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Chapter 2: Regular Expressions & Lexical Analysis

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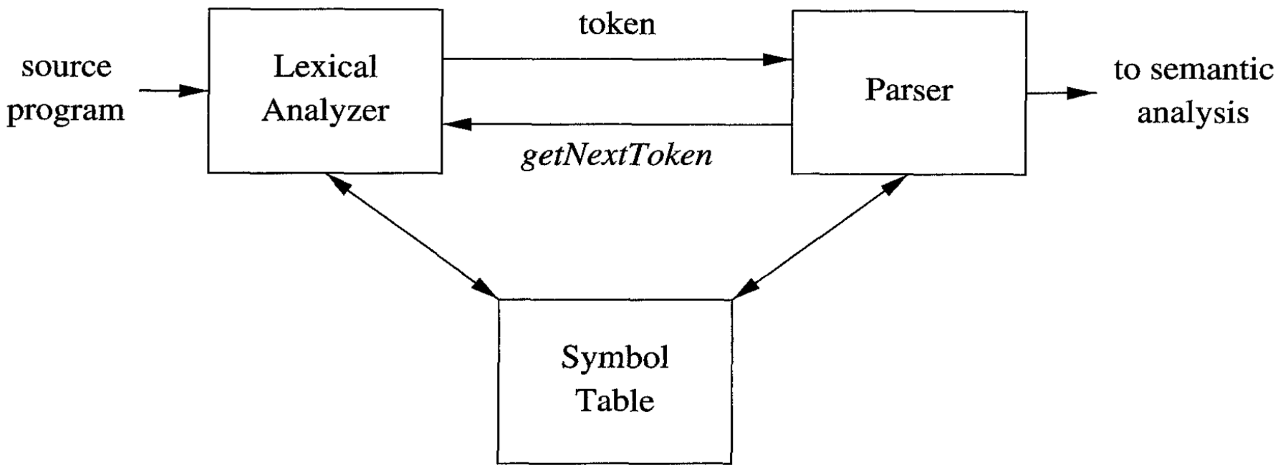
The chapter numbering in lecture notes does not follow that in the textbook.

Outline

- The Role of Lexers: Recognizing Tokens
- Regular Expressions (for specifying tokens)
- Finite Automata (for recognizing patterns)

The Role of Lexical Analyzer

- Read the input characters of the source program, group them into lexemes, and produces a sequence of tokens
- Add lexemes into the symbol table when necessary



The Role of Lexical Analyzer

```
position = initial + rate * 60
```

Lexical Analyzer

```
<id, 1>
<=>
<id, 2>
<+>
<id, 3>
<*>
<60>
```

SYMBOL TABLE

1	position	...
2	initial	...
3	rate	...

Tokens, Patterns, and Lexemes

- A ***lexeme*** is a string of characters that is a lowest-level syntactic unit in programming languages

- A ***token*** is a syntactic category representing a class of lexemes. Formally, it is a pair <token name, attribute value>
  - Token name: an abstract symbol representing the kind of the token
  - Attribute value (optional) points to the symbol table

- Each token has a particular ***pattern***: a description of the form that the lexemes of the token may take

Examples

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 letters and digits	`pi`, `score`, `D2`
number	any numeric constant	`3.14159`, `0`, `6.02e23`
literal	anything but `"`, surrounded by `"`'s	`"core dumped"`

Consider the C statement: `printf("Total = %d\n", score);`

Lexeme	`printf`	`score`	`"Total = %d\n"`	`(`	...
Token	**id**	**id**	**literal**	**left_parenthesis**	...

Attributes for Tokens

- When more than one lexeme match a pattern, the lexical analyzer must provide additional information, named *attribute values*, to the subsequent compiler phases
  - Token names influence parsing decisions
  - Attribute values influence semantic analysis, code generation etc.

- For example, an **id** token is often associated with: (1) its lexeme, (2) type, and (3) the location at which it is first found. Token attributes are stored in the symbol table.

`A = B * 2` →

```
<id, pointer to symbol-table entry for A>
<assign_op>
<id, pointer to symbol-table entry for B>
<mult_op> <number, integer value 2>
```

Lexical Errors

- When none of the patterns for tokens match any prefix of the remaining input
- Example: `int 3a = a * 3;`

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- Regular Expressions (for specifying tokens)
- Finite Automata (for recognizing patterns)

Specification of Tokens

- **Regular expression (正则表达式, regexp for short)** is an important notation for specifying lexeme patterns
- Content of this part
  - Strings and Languages (串和语言)
  - Operations on Languages (语言上的运算)
  - Regular Expressions
  - Regular Definitions (正则定义)
  - Extensions of Regular Expressions

Strings and Languages

- **Alphabet (字母表)**: any finite set of symbols
  - Examples of symbols: letters, digits, and punctuations
  - Examples of alphabets: {1, 0}, ASCII, Unicode
- A **string (串)** over an alphabet is a finite sequence of symbols drawn from the alphabet
  - The length of a string *s*, denoted $|s|$, is the number of symbols in *s* (i.e., cardinality)
  - Empty string (空串): the string of length 0, ϵ

Terms (using banana for illustration)

- **Prefix (前缀) of string *s*:** any string obtained by removing 0 or more symbols from the end of *s* (ban, banana, ϵ)
- **Proper prefix (真前缀):** a prefix that is not ϵ and not *s* itself (ban)
- **Suffix (后缀):** any string obtained by removing 0 or more symbols from the beginning of *s* (nana, banana, ϵ).
- **Proper suffix (真后缀):** a suffix that is not ϵ and not equal to *s* itself (nana)

Terms Cont.

- **Substring (子串) of s:** any string obtained by removing any prefix and any suffix from s (banana, nan, ϵ)
- **Proper substring (真子串):** a substring that is not ϵ and not equal to s itself (nan)
- **Subsequence (子序列):** any string formed by removing 0 or more not necessarily consecutive symbols from s (bnn)

How many substrings & subsequences does banana have?

(Two substrings are different if they have different start/end index)

String Operations (串的运算)

- **Concatenation (连接)**: the concatenation of two strings x and y, denoted xy, is the string formed by appending y to x
  - x = dog, y = house, xy = doghouse

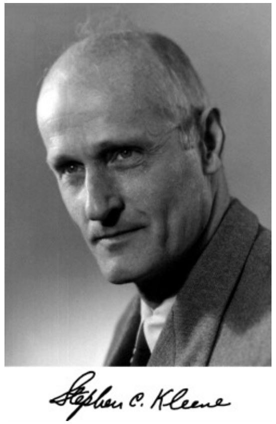
- **Exponentiation (幂/指数运算):** $s^0 = \epsilon$, $s^1 = s$, $s^i = s^{i-1}s$
  - x = dog, $x^0 = \epsilon$, x^1 = dog, x^3 = dogdogdog

Language (语言)

- A **language** is any **countable set**[1] of strings over some fixed alphabet
  - The set containing only the empty string, that is $\{\epsilon\}$, is a language, denoted $\emptyset$
  - The set of all grammatically correct English sentences
  - The set of all syntactically well-formed C programs

[1] In mathematics, a countable set is a set with the same cardinality (number of elements) as some subset of the set of natural numbers. A countable set is either a finite set or a countably infinite set.

Operations on Languages (语言的运算)



- 并，连接，Kleene闭包，正闭包

OPERATION	DEFINITION AND NOTATION
Union of L and M	$L \cup M = \{s \mid s \text{ is in } L \text{ or } s \text{ is in } M\}$
Concatenation of L and M	$LM = \{st \mid s \text{ is in } L \text{ and } t \text{ is in } M\}$
Kleene closure of L	$L^* = \cup_{i=0}^{\infty} L^i$
Positive closure of L	$L^+ = \cup_{i=1}^{\infty} L^i$

The exponentiation of L can be defined using concatenation. L^n means concatenating L n times.

https://en.wikipedia.org/wiki/Stephen_Cole_Kleene

Examples

- L = {A, B, …, Z, a, b, …, z} 52 English letters
- D = {0, 1, …, 9} 10 digits

$L \cup D$	{A, B, …, Z, a, b, …, z, 0, 1, …,9}
LD	the set of 520 strings of length two, each consisting of one letter followed by one digit
L^4	the set of all 4-letter strings
L^*	the set of all strings of letters, including ϵ
$L(L \cup D)^*$	?
D^+	?

