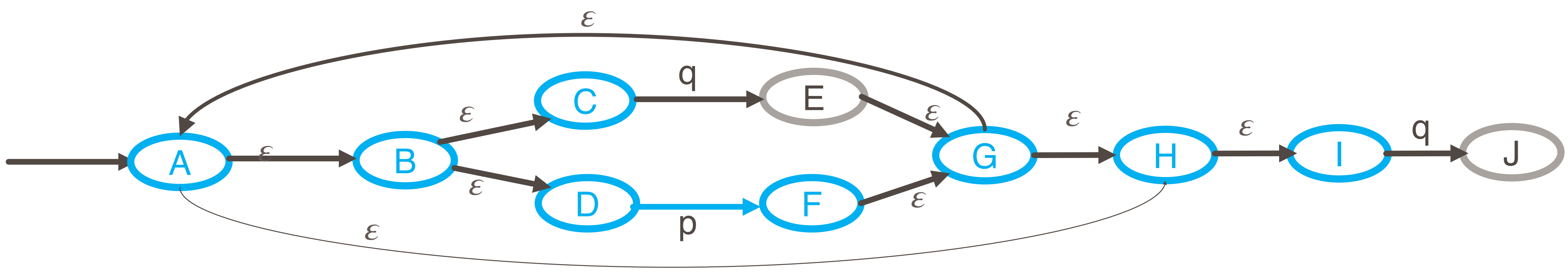


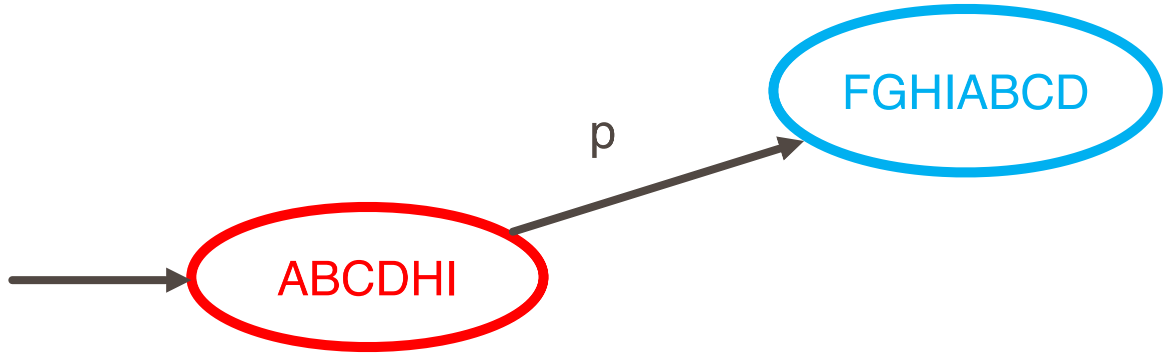
NFA to DFA



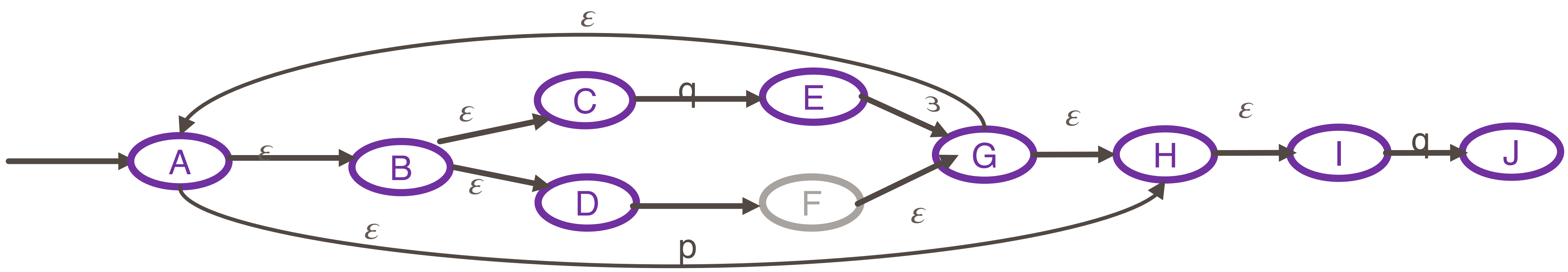


