Compiler course

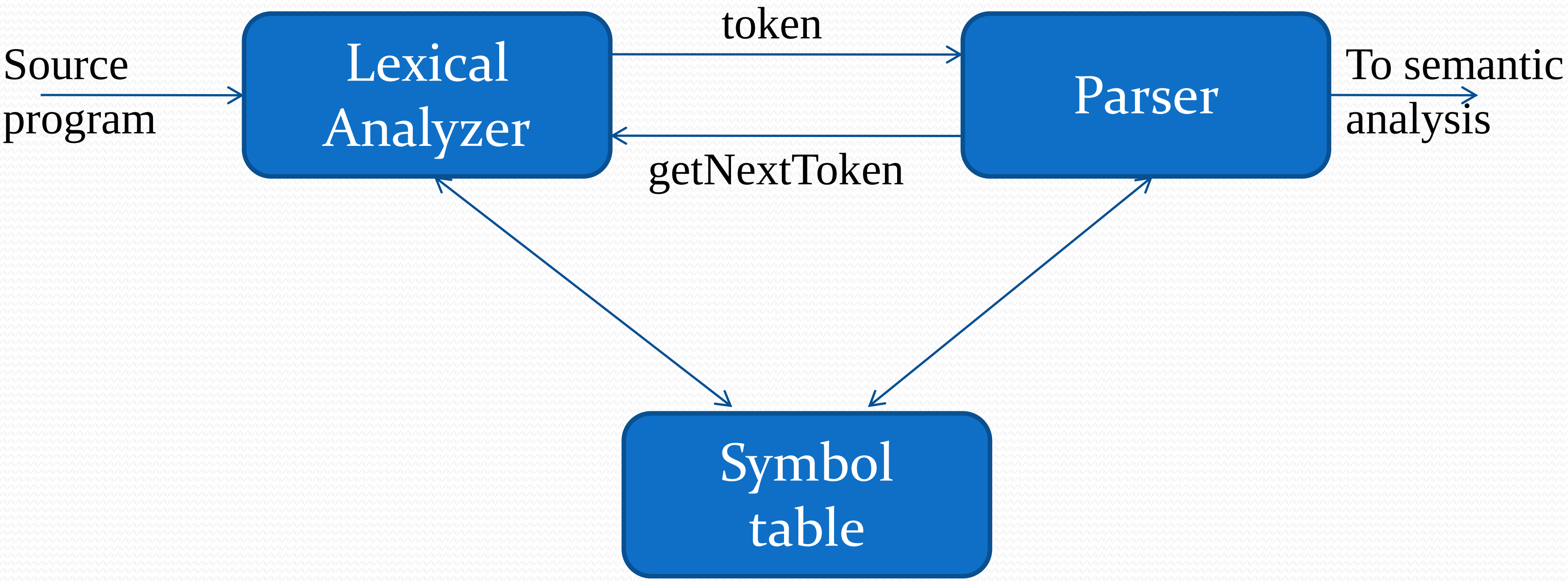
Chapter 3

Lexical Analysis

Outline

- Role of lexical analyzer
- Specification of tokens
- Recognition of tokens
- Lexical analyzer generator
- Finite automata
- Design of lexical analyzer generator

The role of lexical analyzer



Why to separate Lexical analysis and parsing

1. Simplicity of design
2. Improving compiler efficiency
3. Enhancing compiler portability

Tokens, Patterns and Lexemes

- A token is a pair a token name and an optional token value
- A pattern is a description of the form that the lexemes of a token may take
- A lexeme is a sequence of characters in the source program that matches the pattern for a token

Example

Token	Informal description	Sample lexemes
if	Characters i, f	if
else	Characters e, l, s, e	else
comparison	< or > or <= or >= or == or !=	<=, !=
id	Letter followed by letter and digits	pi, score, D2
number	Any numeric constant	3.14159, 0, 6.02e23
literal	Anything but " sorrounded by "	"core dumped"

printf("total = %d\n", score);

Attributes for tokens

- E = M * C ** 2
  - <id, pointer to symbol table entry for E>
  - <assign-op>
  - <id, pointer to symbol table entry for M>
  - <mult-op>
  - <id, pointer to symbol table entry for C>
  - <exp-op>
  - <number, integer value 2>

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

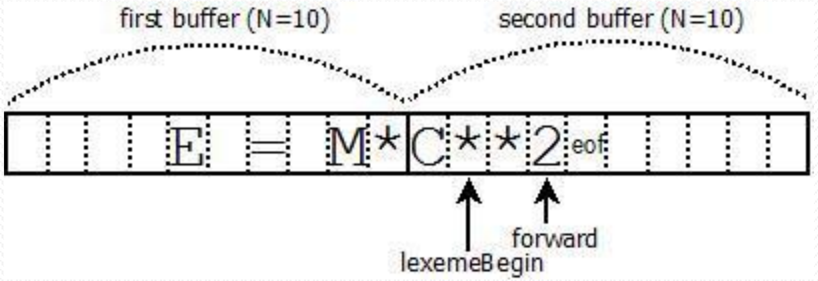
- Panic mode: successive characters are ignored until we reach to a well formed token
- Delete one character from the remaining input
- Insert a missing character into the remaining input
- Replace a character by another character
- Transpose two adjacent characters

Input Buffering

- How to speed the reading of source program ?
- to look one additional character ahead
- e.g.
  - to see the end of an **identifieryou must see a character**
  - which is not a letter or a digit
  - not a part of the lexeme for **id**
  - in C
  - -,= , <
  - ->, ==, <=
- two buffer scheme that handles large lookaheadssafely
- sentinels –improvement which saves time checking buffer ends

Buffer pairs

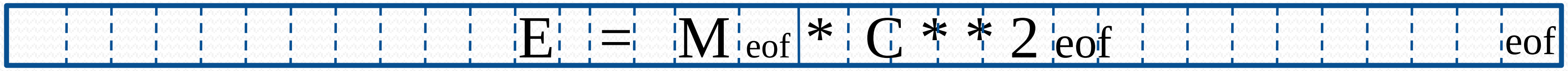
- Buffer size N
- N = size of a disk block (4096)
- read N characters into a buffer
- one system call
- not one call per character
- read < N characters we encounter **eof**
- two pointers to the input are maintained
  - *lexemeBegin–marks the beginning of the current lexeme*
  - *forward–scans ahead until a pattern match is found*



Sentinels

- *Forward pointer*
  - to test if it is at the end of the buffer
  - to determine what character is read (multiwaybranch)
- sentinel
  - added at each buffer end
  - can not be part of the source program
  - character **eofis a natural choice**
  - retains the role of entire input end
  - when appears other than at the end of a buffer it means that the input is at an end