Note: L, D might seem to be the alphabets of letters and digits. We define them to be languages: all strings happen to be of length one.

Regular Expressions - For Describing Languages/Patterns

Rules that define regexps over an alphabet Σ:

- **BASIS**: two rules form the basis:
  - ϵ is a regexp, $L(\epsilon) = \{\epsilon\}$
  - If a is a symbol in Σ, then a is a regexp, and $L(a) = \{a\}$
- **INDUCTION:** Suppose r and s are regexps denoting the languages $L(r)$ and $L(s)$
  - $(r)|(s)$ is a regexp denoting the language $L(r) \cup L(s)$
  - $(r)(s)$ is a regexp denoting the language $L(r)L(s)$
  - $(r)^*$ is a regexp denoting $(L(r))^*$
  - (r) is a regexp denoting $L(r)$, that is, additional parentheses do not change the language an expression denotes.

Regular Expressions Cont.

- Following the rules, regexps often contain unnecessary pairs of parentheses. We may drop some if we adopt the conventions:
  - **Precedence (优先级):** closure * > concatenation > union |
  - **Associativity (结合性):** All three operators are left associative, meaning that operations are grouped from the left.
    - For example, a | b | c would be interpreted as (a | b) | c
- Example: $(a) \mid ((b)^{*}(c))$ can be simplified as $a \mid b^{*}c$

Regular Expressions Examples

- Let $\Sigma = \{a, b\}$
  - a|b denotes the language {a, b}
  - (a|b)(a|b) denotes {aa, ab, ba, bb}
  - a^* denotes $\{\epsilon$, a, aa, aaa, …}
  - $(a|b)^*$ denotes the set of all strings consisting of 0 or more *a*'s or *b*'s: $\{\epsilon$, a, b, aa, ab, ba, bb, aaa, …}
  - $a|a^*b$ denotes the string *a* and all strings consisting of 0 or more *a*'s and ending in *b*: {a, b, ab, aab, aaab, …}

Regular Language (正则语言)

- A **regular language** is a language that can be defined by a regexp
- If two regexps r and s denote the same language, they are *equivalent*, written as $r = s$

(a | b)(a | b)

=

aa | ab | ba | bb

?

Algebraic Laws

- Each law below asserts that expressions of two different forms are equivalent

LAW	DESCRIPTION
$r \mid s = s \mid r$	$\mid$ is commutative
$r \mid (s \mid t) = (r \mid s) \mid t$	$\mid$ is associative
$r(st) = (rs)t$	Concatenation is associative
$r(s \mid t) = rs \mid rt;\ (s \mid t)r = sr \mid tr$	Concatenation distributes over $\mid$
$\epsilon r = r\epsilon = r$	ϵ is the identity for concatenation
$r^* = (r \mid \epsilon)^*$	ϵ is guaranteed in a closure
$r^{**} = r^*$	$*$ is idempotent

| can be viewed as + in arithmetics, concatenation can be viewed as ×, * can be viewed as the power operator.

Regular Definitions (正则定义)

- For notational convenience, we can give names to certain regexps and use those names in subsequent expressions

If Σ is an alphabet of basic symbols, then a ***regular definition*** is a sequence of definitions of the form:

$$d_1 \rightarrow r_1$$
$$d_2 \rightarrow r_2$$
$$\ldots$$
$$d_n \rightarrow r_n$$

where:

- Each d_i is a new symbol not in Σ and not the same as the other d's
- Each r_i is a regexp over the alphabet $\Sigma \cup \{d_1, d_2, \ldots, d_{i-1}\}$

Each new symbol denotes a regular language. The second rule means that you may reuse previously-defined symbols.

Examples

- Regular definition for C identifiers

$$\begin{array}{rcl} letter\_ & \rightarrow & \mathtt{A} \mid \mathtt{B} \mid \cdots \mid \mathtt{Z} \mid \mathtt{a} \mid \mathtt{b} \mid \cdots \mid \mathtt{z} \mid \_ \\ digit & \rightarrow & \mathtt{0} \mid \mathtt{1} \mid \cdots \mid \mathtt{9} \\ id & \rightarrow & letter\_\ (\ letter\_ \mid digit\ )^* \end{array}$$

`_hello` valid?

`3times` valid?

- Regexp for C identifiers

```
(A|B|...|Z|a|b|...|z|_)((A|B|...|Z|a|b|...|z|_)|(0|1|
...|9))*
```

Extensions of Regular Expressions

- **Basic operators:** union |, concatenation, and Kleene closure * (proposed by Kleene in 1950s)
- A few **notational extensions**:
  - One or more instances: the unary, postfix operator $^+$
    - $r^+ = rr^*$, $r^* = r^+ \mid \epsilon$
  - Zero or one instance: the unary postfix operator ?
    - $r? = r \mid \epsilon$
  - Character classes: shorthand for a logical sequence
    - $[a_1a_2\ldots a_n] = a_1 \mid a_2 \mid \ldots \mid a_n$
    - $[a\text{-}e] = a \mid b \mid c \mid d \mid e$
- The extensions are only for notational convenience, they do not change the descriptive power of regexps

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- The Role of Lexers: Recognizing Tokens
- Regular Expressions (for specifying tokens)
- Finite Automata (for recognizing patterns)

  - NFA & DFA
  - NFA → DFA
  - Regexp → NFA
  - Combining NFAs

Finite Automata (有穷自动机)

- Finite automata are the simplest machines to recognize patterns
- They take a string as input and output "yes" (pattern is matched) or "no" (pattern is unmatched).
  - **Nondeterministic finite automata (NFA, 非确定有穷自动机):** A symbol can label several edges out of the same state (allowing multiple target states), and the empty string ϵ is a possible label.
  - **Deterministic finite automata (DFA, 确定有穷自动机):** For each state and for each symbol in the input alphabet, there is exactly one edge with that symbol leaving that state.
- NFA and DFA recognize the same languages, **regular languages**, which regexps can describe.

Nondeterministic Finite Automata

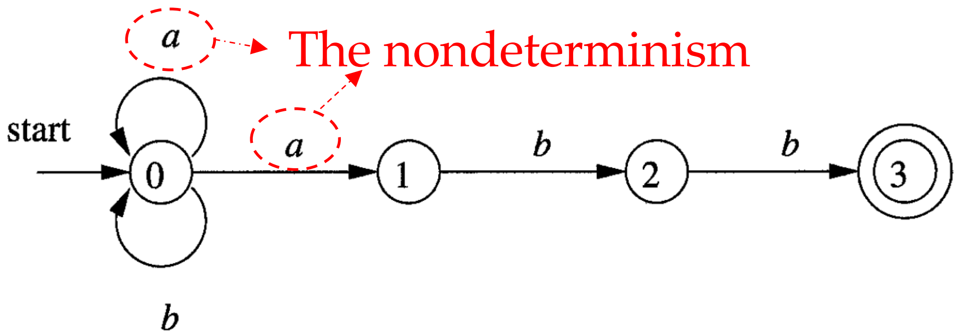
- An **NFA** is a 5-tuple, consisting of:

  1. A finite set of states S
  2. A set of input symbols Σ, the *input alphabet*. We assume that the empty string ϵ is never a member of Σ
  3. A *transition function* that gives, for each state, and for each symbol in $\Sigma \cup \{\epsilon\}$ a set of *next states*
  4. A *start state* (or initial state) s_0 from S
  5. A set of *accepting states* (or *final states*) F, a subset of S