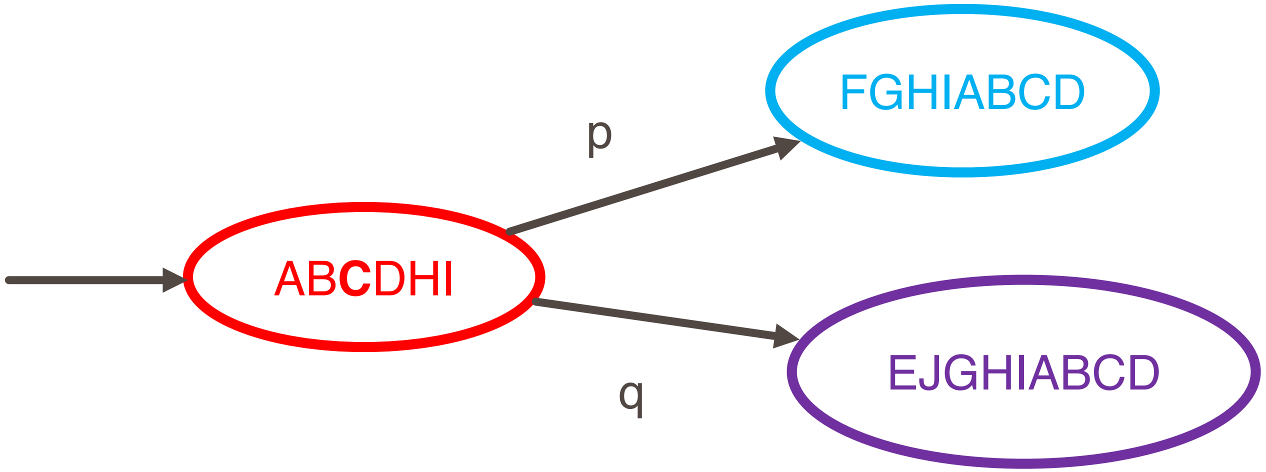
NFA to DFA



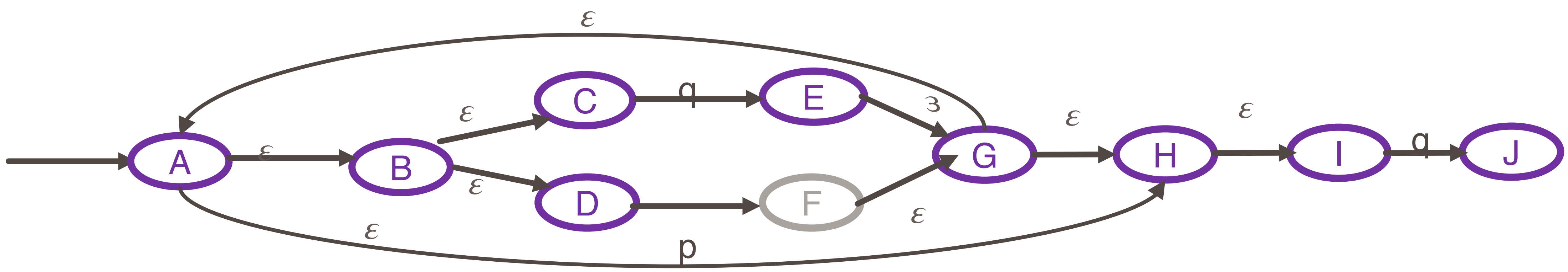


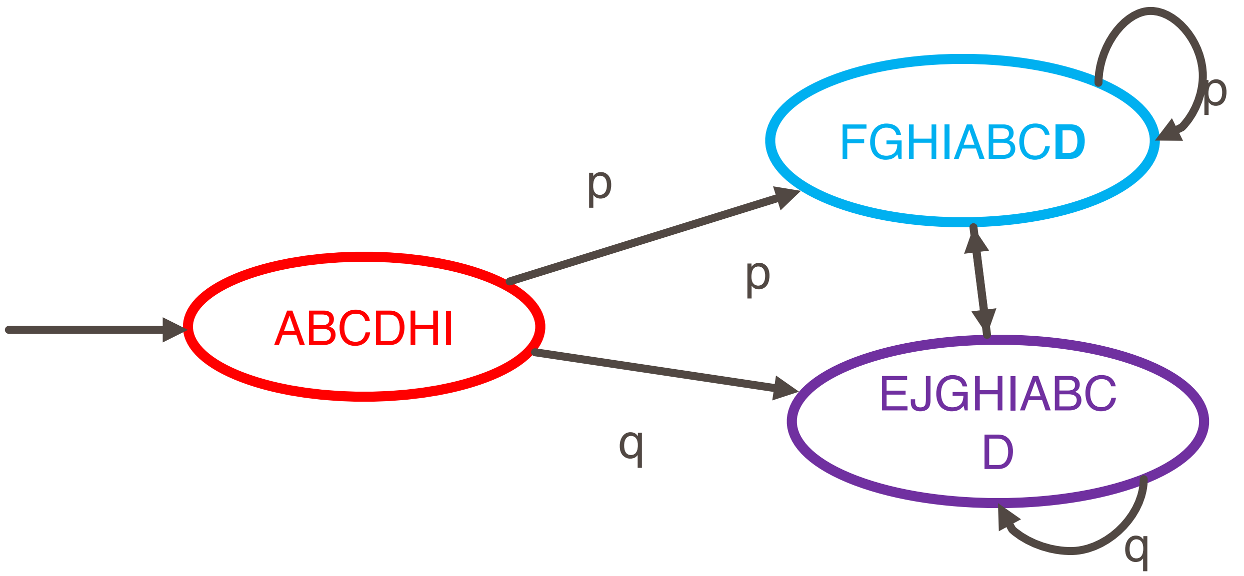
NFA to DFA