Sentinels



E = M eof * C * * 2 eof eof

```
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 /* eof within a buffer marks the end of input */
                        terminate lexical analysis;
            break;
    cases for the other characters;
}
```

Specification of tokens

- In theory of compilation regular expressions are used to formalize the specification of tokens
- Regular expressions are means for specifying regular languages
- Example:
    - Letter_(letter_ | digit)*
- Each regular expression is a pattern specifying the form of strings

Regular expressions

- ε is a regular expression, $L(\varepsilon) = \{\varepsilon\}$
- If a is a symbol in Σ then a is a regular expression, $L(a) = \{a\}$
- $(r) | (s)$ is a regular expression denoting the language $L(r) \cup L(s)$
- $(r)(s)$ is a regular expression denoting the language $L(r)L(s)$
- $(r)^*$ is a regular expression denoting (L9r))*
- (r) is a regular expression denting $L(r)$

Regular definitions

d1 -> r1

d2 -> r2

…

dn -> rn

- Example:

letter_ -> A | B | … | Z | a | b | … | Z | _

digit -> 0 | 1 | … | 9

id -> letter_ (letter_ | digit)*

Extensions

- One or more instances: (r)+
- Zero of one instances: r?
- Character classes: [abc]

- Example:
  - letter_ -> [A-Za-z_]
  - digit -> [0-9]
  - id -> letter_(letter|digit)*

Recognition of tokens

- Starting point is the language grammar to understand the tokens:

stmt -> **if** expr **then** stmt

| **if** expr **then** stmt **else** stmt

| ε

expr -> term **relop** term

| term

term -> **id**

| **number**

Recognition of tokens (cont.)

- The next step is to formalize the patterns:

  digit -> [0-9]

  Digits -> digit+

  number -> digit(.digits)? (E[+-]? Digit)?

  letter -> [A-Za-z_]

  id -> letter (letter|digit)*

  If -> if

  Then -> then

  Else -> else

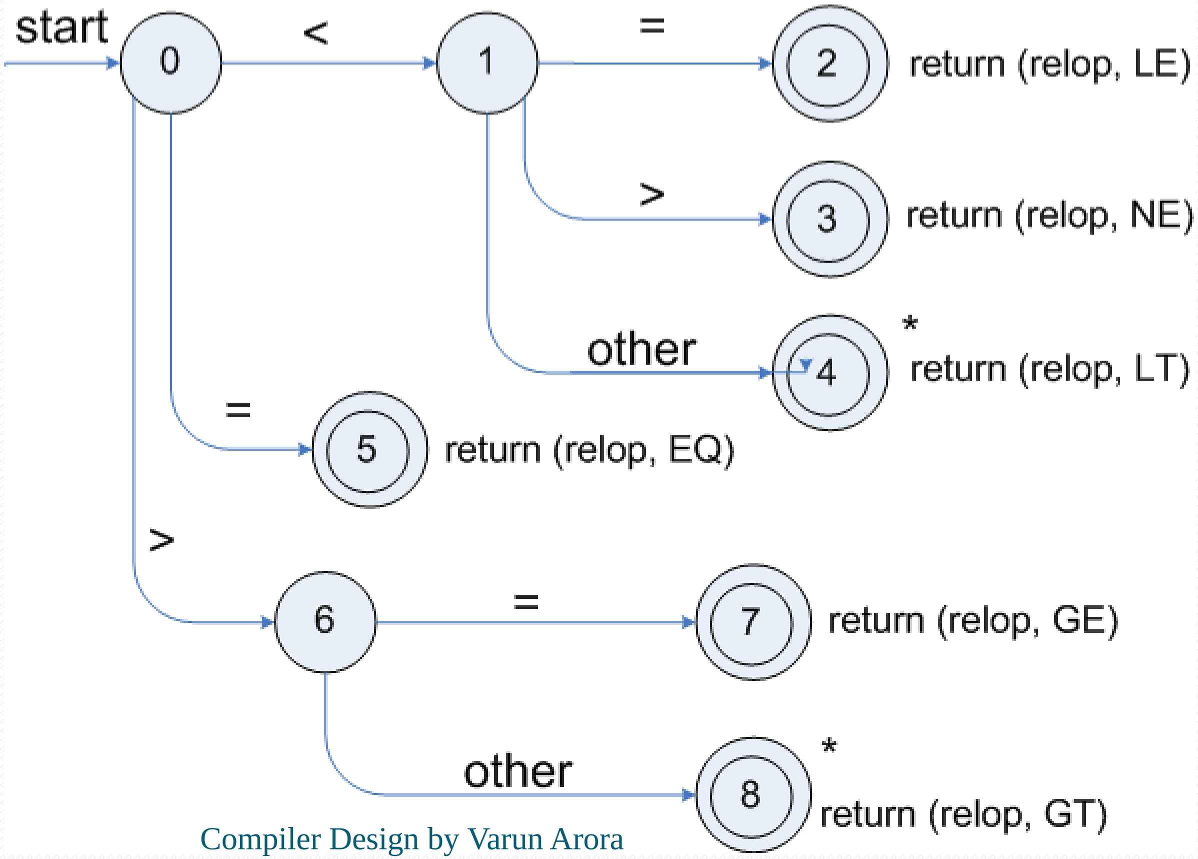
  Relop -> < | > | <= | >= | = | <>

- We also need to handle whitespaces:

  ws -> (blank | tab | newline)+

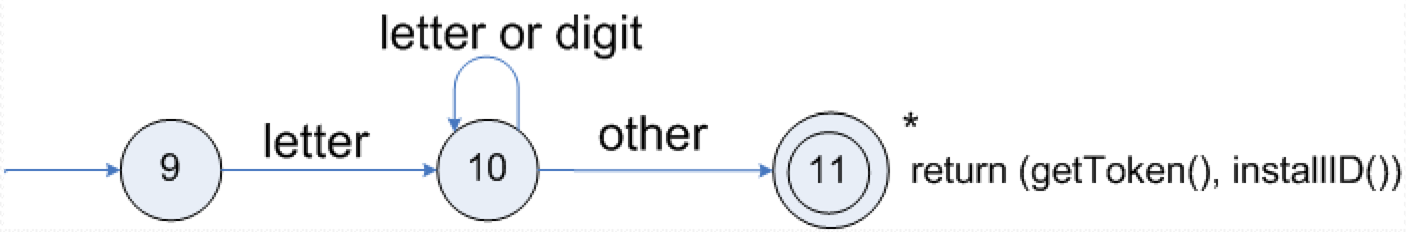
Transition diagrams

- Transition diagram for relop



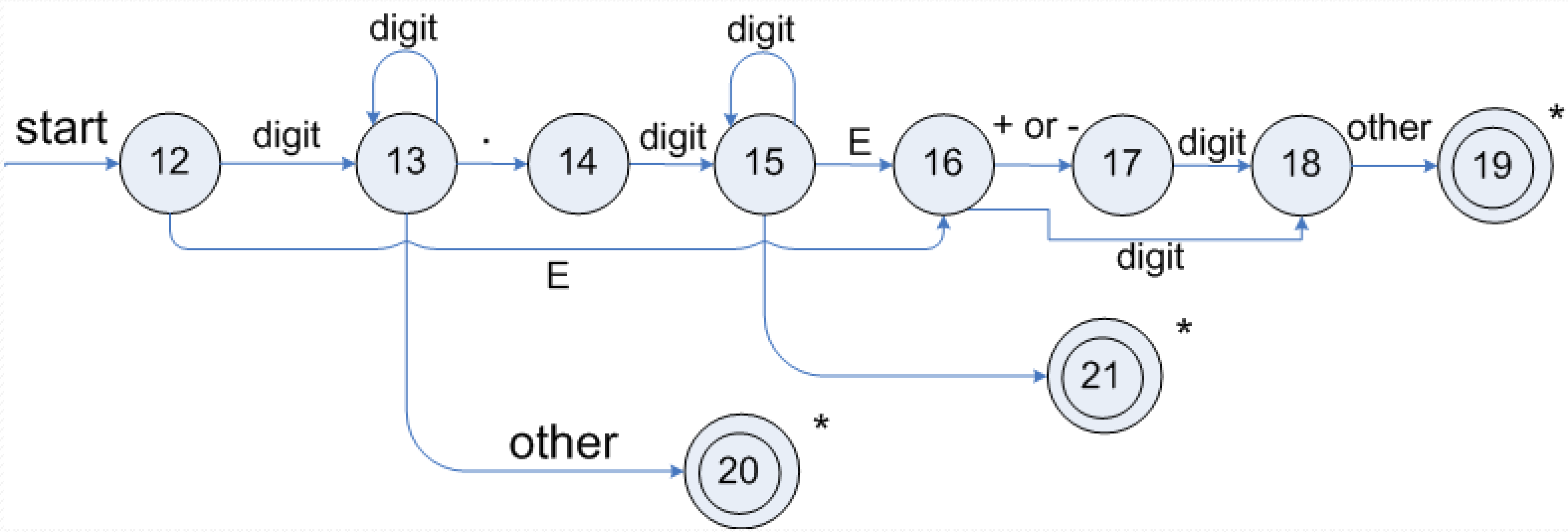
Transition diagrams (cont.)

- Transition diagram for reserved words and identifiers



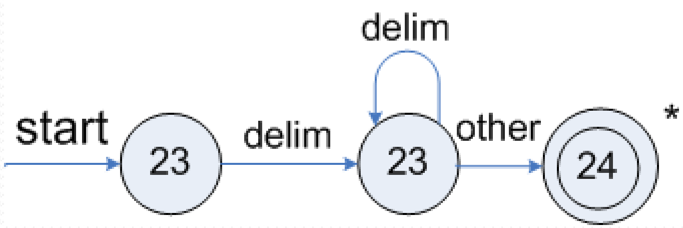
Transition diagrams (cont.)

- Transition diagram for unsigned numbers



Transition diagrams (cont.)

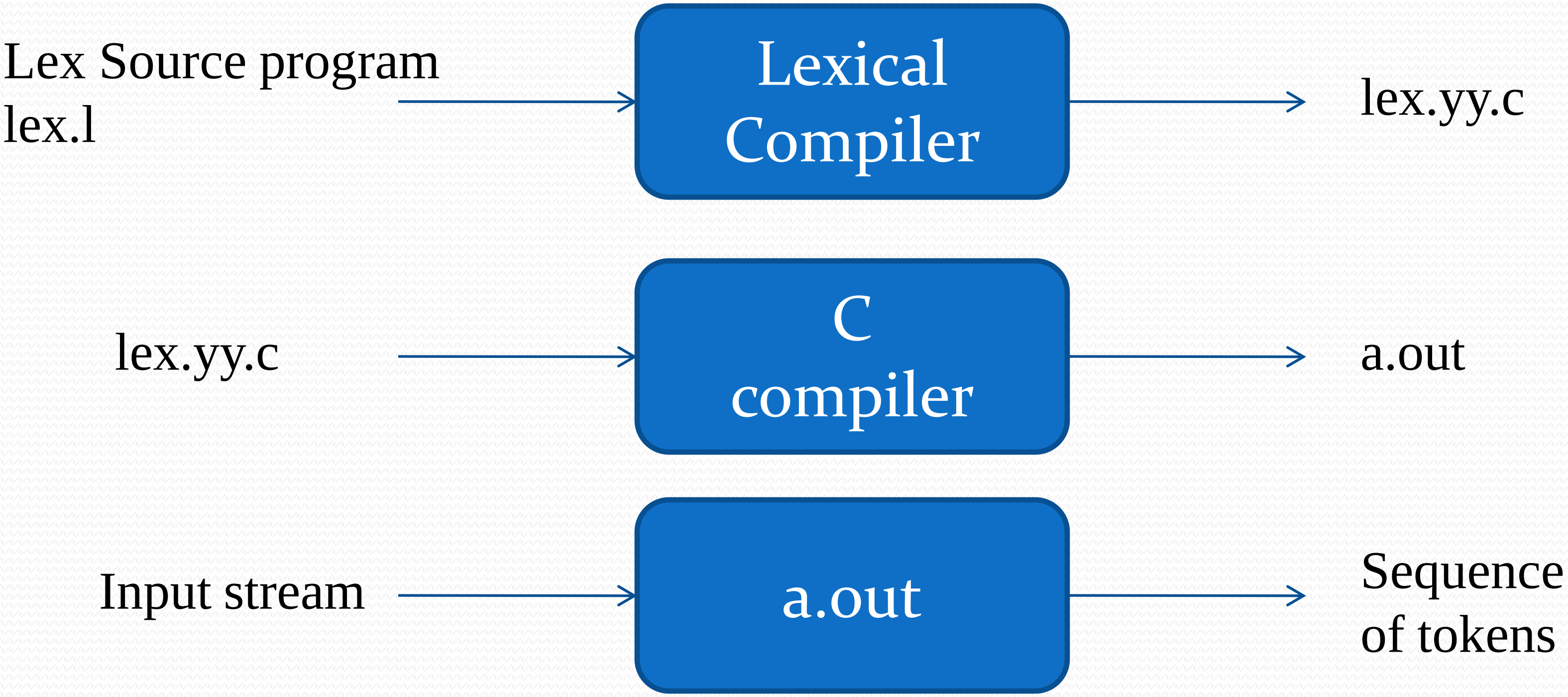
- Transition diagram for whitespace



Architecture of a transition-diagram-based lexical analyzer

```
TOKEN getRelop()
{
    TOKEN retToken = new (RELOP)
    while (1) {            /* repeat character processing until a
                                        return or failure occurs  */
    switch(state) {
             case 0: c= nextchar();
                           if (c == ‘<‘) state = 1;
                           else if (c == ‘=‘) state = 5;
                           else if (c == ‘>’) state = 6;
                           else fail();  /* lexeme is not a relop */
                           break;
             case 1: …
             …
             case 8: retract();
                          retToken.attribute = GT;
                          return(retToken);
    }
```