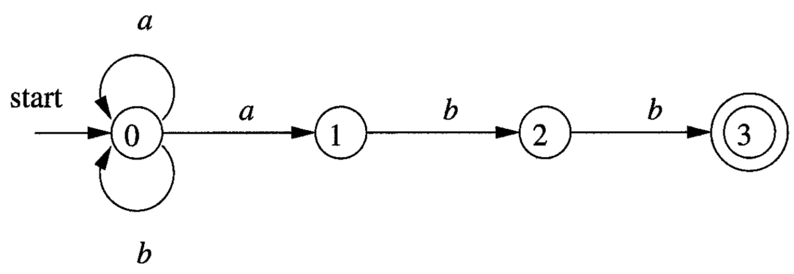
NFA Example

- S = {0, 1, 2, 3}
- Σ = {a, b}
- Start state: 0
- Accepting states: {3}
- Transition function
  - (0, a) → {0, 1}   (0, b) → {0}
  - (1, b) → {2}   (2, b) → {3}

The NFA can be represented as a Transition Graph:



Transition Table

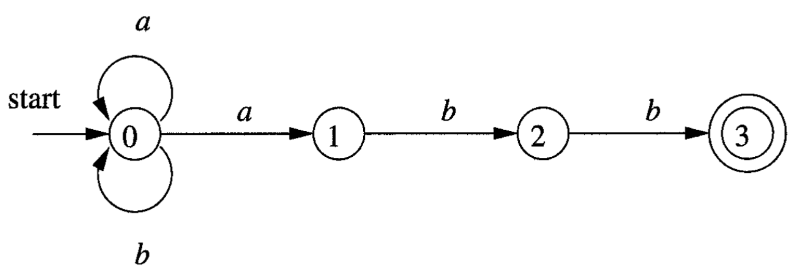


- Another representation of an NFA
  - Rows correspond to states
  - Columns correspond to the input symbols or ϵ
  - The table entry for a state-input pair lists the set of next states
  - $\emptyset$: the transition function has no information about the state-input pair (the move is not allowed)

STATE	a	b	ϵ
0	$\{0, 1\}$	$\{0\}$	$\emptyset$
1	$\emptyset$	$\{2\}$	$\emptyset$
2	$\emptyset$	$\{3\}$	$\emptyset$
3	$\emptyset$	$\emptyset$	$\emptyset$

Acceptance of Input Strings

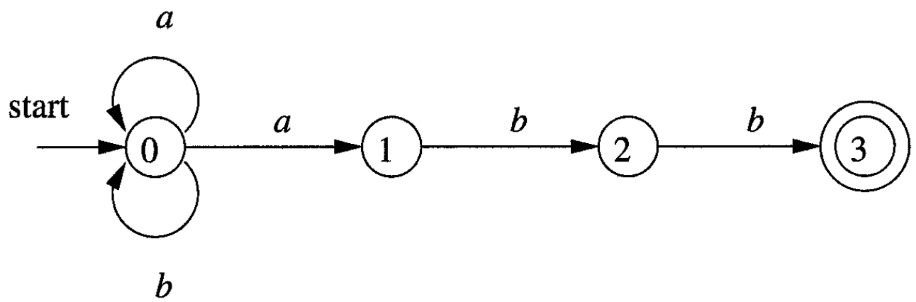
- An NFA accepts an input string x if and only if
  - There is a path in the transition graph from the start state to one accepting state, such that the symbols along the path form x (ϵ labels are ignored).



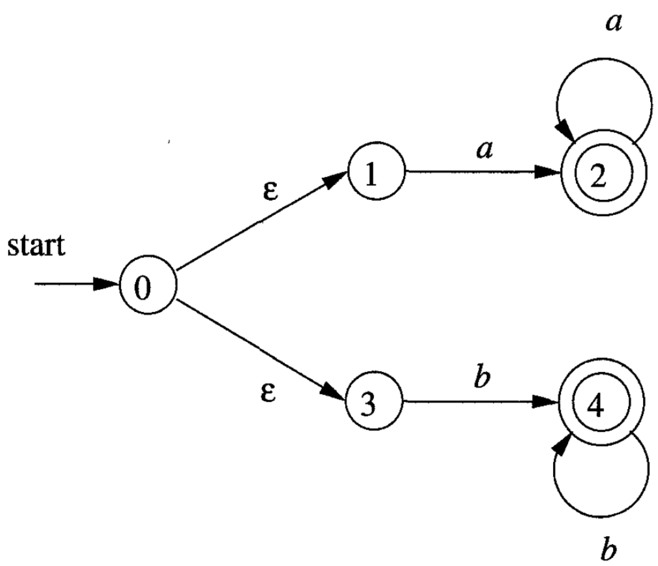
accepts the string *aabb*

- The language defined or accepted by an NFA
  - The set of strings labelling some path from the start state to an accepting state

NFA and Regular Languages



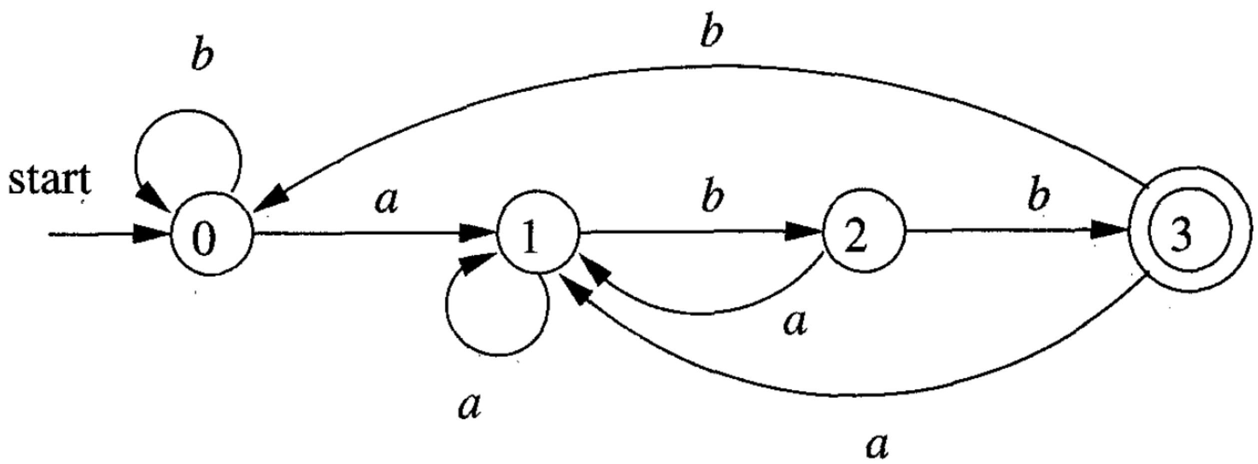
$L((a \mid b)^* abb)$



$L(aa^* \mid bb^*)$

Deterministic Finite Automata (DFA)

- A **<u>DFA</u>** is a special NFA where:
  - There are no moves on input ϵ
  - For each state s and input symbol a, there is exactly one edge out of s labeled a (i.e., exactly one target state)



Simulating a DFA

- **Input:**
  - String x terminated by an end-of-file character **eof**.
  - DFA D with *start state* s_0, *accepting states* F, and transition function *move*
- **Output:** Answer "yes" if D accepts x; "no" otherwise