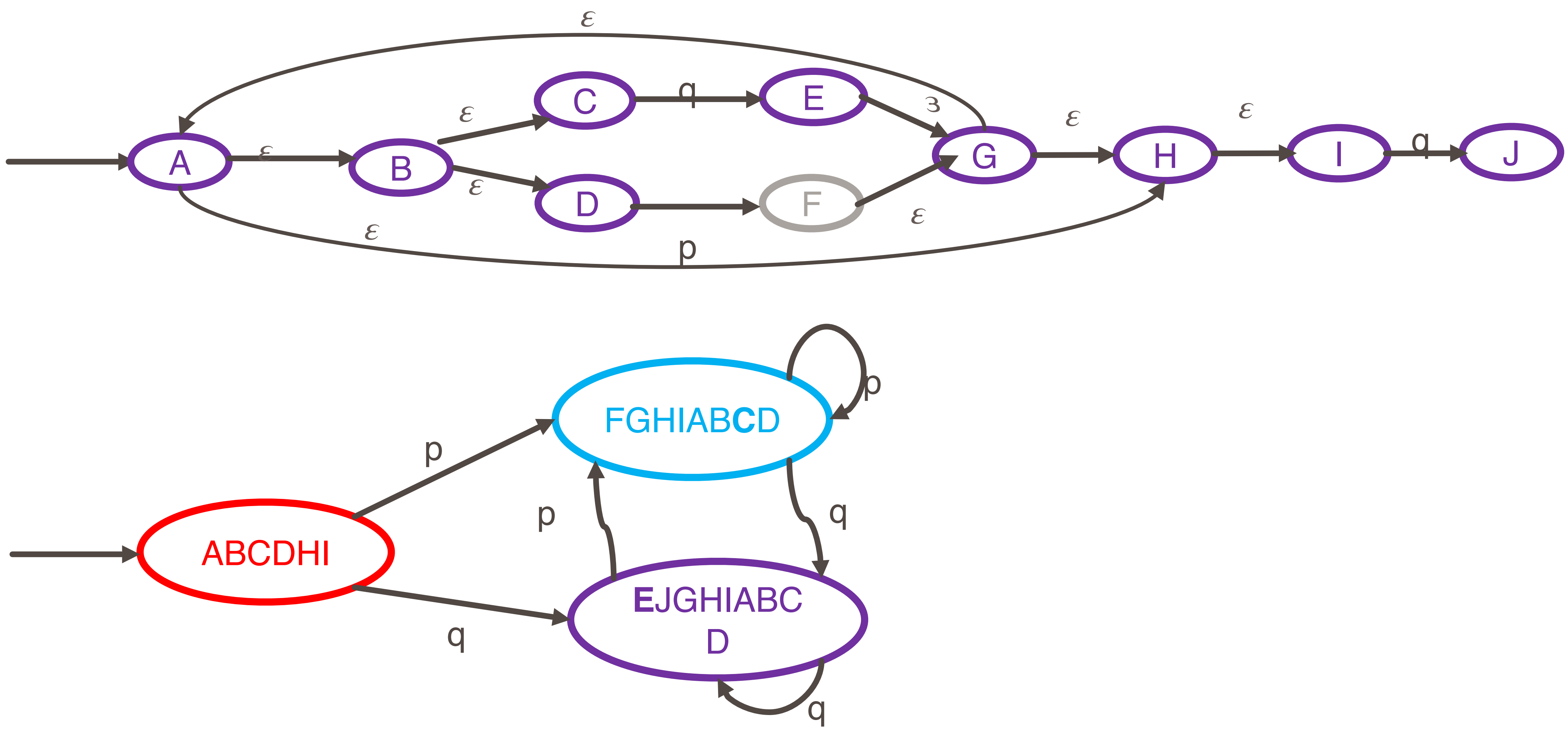


NFA to DFA

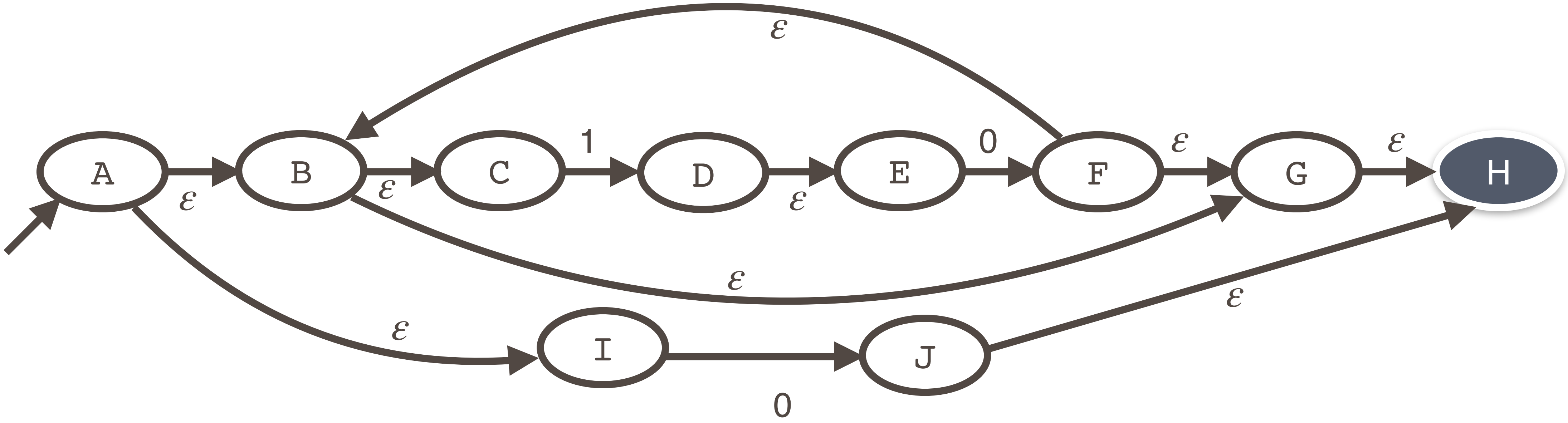




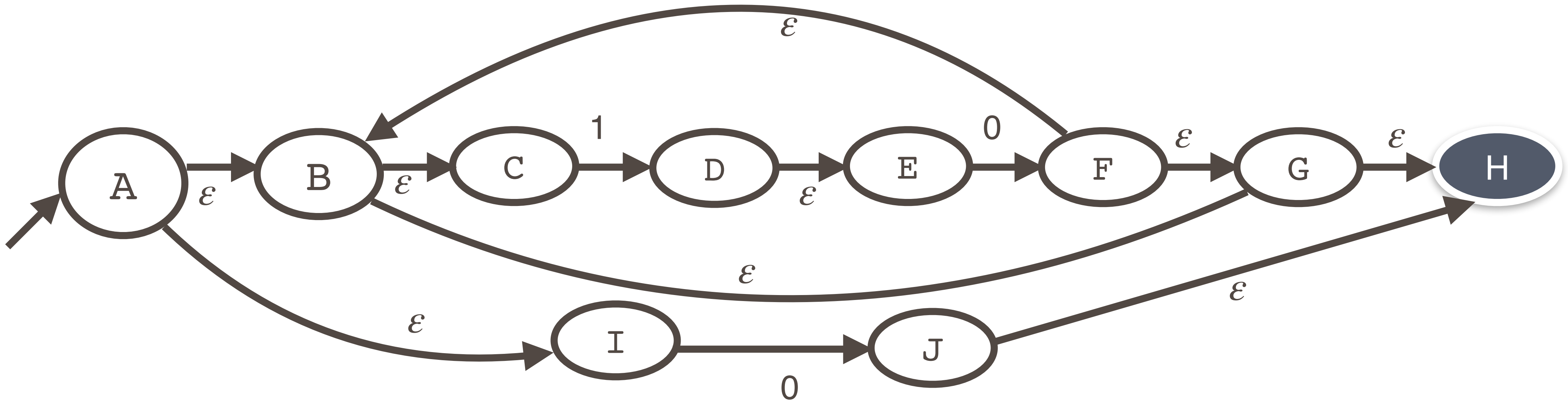