Lexical Analyzer Generator - Lex



Structure of Lex programs

declarations
%%
translation rules → Pattern {Action}
%%
auxiliary functions

Example

```
%{
    /* definitions of manifest constants
    LT, LE, EQ, NE, GT, GE,
    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 = (int) installID(); return(ID); }
{number}    {yylval = (int) installNum(); return(NUMBER);}
…
```

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

Int installNum() { /* similar to
    installID, but puts numerical
    constants into a separate table */
}
```

Finite Automata

- Regular expressions = specification
- Finite automata = implementation

- A finite automaton consists of
  - An input alphabet Σ
  - A 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

$$s_1 \xrightarrow{a} s_2$$

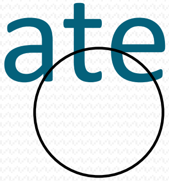
- Is read

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

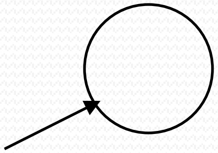
- If end of input
  - If in accepting state => accept, othewise => reject
- If no transition possible => reject

Finite Automata State Graphs

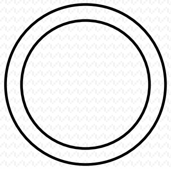
- A state



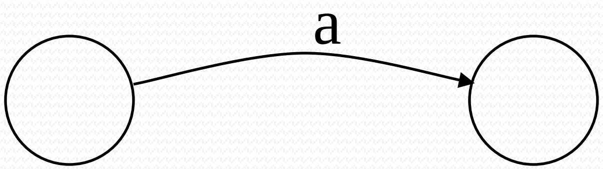
- The start state



- An accepting state

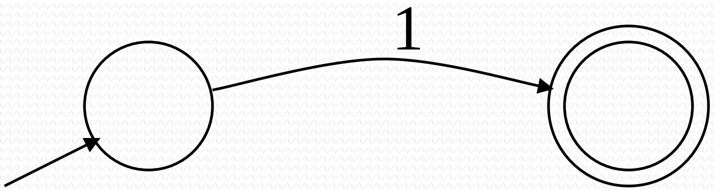


- A transition



A Simple Example

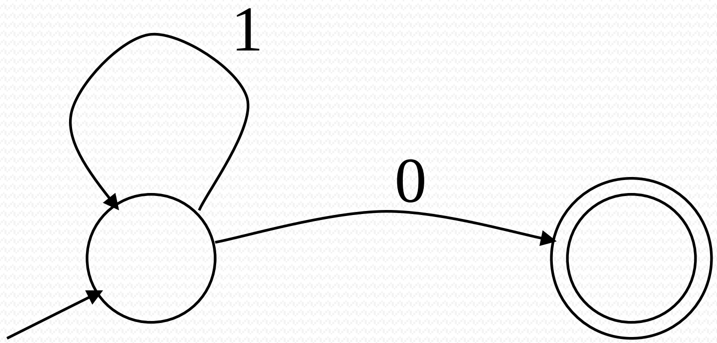
- A finite automaton that accepts only “1”



- A finite automaton accepts a string if we can follow transitions labeled with the characters in the string from the start to some accepting state

Another Simple Example

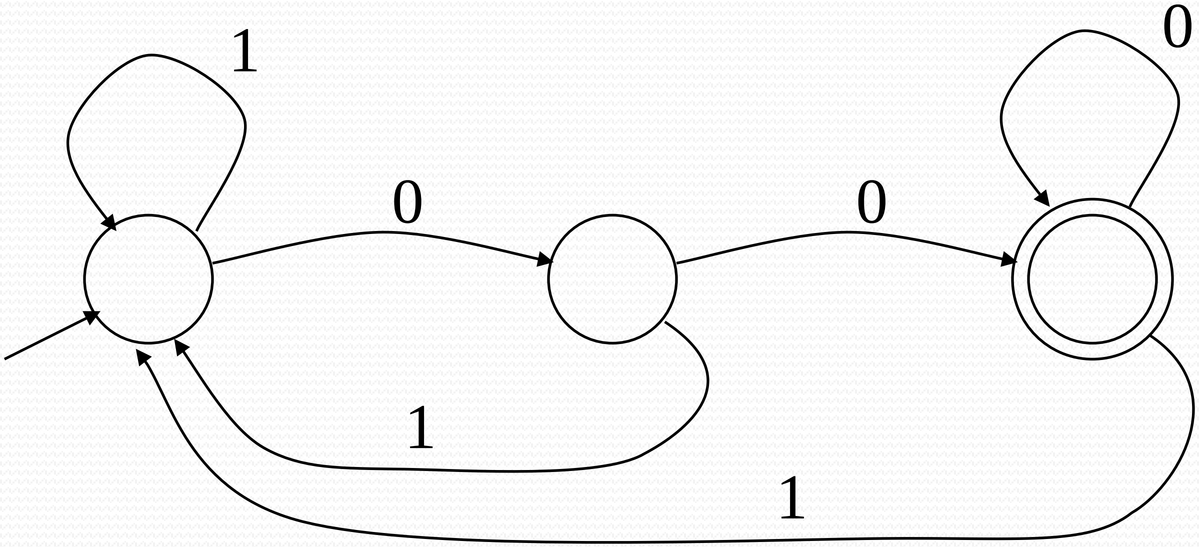
- A finite automaton accepting any number of 1's followed by a single 0
- Alphabet: {0,1}



- Check that "1110" is accepted but "110…" is not

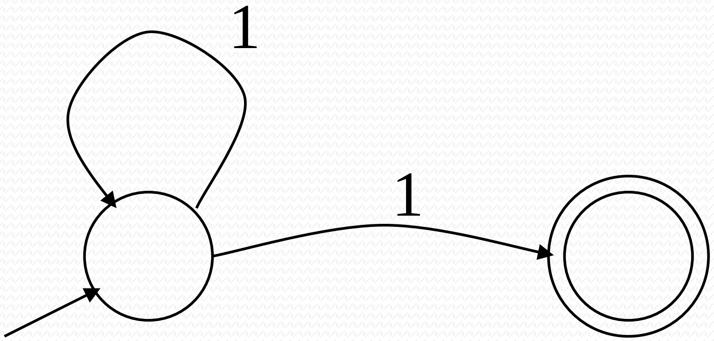
And Another Example

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



And Another Example

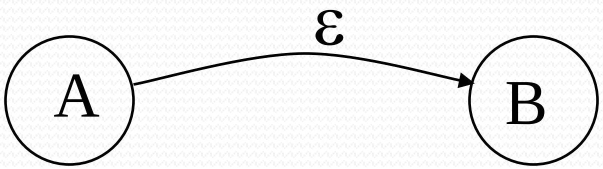
- Alphabet still { 0, 1 }