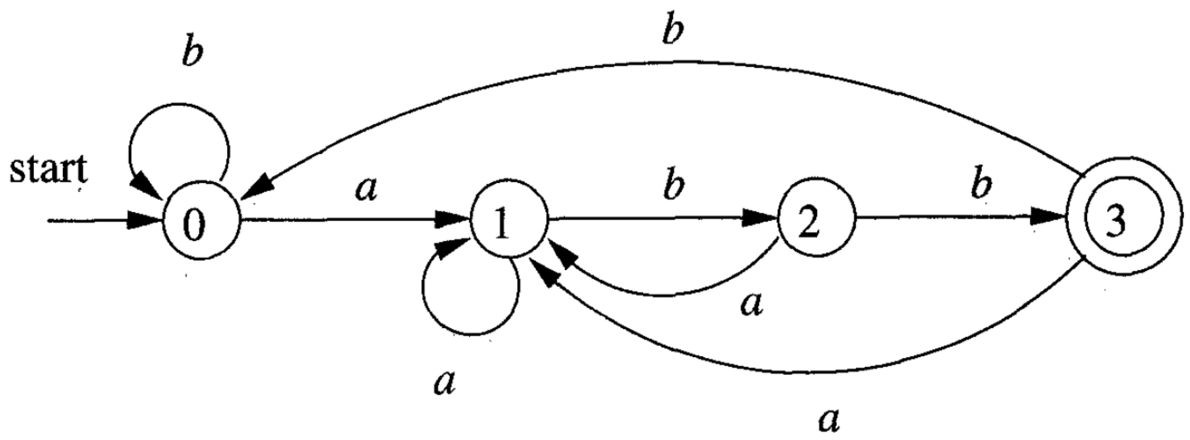
```
s = s0;
c = nextChar();
while ( c != eof ) {
        s = move(s, c);
        c = nextChar();
}
if ( s is in F ) return "yes";
else return "no";
```

We can see from the algorithm:

- DFA can efficiently accept/reject strings (i.e., recognize patterns)

DFA Example

- Given the input string *ababb*, the DFA below enters the sequence of states 0, 1, 2, 1, 2, 3 and returns "yes"



What's the language defined by this DFA?

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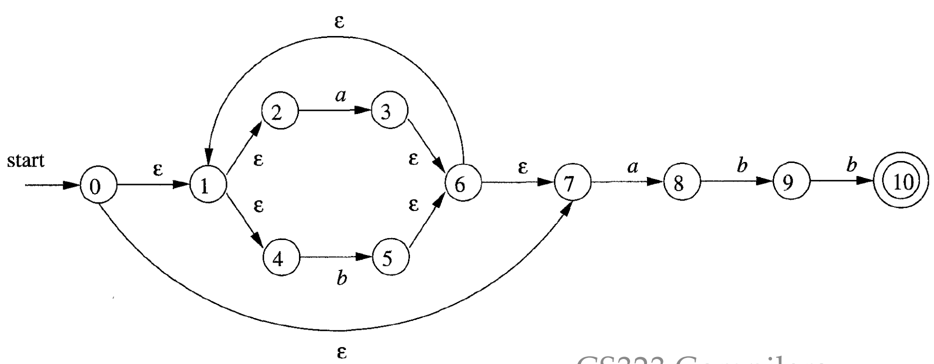
From Regular Expressions to Automata

- Regexps concisely & precisely describe the patterns of tokens
- DFA can efficiently recognize patterns (comparatively, the simulation of NFA is less straightforward*)
- When implementing lexical analyzers, regexps are often converted to DFA:
  - Regexp → NFA → DFA
  - Algorithms: Thompson's construction + subset construction

* There may be multiple transitions at a state when seeing a symbol

Conversion of an NFA to a DFA

- The <u>**subset construction**</u> algorithm (子集构造法)
  - **Insight:** Each state of the constructed DFA corresponds to a set of NFA states
    - Why? Because after reading the input $a_1a_2\ldots a_n$, the DFA reaches one state while the NFA may reach multiple states
  - **Basic idea:** The algorithm simulates "in parallel" all possible moves an NFA can make on a given input string to map a set of NFA states to a DFA state.

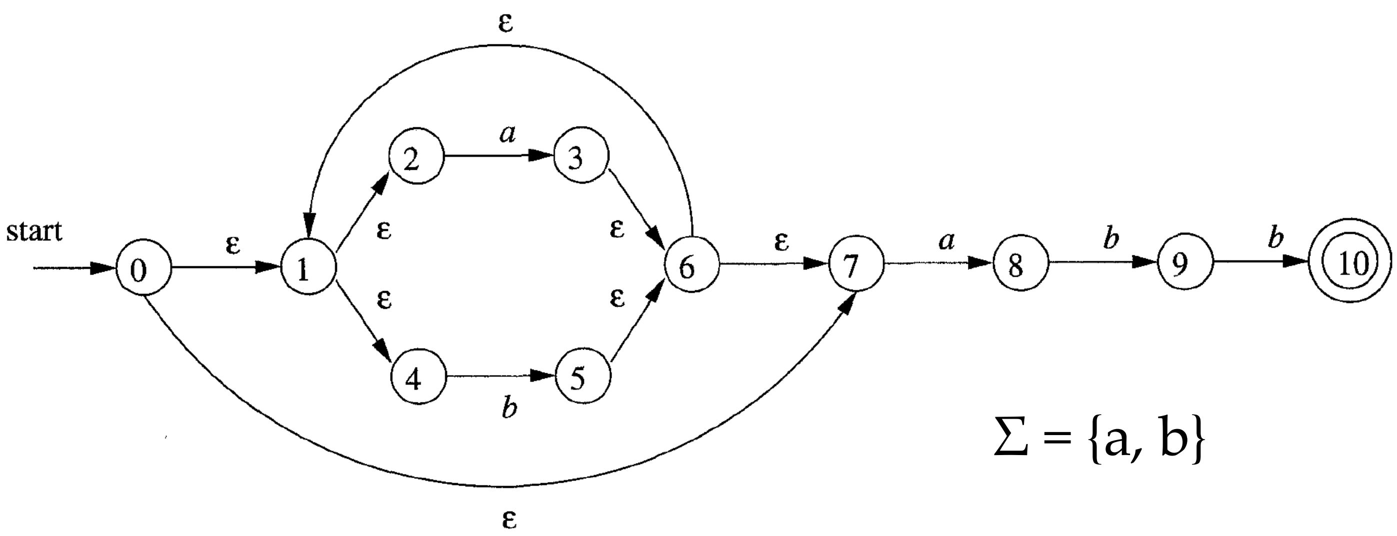


After reading "a", the NFA may reach any of these states:

3, 6, 1, 7, 2, 4, 8

Example for Algorithm Illustration

- The NFA below accepts the string *babb*
  - There exists a path from the start state 0 to the accepting state 10, on which the labels on the edges form the string *babb*



$\Sigma = \{a, b\}$

Subset Construction Technique

- Operations used in the algorithm:
  - ***ϵ-closure*(*s*):** Set of NFA states reachable from NFA state s on ϵ-transitions alone
  - ***ϵ-closure*(*T*):** Set of NFA states reachable from some NFA state s in set T on ϵ-transitions alone
    - That is, $\bigcup_{s\ in\ T} \epsilon\text{–}closure(s)$
  - ***move*(*T, a*):** Set of NFA states to which there is a transition on input symbol a from some state s in T (i.e., the target states of those states in T when seeing a)

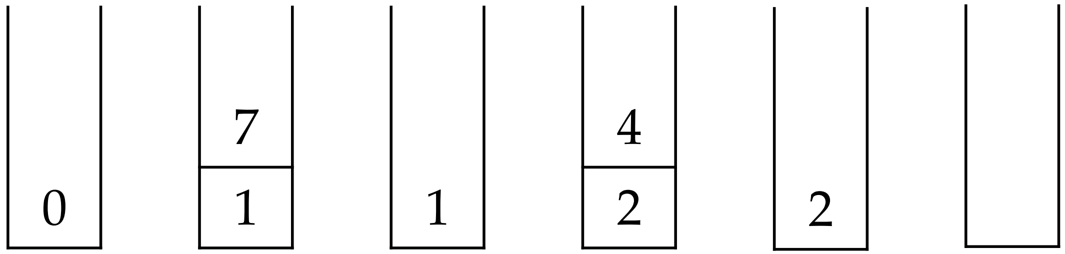
Subset Construction Technique

- **Computing ϵ-*closure*(*T*)**
  - It is a graph traversal process (only consider ϵ edges)
  - Computing ϵ-*closure*(s) is the same (when T has only one state)