NFA to DFA

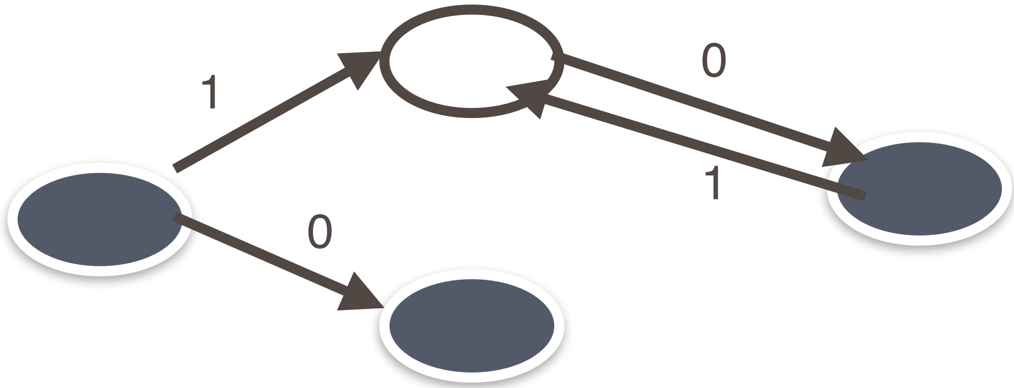

ε
A
B
C
D
E
F
G
H
I
J
q
p
ε
ε
ε
ε
ε
ε
ε
ε
ε
q
ABCDHI
FGHIABCD
EJGHIABC
D
p
p
p
q
q
q