- The operation of the automaton is not completely defined by the input
  - On input “11” the automaton could be in either state

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
- *Finite* automata have *finite* memory
  - Need only to encode the current state

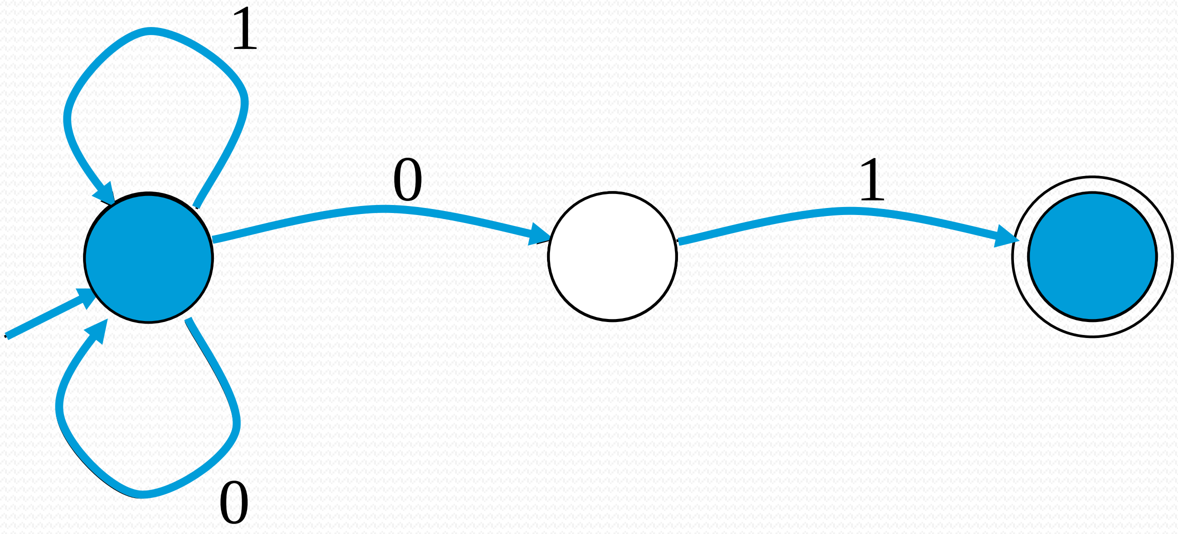
Execution of Finite Automata

- 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: 1 0 1
- Rule: NFA accepts if it can get in a final state

NFA vs. DFA (1)

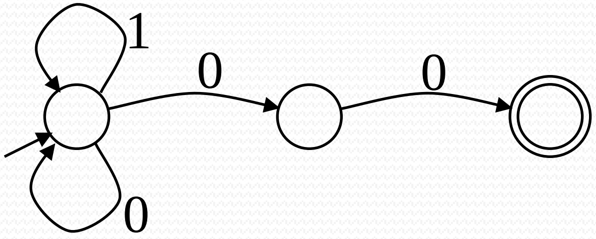
- NFAs and DFAs recognize the same set of languages (regular languages)

- DFAs are easier to implement
  - There are no choices to consider

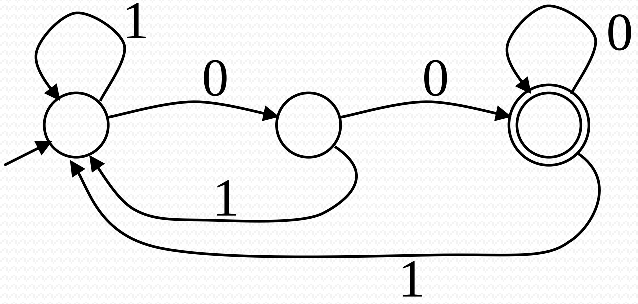
NFA vs. DFA (2)

- For a given language the NFA can be simpler than the DFA

NFA



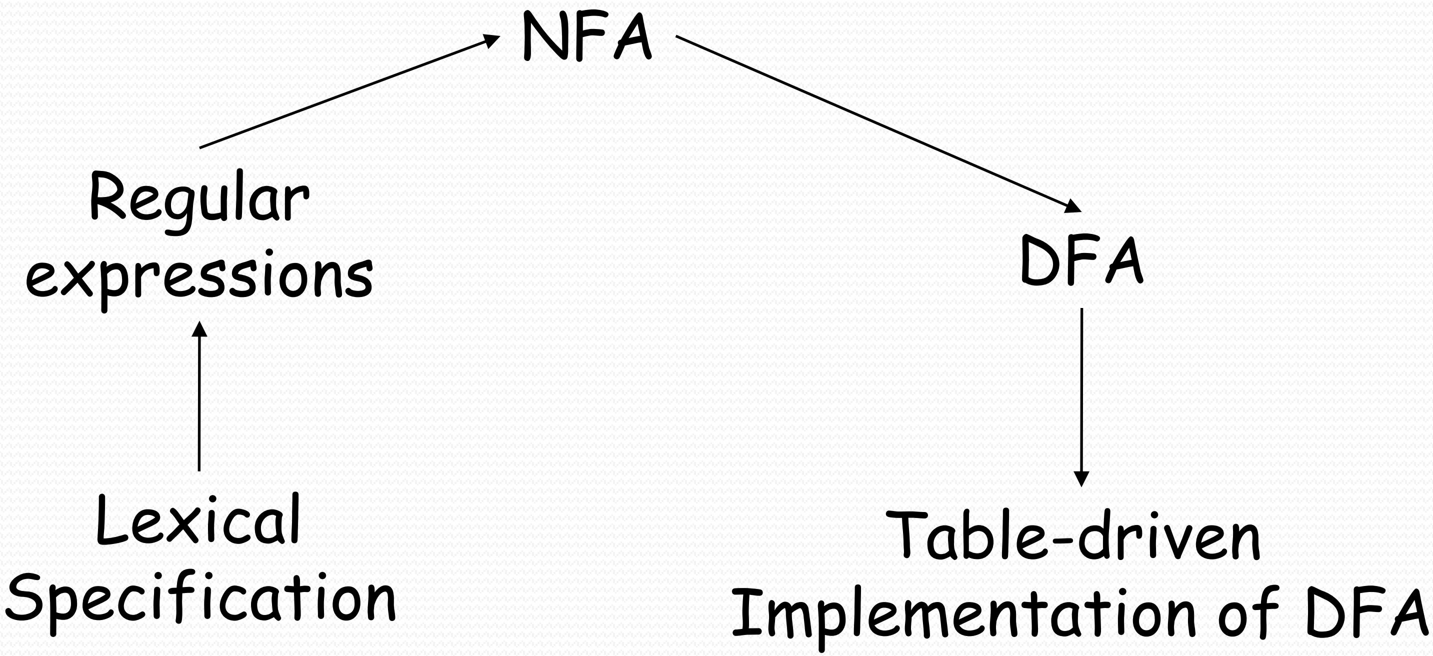
DFA



- DFA can be exponentially larger than NFA

Regular Expressions to Finite Automata

- High-level sketch



NFA

Regular expressions