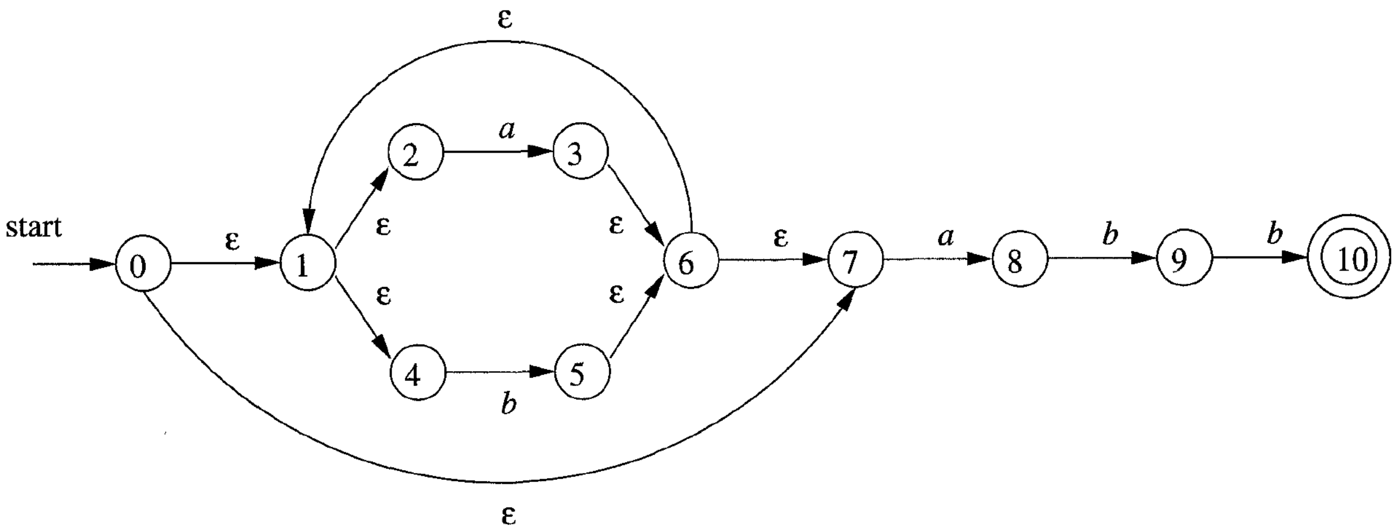
```
push all states of T onto stack;
initialize ϵ-closure(T) to T;
while ( stack is not empty ) {
        pop t, the top element, off stack;
        for ( each state u with an edge from t to u labeled ϵ )
                if ( u is not in ϵ-closure(T) ) {
                        add u to ϵ-closure(T);
                        push u onto stack;
                }
}
```

Illustrative Example

- ϵ-*closure*(0) = ?

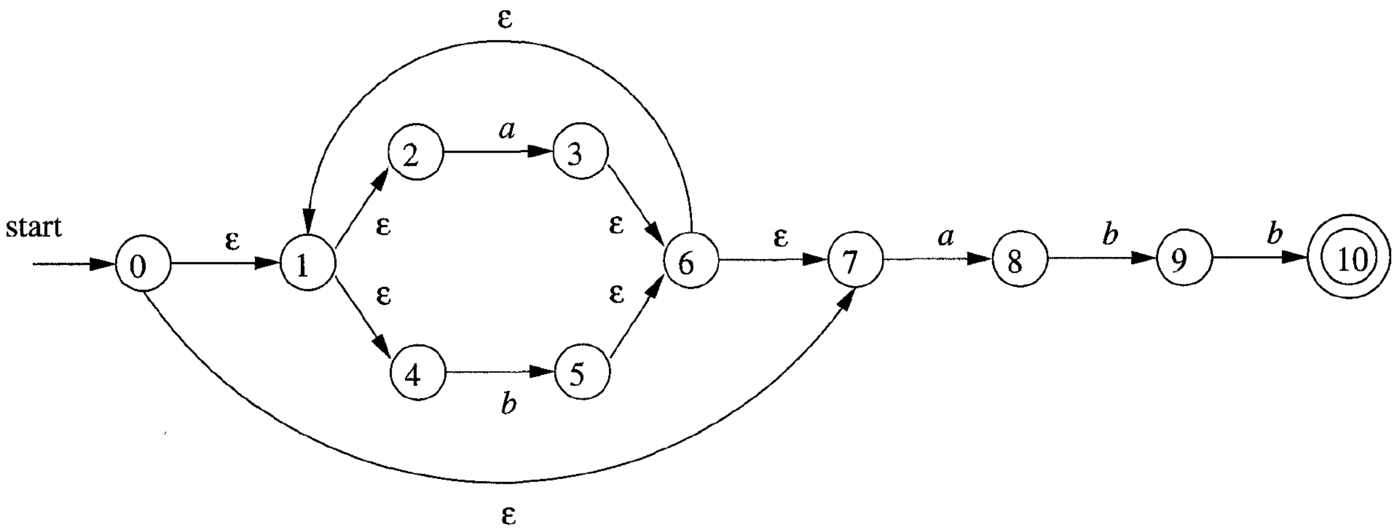


Push 0	Pop 0, Push 1, 7	Pop 7	Pop 1, Push 2, 4	Pop 4	Pop 2
{0}	{0, 1, 7}		{0, 1, 7, 2, 4}		



Exercise

- ϵ-*closure*({3, 8}) = ?



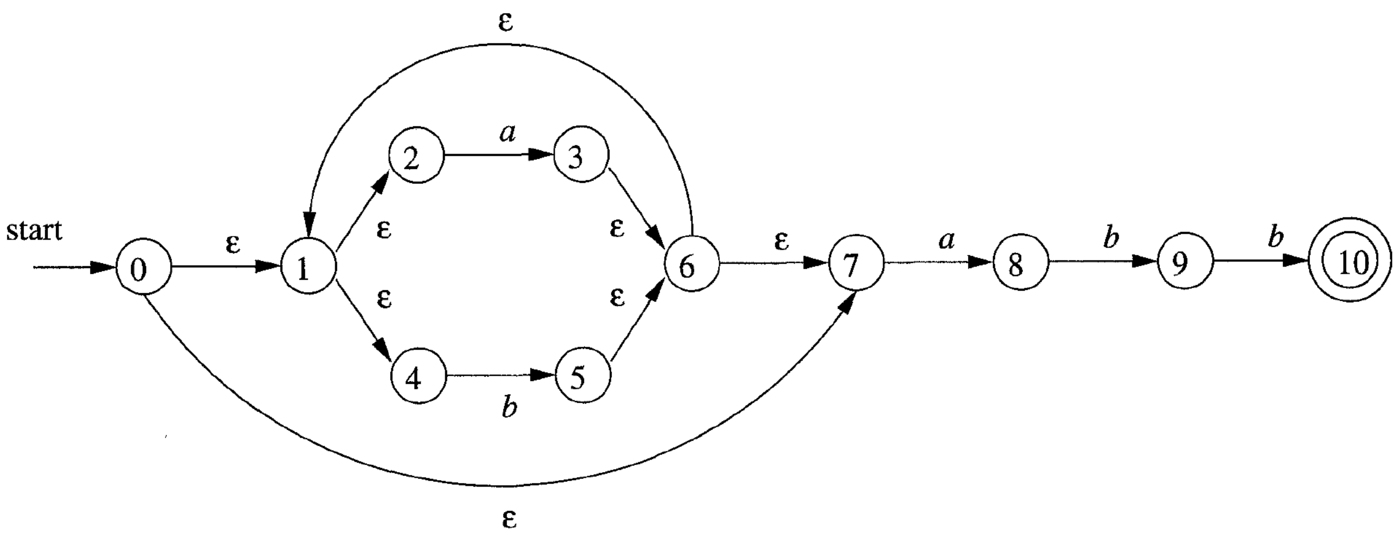
Subset Construction Technique Cont.