Example: NFA to DFA

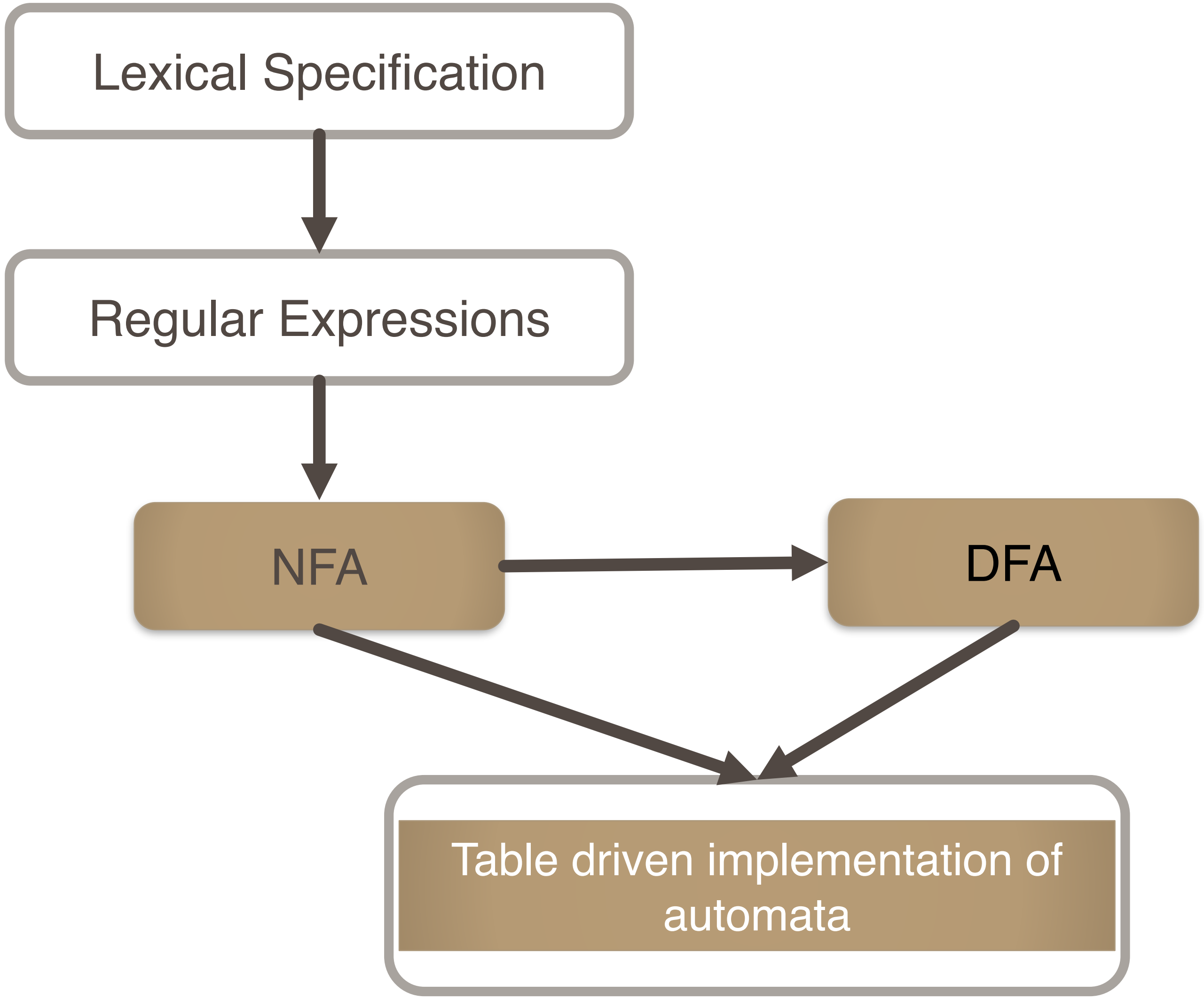


Example: NFA to DFA





NFA to DFA


Lexical Specification
Regular Expressions
NFA
DFA
Table driven implementation of automata

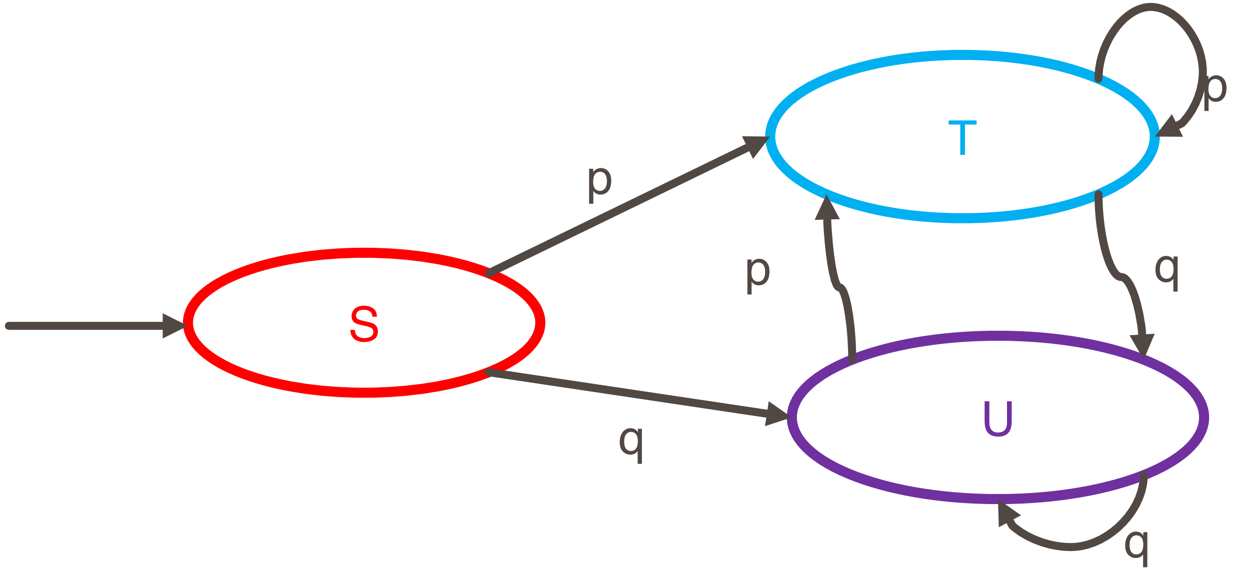
Implementing DFA

- A DFA can be implemented by a 2D table T
  - One dimension is states
  - Another dimension is input symbol
  - For every transition $s_i \rightarrow^a s_k$: define T[i,a] = k

Implementing DFA

Table A

	p	q
S	T	U
T	T	U
U	T	U




```
i = p;
state = 0;
while(input[i]) {
        state = A[state,input[i]];
        i++;
    }
```