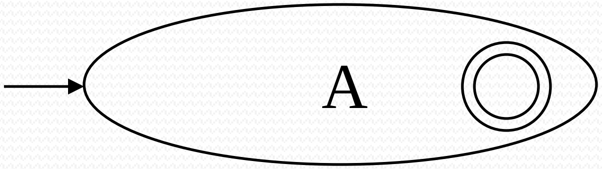
DFA

Lexical Specification

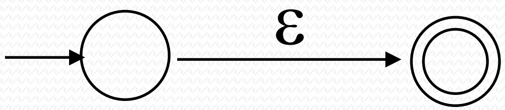
Table-driven Implementation of DFA

Regular Expressions to NFA (1)

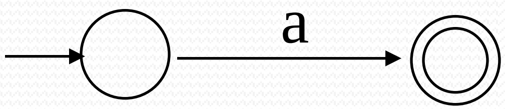
- For each kind of rexp, define an NFA
  - Notation: NFA for rexp A



- For ε

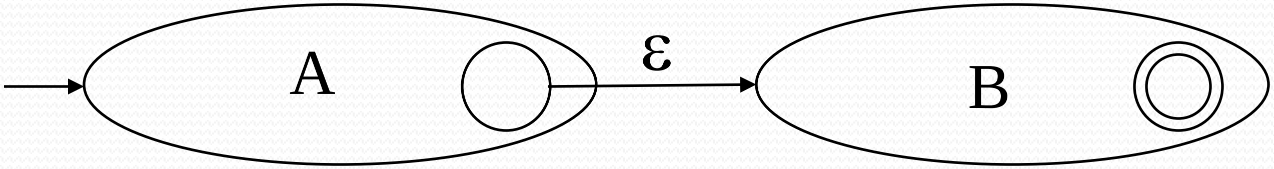


- For input a

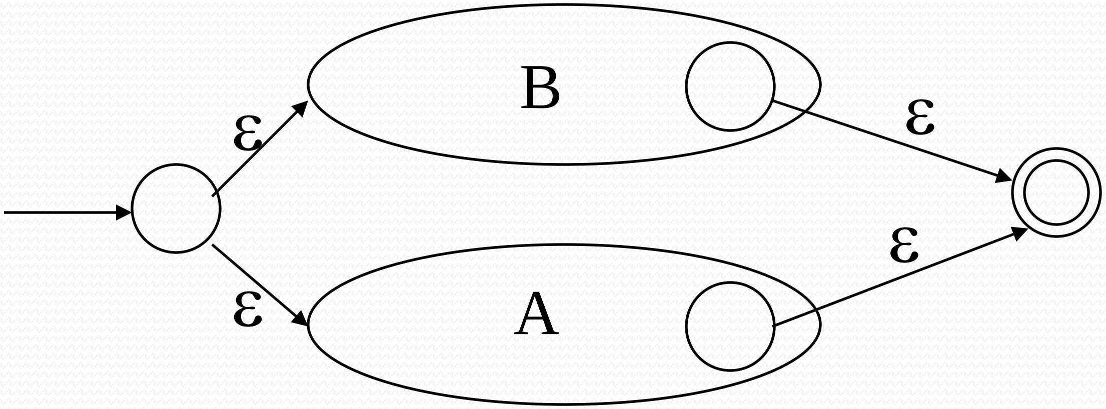


Regular Expressions to NFA (2)

- For AB

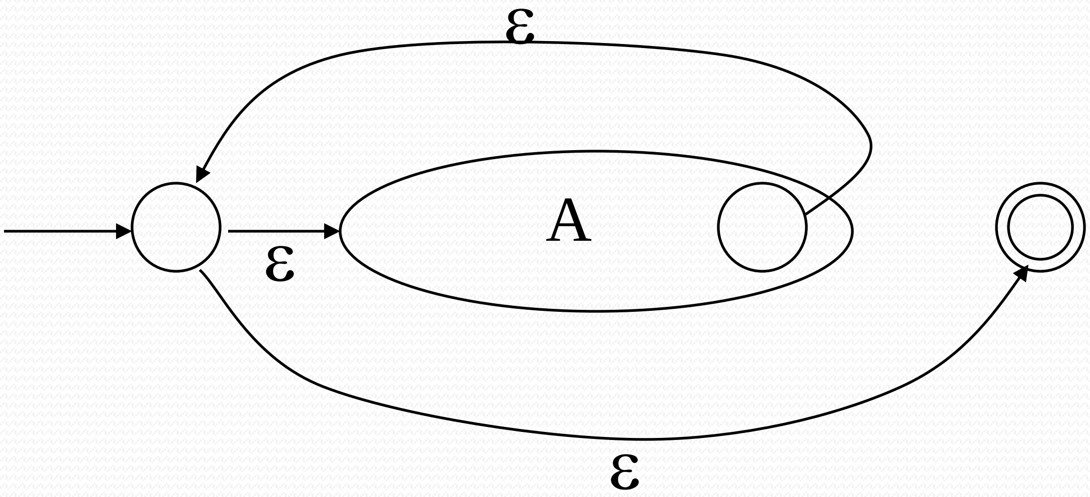


- For A | B



Regular Expressions to NFA (3)

- For A*

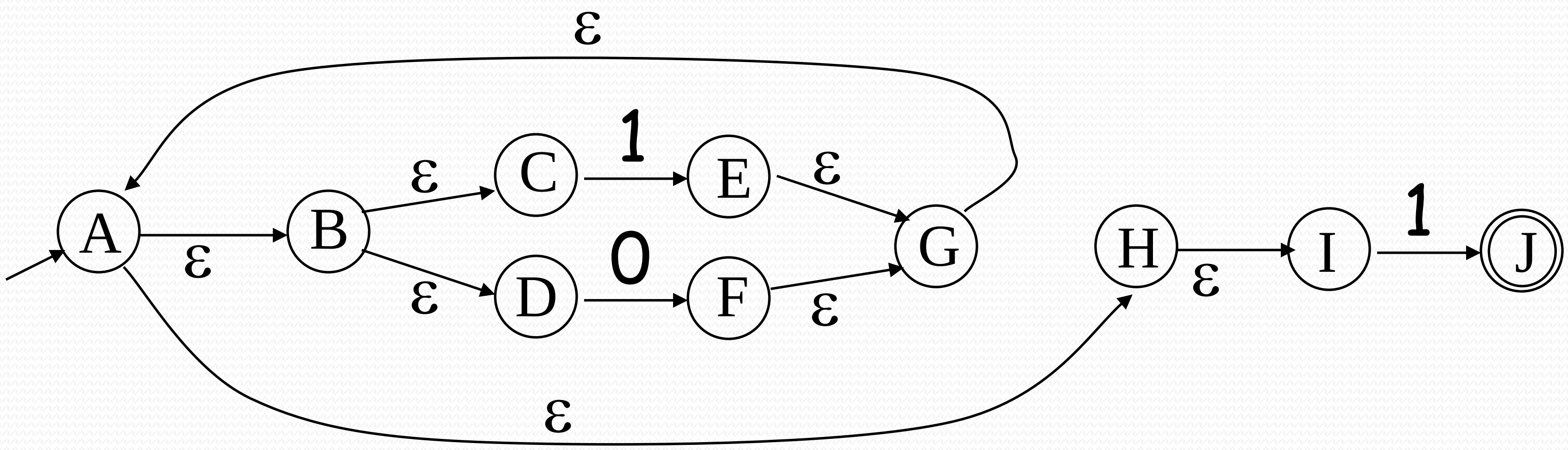


Example of RegExp -> NFA conversion

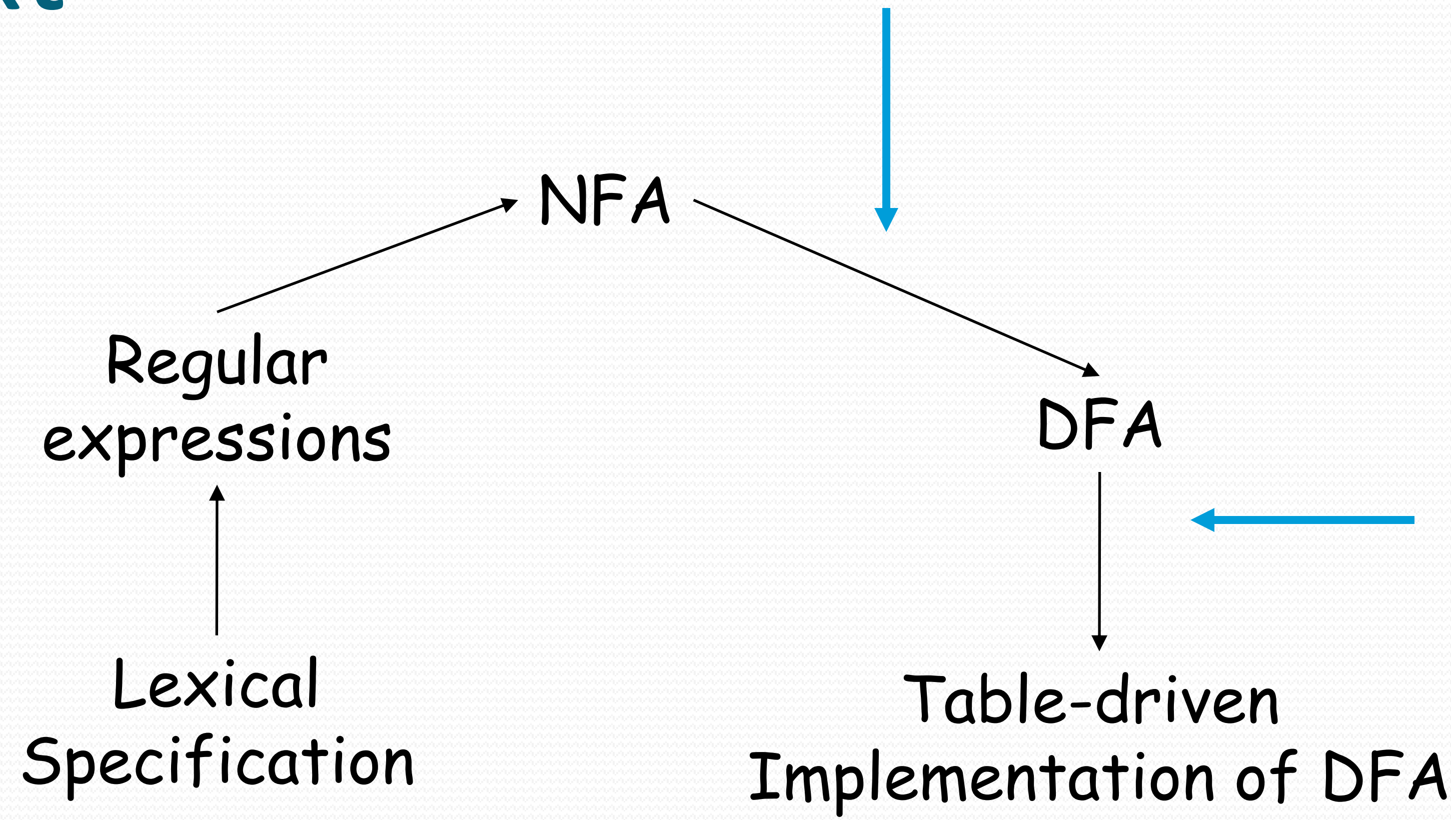
- Consider the regular expression

  (1 | 0)*1

- The NFA is



Next



NFA

Regular expressions

DFA

Lexical Specification

Table-driven Implementation of DFA

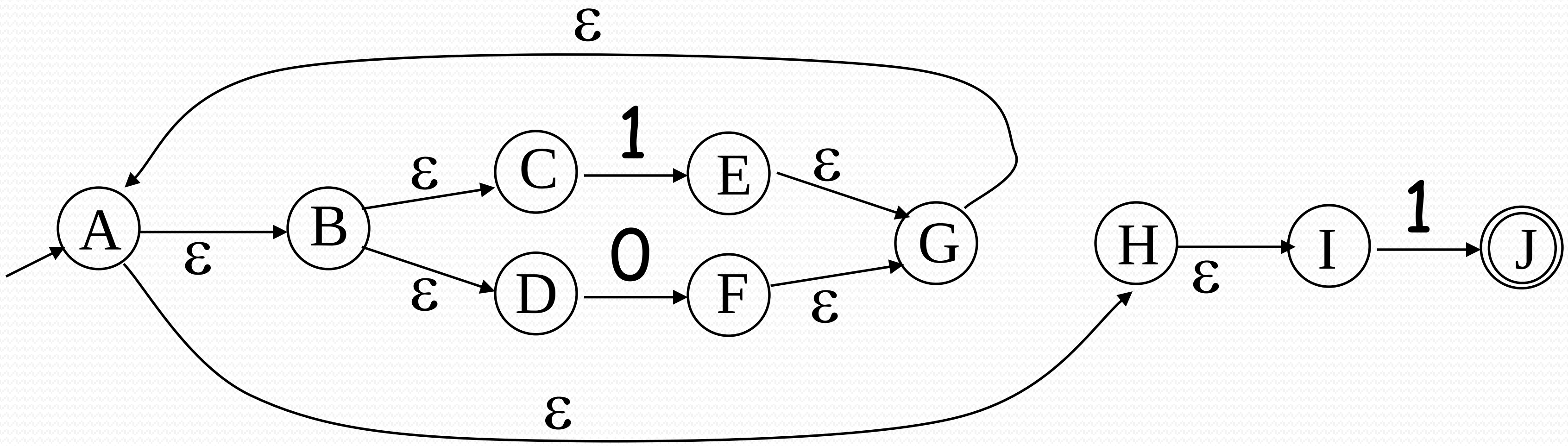
NFA to DFA. The Trick

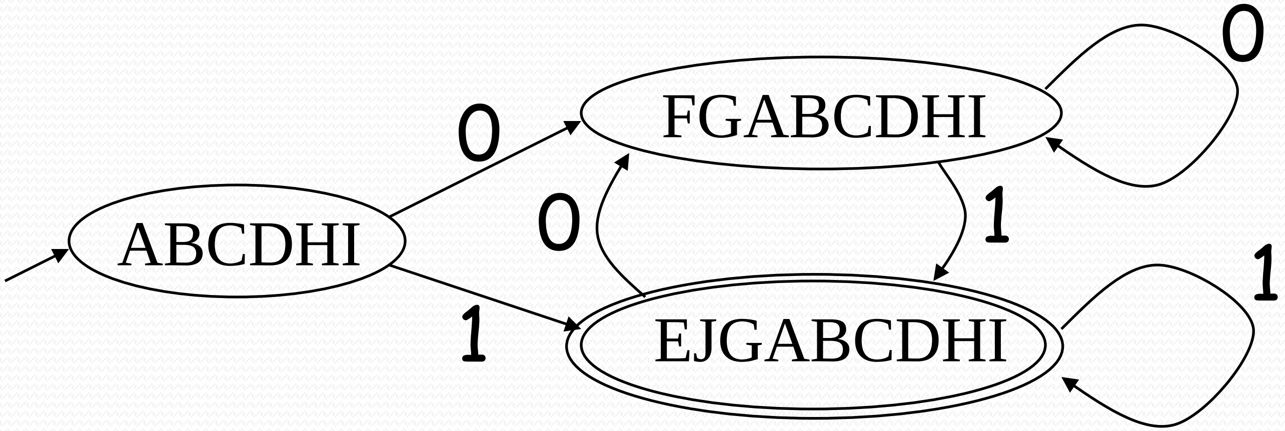
- Simulate the NFA
- Each state of resulting DFA