- The construction of the DFA *D*'s states, *Dstates*, and the transition function *Dtran* is also a search process
  - Initially, the only state in *Dstates* is ϵ-*closure*(s_0) and it is unmarked
    - Unmarked state means that its next states have not been explored

```
while ( there is an unmarked state T in Dstates ) {
        mark T;
        for ( each input symbol a ) {  // find the next states of T
                U = ε-closure(move(T, a));
                if ( U is not in Dstates )
                        add U as an unmarked state to Dstates;
                Dtran[T, a] = U;
        }
}
```

Illustrative Example

- Initially, Dstates only has one unmarked state:
  - ϵ-*closure*(0) = {0, 1, 2, 4, 7} -- A
- Dtran is empty



Illustrative Example

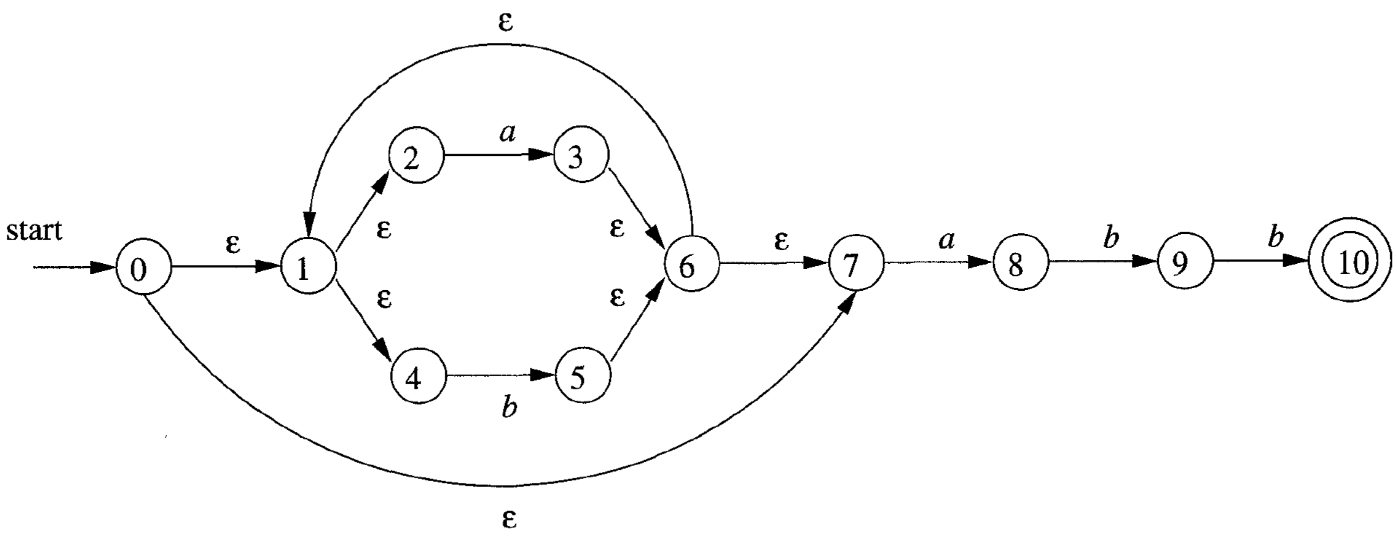
{0, 1, 2, 4, 7} -- A

ϵ-*closure*(*move*[A, a])

= ϵ-*closure*({3, 8})

= {1, 2, 3, 4, 6, 7, 8}

- We get an unseen state {1, 2, 3, 4, 6, 7, 8} -- B
- Update Dstates: {A, B}
- Update Dtran: {[A, a] ➔ B}



Illustrative Example

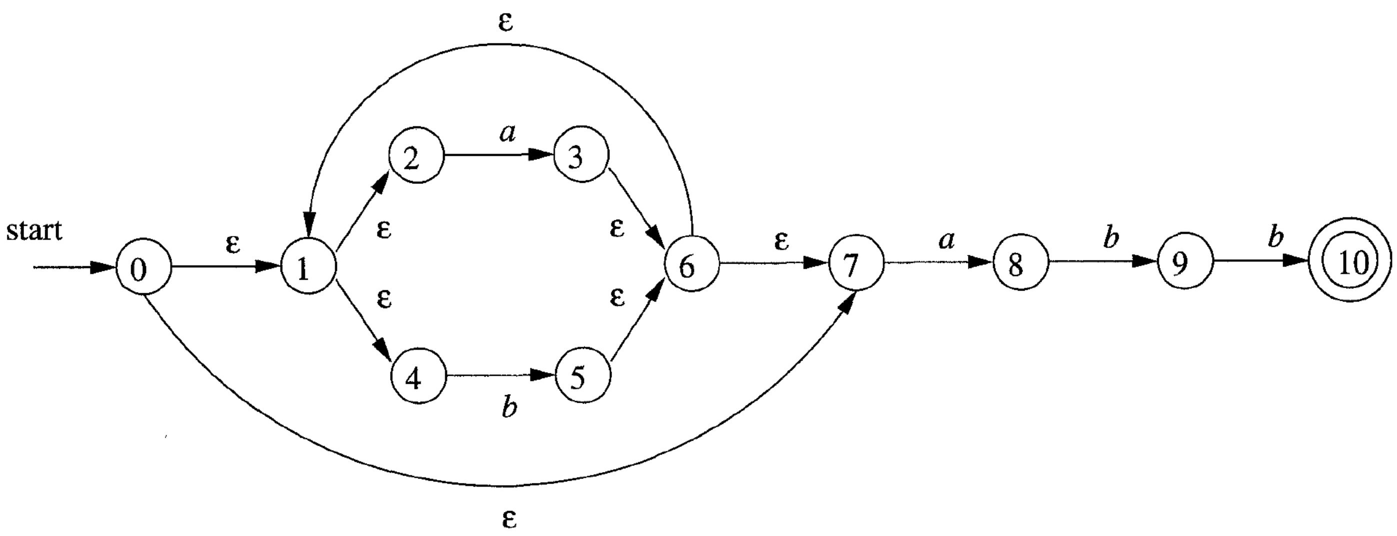
{0, 1, 2, 4, 7} -- A

ϵ-closure(*move*[A, b])

= *ϵ-closure*({5})

= {1, 2, 4, 5, 6, 7}

- We get an unseen state {1, 2, 4, 5, 6, 7} -- C
- Update Dstates: {A, B, C}
- Update Dtran: {[A, a] ➔ B, [A, b] ➔ C}



Illustrative Example

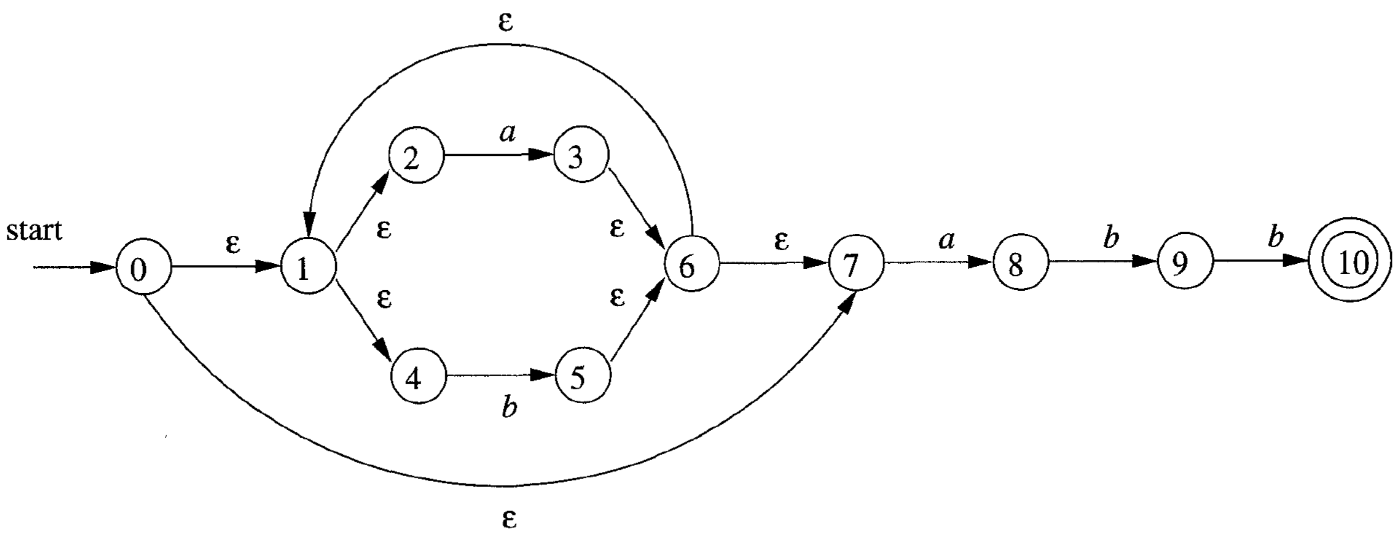
{1, 2, 3, 4, 6, 7, 8} -- B

ϵ-*closure*(*move*[B, a])