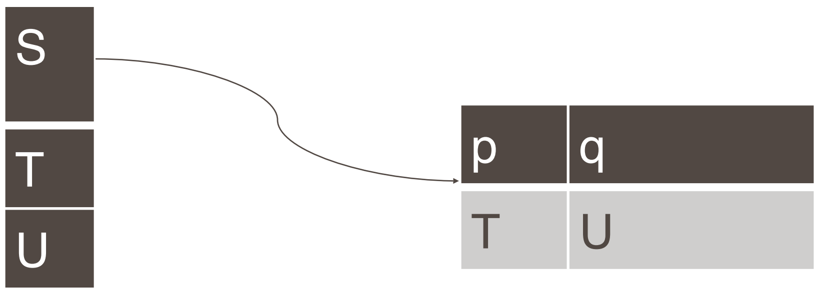
Implementing DFA

Table A

	p	q
S	T	U
T	T	U
U	T	U

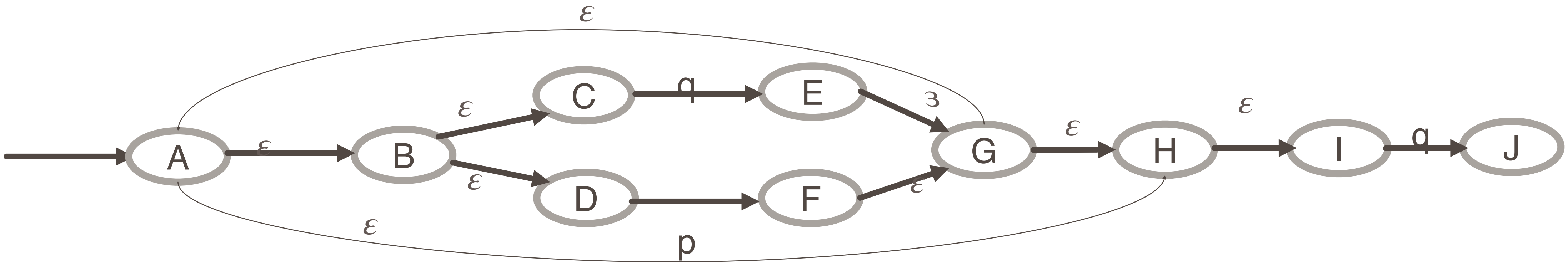
A lot of duplicate entries

Table B



Compact but need an extra indirection
- Inner loop will be slower

Implementing DFA

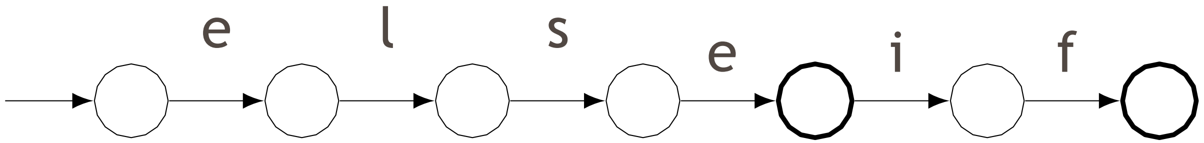


	p	q	
A			{B,H}
B			{C,D}
C		{E}	
…			

Deal with set of states rather than single state-→ inner loop is complicated

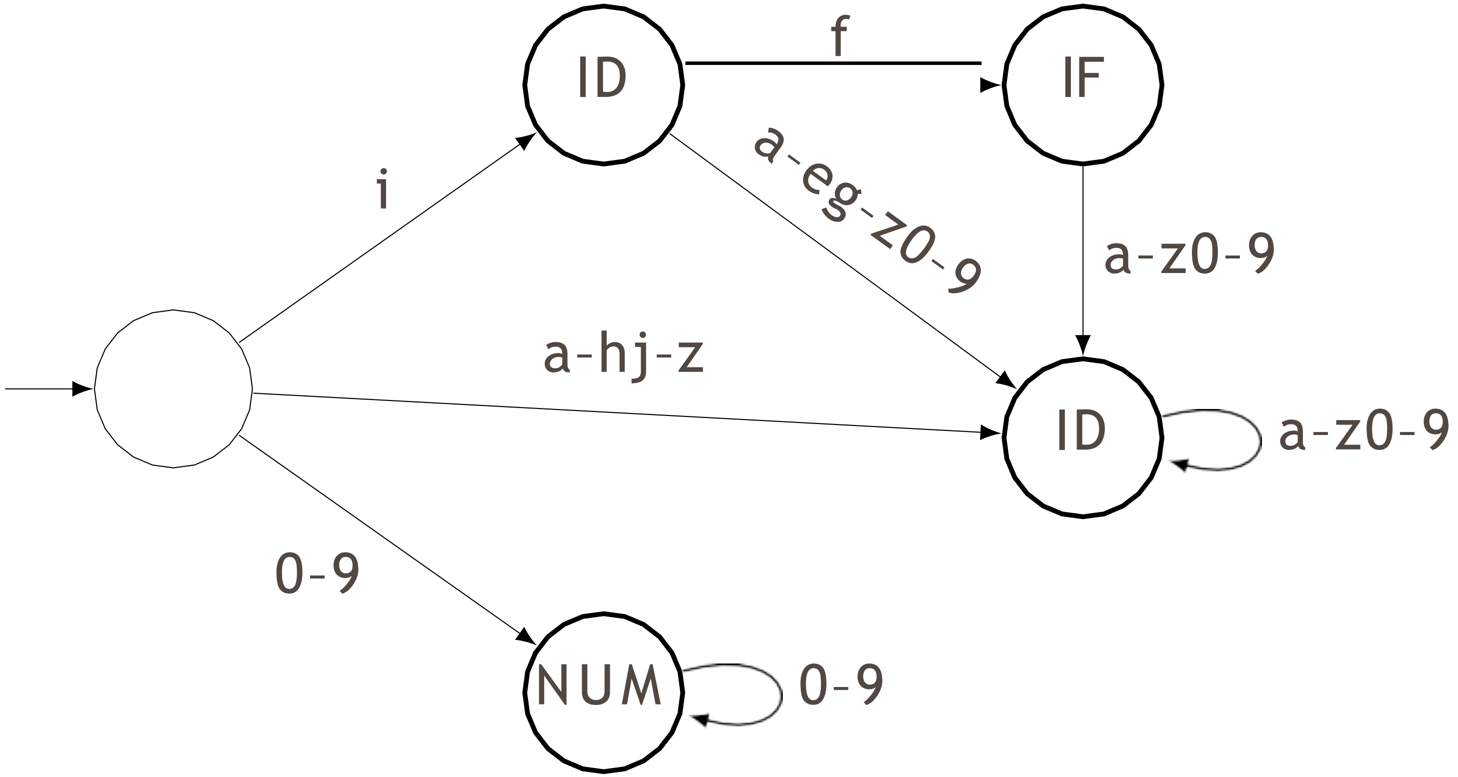
Deterministic Finite Automata: Example

```
{
   type token = ELSE | ELSEIF
}

rule token =
  parse "else"{ ELSE }
      | "elseif"{ ELSEIF }
```