  = a non-empty subset of states of the NFA
- Start state

  = the set of NFA states reachable through ε-moves from NFA start state
- Add a transition $S \rightarrow^{a} S'$ to DFA iff
  - S' is the set of NFA states reachable from the states in S after seeing the input a
    - considering ε-moves as well

NFA -> DFA Example





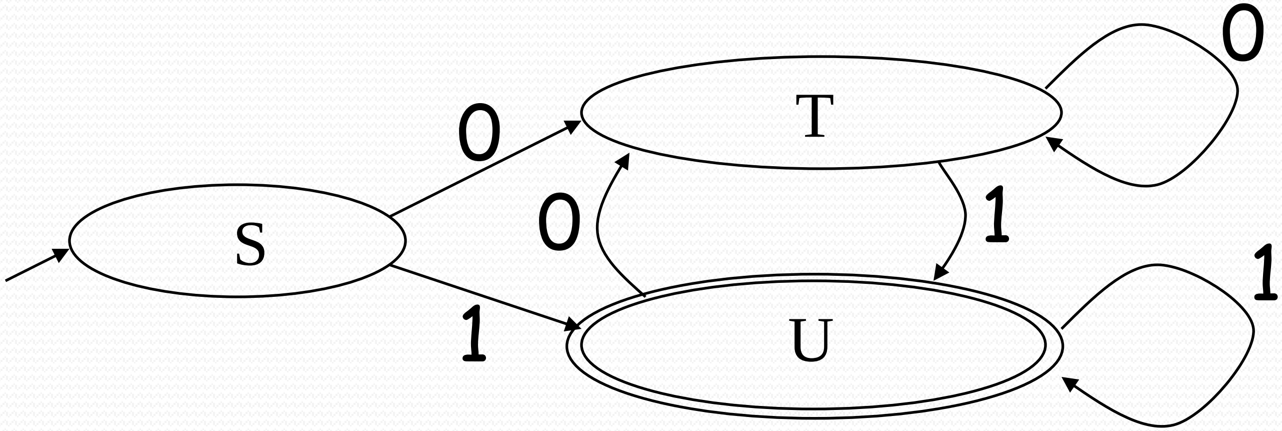
NFA to DFA. Remark

- An NFA may be in many states at any time
- How many different states ?
- If there are N states, the NFA must be in some subset of those N states
- How many non-empty subsets are there?
  - $2^N - 1$ = finitely many, but exponentially many

Implementation

- A DFA can be implemented by a 2D table T
  - One dimension is “states”
  - Other dimension is “input symbols”
  - 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 or jflex

- But, DFAs can be huge

- In practice, flex-like tools trade off speed for space in the choice of NFA and DFA representations

Readings

- Chapter 3 of the book