= ϵ-*closure*({3, 8})

= {1, 2, 3, 4, 6, 7, 8}

- The state {1, 2, 3, 4, 6, 7, 8} already exists (B)
- No need to update Dstates: {A, B, C}
- Update Dtran: {[A, a] ➔ B, [A, b] ➔ C, [B, a] ➔ B}



Illustrative Example

- Eventually, we will get the following DFA:
  - Start state: A; Accepting states: {E}

NFA State	DFA State	a	b
$\{0, 1, 2, 4, 7\}$	A	B	C
$\{1, 2, 3, 4, 6, 7, 8\}$	B	B	D
$\{1, 2, 4, 5, 6, 7\}$	C	B	C
$\{1, 2, 4, 5, 6, 7, 9\}$	D	B	E
$\{1, 2, 4, 5, 6, 7, 10\}$	E	B	C

This DFA can be further minimized: A and C have the same moves on all symbols and can be merged.

Outline

- The Role of Lexers: Recognizing Tokens
- Regular Expressions (for specifying tokens)
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Regular Expression to NFA

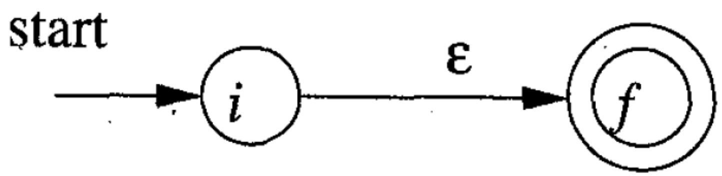
Thompson’s construction algorithm (Thompson构造法)

- The algorithm works recursively by splitting a regular expression into subexpressions, from which the NFA will be constructed using the following rules:
  - **Two basis rules (基本规则):** handle subexpressions with no operators
  - **Three inductive rules (归纳规则):** construct larger NFAs from the smaller NFAs for subexpressions

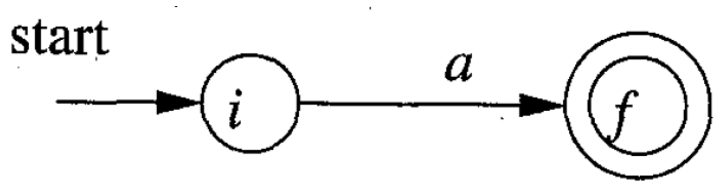
Thompson's Construction Algorithm

Two basis rules:

1. The empty expression ϵ is converted to



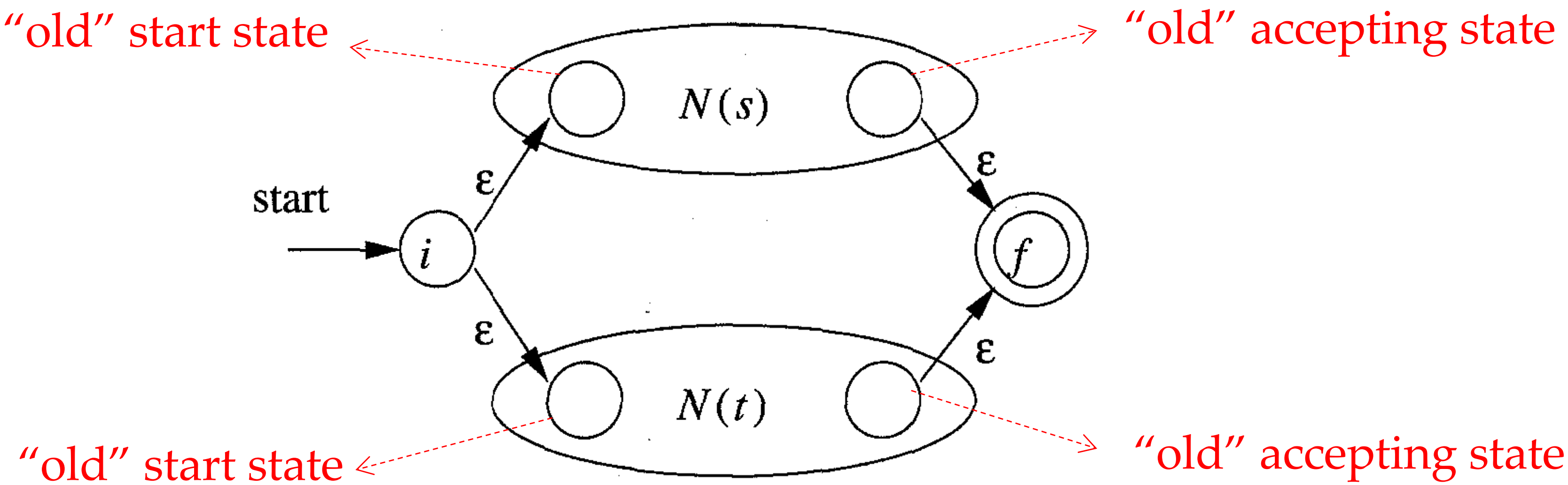
2. Any subexpression a (a single symbol in input alphabet) is converted to