Deterministic Finite Automata

```
{ type token = IF | ID of string | NUM of string }

rule token =
  parse "if"{ IF }
        | ['a'-'z'] ['a'-'z' '0'-'9'] as lit { ID(lit) }
        | ['0'-'9']+                  * as num { NUM(num) }
```

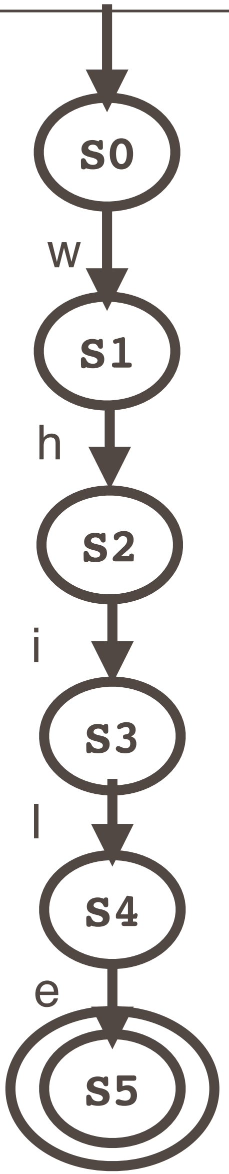


PROGRAMMING ASSIGNMENT1

Recognizing Lexemes:
a simple character by character formulation

Recognize word while

```
c=NextChar();
if(c!=‘w’) { /*do something*/}
else {
  c=NextChar();
  if(c!=‘h’) { /*do something*/}
  else {
    c=NextChar();
    if(c!='i'){ /*do something*/}
    else {
      c=NextChar();
      if(c!='l'){ /*do something*/}
      else{
        c=NextChar();
        if(c!='e'){ /*do something*/}
        else{
          /*report success*/
        }}}}
```

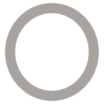
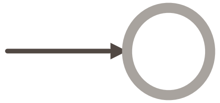
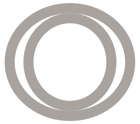


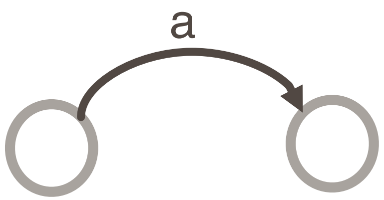
Si s are all abstract states of computation

Recognizing Lexemes

- x = 1

A Formalism of Recognizer

- A finite automaton consists of
  - An input Alphabet: Σ
  - A finite set of states: S 
  - A start state: 
  - A set of accepting states: $F \subseteq S$ 
  - A set of transitions state: state1 $\xrightarrow{input}$ state2



A Formalism of Recognizer

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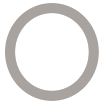
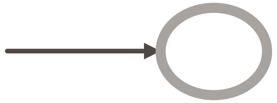
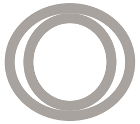


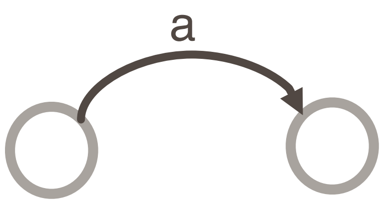
  - A start state: S0



  - A set of accepting states: F $\subseteq$ S



  - A set of transitions state δ: state1 $\xrightarrow{input}$ state2



S=$\{S_0, S_1, S_2, S_3\}$

Σ = {x,=,1}

$\delta = \{S_0 \xrightarrow{x} S_1, S_0 \xrightarrow{=} S_2, S_0 \xrightarrow{1} S_3\}$

$S_0 = S_0$

$F = \{S_1, S_2, S_3\}$

A simple parser for x=1

```
c=NextChar();
state=S_0
while(c!='eof' and state!=S_err) {
    state=δ(state, c)
    c=NextChar();
}

if(state ∈ F)
    /* report acceptance */
else
    /* report failure */
```

S=$\{S_0, S_1, S_2, S_3\}$

Σ = {x,=,1}

$\delta = \{S_0 \xrightarrow{x} S_1, S_0 \xrightarrow{+} S_2, S_0 \xrightarrow{1} S_3\}$

$S_0 = S_0$

$F = \{S_1, S_2, S_3\}$

Example: Lexeme Recognition

- Show simple state transition of : e = m * c ** 2

S=$\{S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$

Σ = {e,m,c,*,**,2,=}

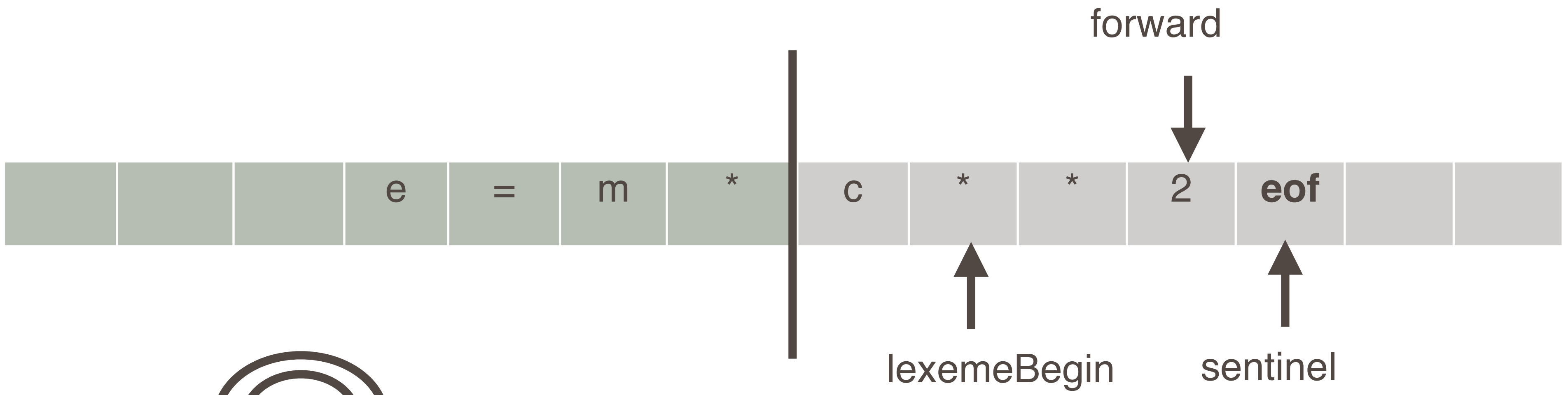
$$\delta = \{S_0 \xrightarrow{\text{e}} S_1, S_0 \xrightarrow{=} S_2, S_0 \xrightarrow{\text{m}} S_3, S_0 \xrightarrow{*} S_4, S_4 \xrightarrow{*} S_5, S_0 \xrightarrow{\text{c}} S_6, S_0 \xrightarrow{2} S_7\}$$

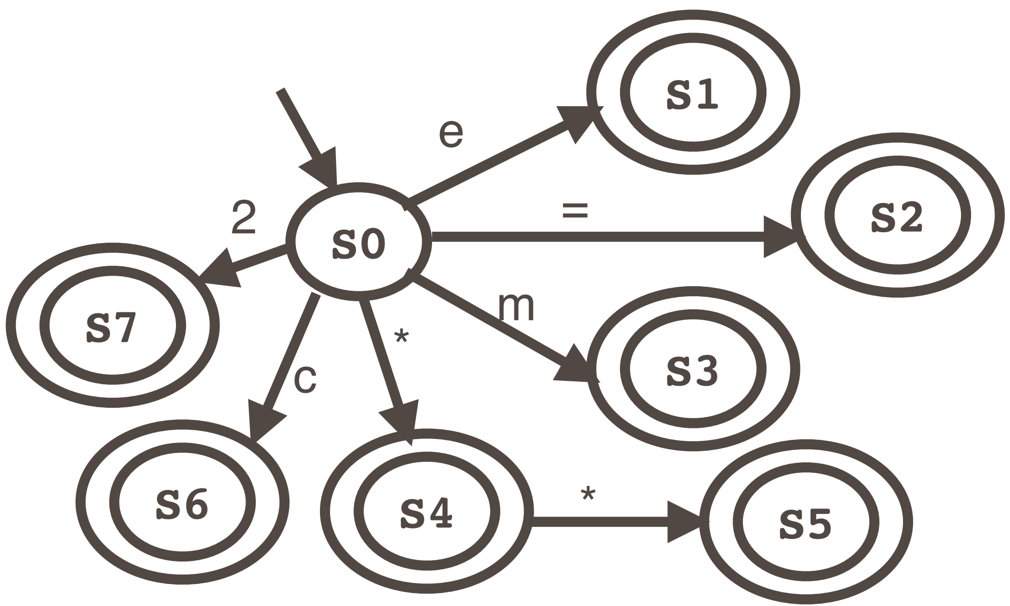
$$S_0 = S_0$$

$$F = \{S_1, S_2, S_3, S_4, S_5, S_6, S_7\}$$

Input Buffering

- e = m * c ** 2m





Question?

- Can we run out of buffer space?