Thompson's Construction Algorithm

The inductive rules: the union case

- ***s* | *t* :** $N(s)$ and $N(t)$ are NFAs for subexpressions s and t

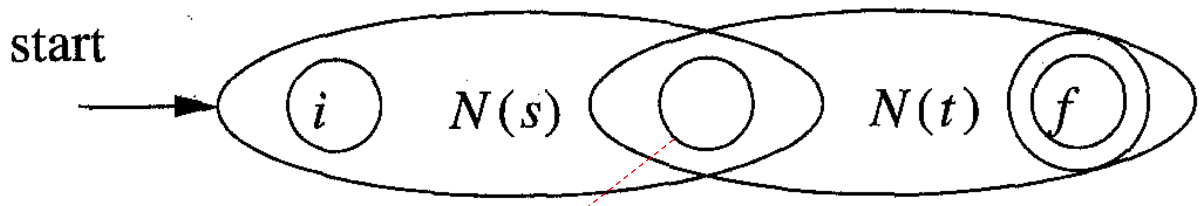


By construction, the NFAs have only one start state and one accepting state

Thompson's Construction Algorithm

The inductive rules: the concatenation case

- ***st*** **:** $N(s)$ and $N(t)$ are NFAs for subexpressions s and t

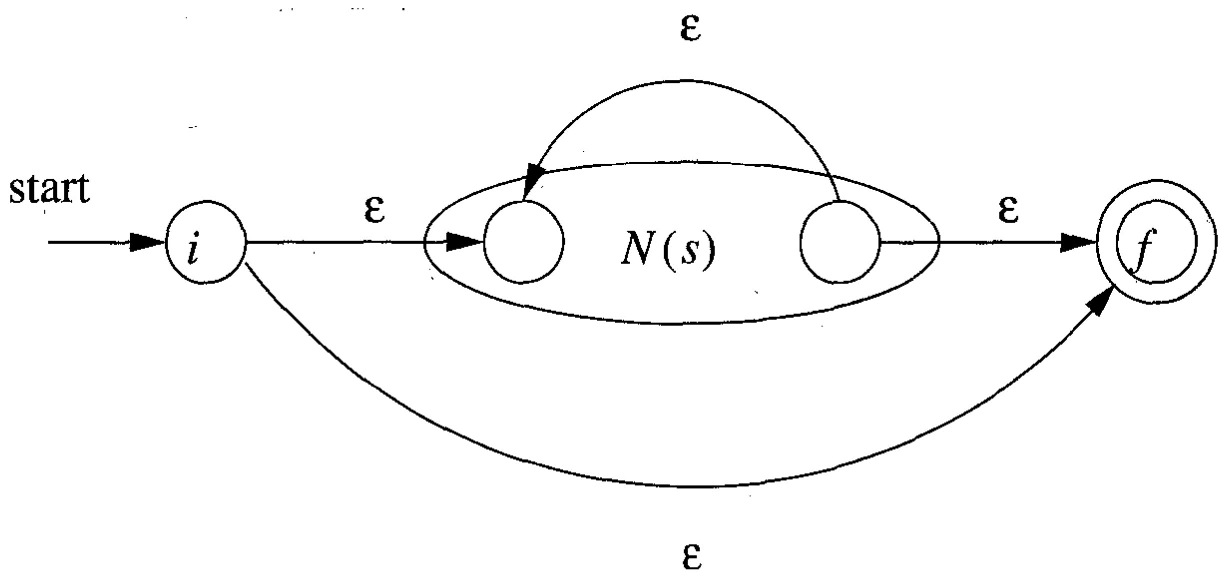


Merging the accepting state of $N(s)$ and the start state of $N(t)$

Thompson's Construction Algorithm

The inductive rules: the Kleene star case

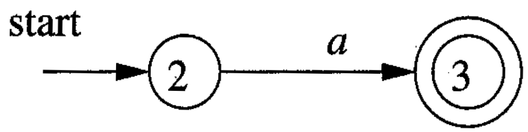
- s^* : $N(s)$ is the NFA for subexpression s



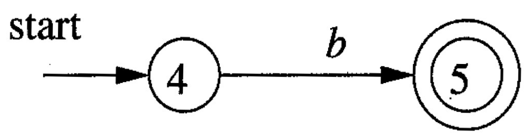
Example

Use Thompson's algorithm to construct an NFA for the regexp r = **(a | b)*a**

1. NFA for the first **a** (apply basis rule #1)

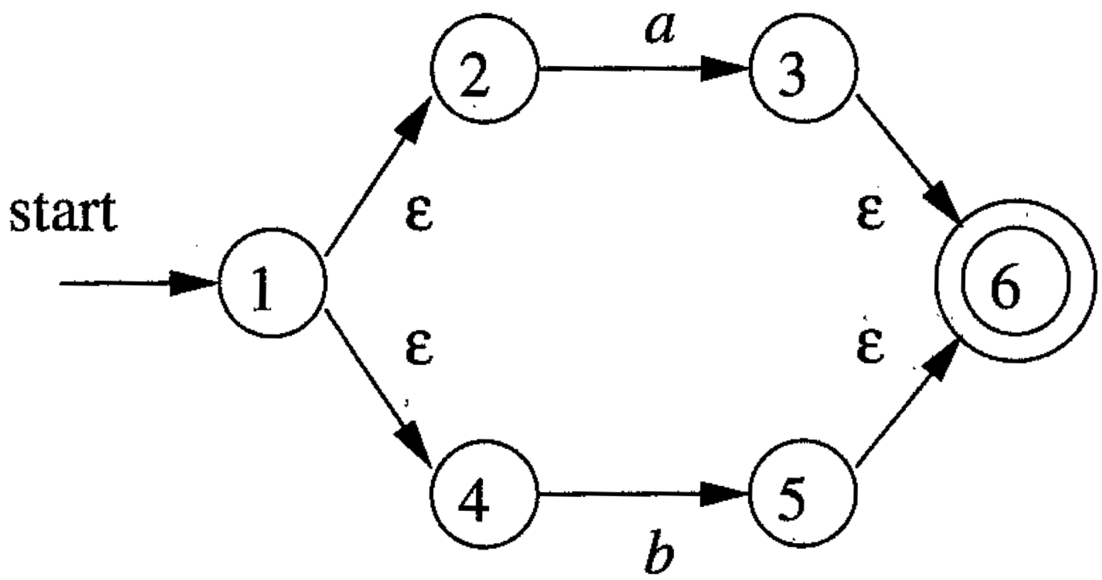


2. NFA for the first **b** (apply basis rule #1)



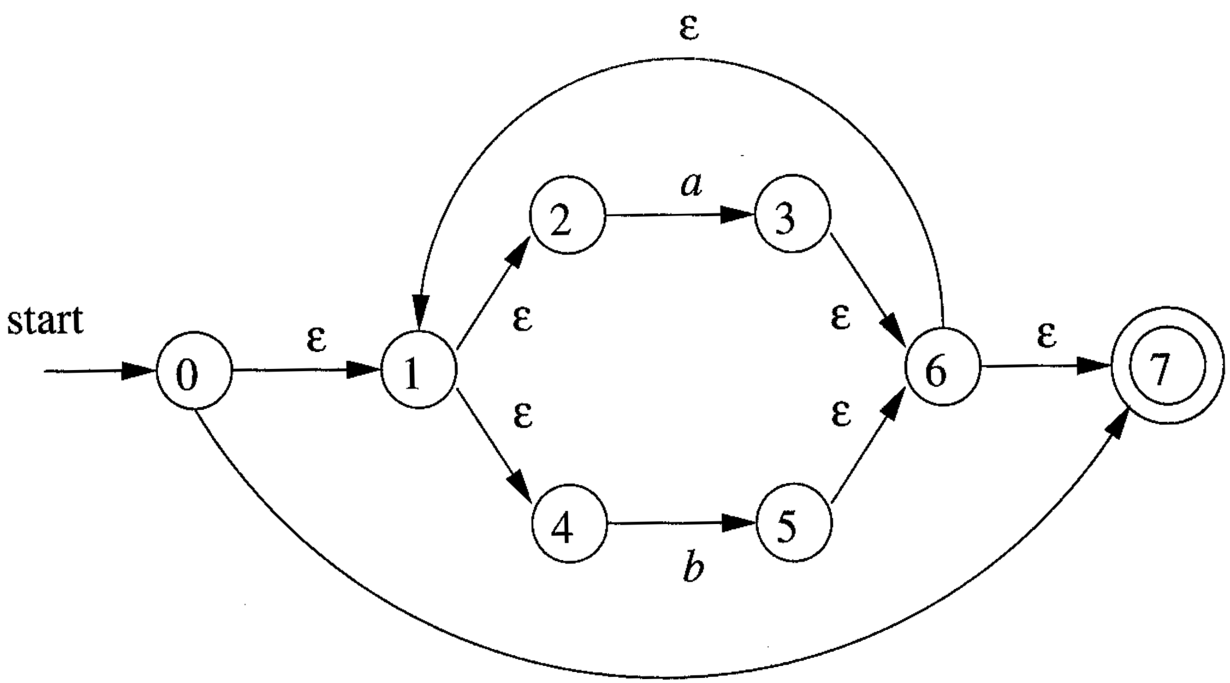
Example $r = (\mathbf{a}|\mathbf{b})^*\mathbf{a}$

3. NFA for **(a|b)** (apply inductive rule #1)



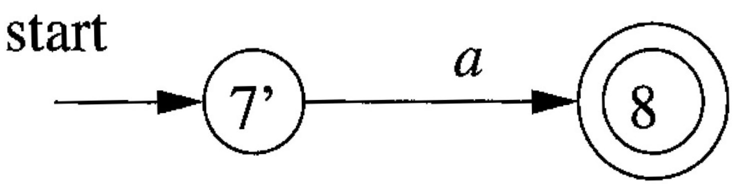
Example $r = (\mathbf{a} \mid \mathbf{b})^* \mathbf{a}$

4. NFA for $(\mathbf{a} \mid \mathbf{b})^*$ (apply inductive rule #3)



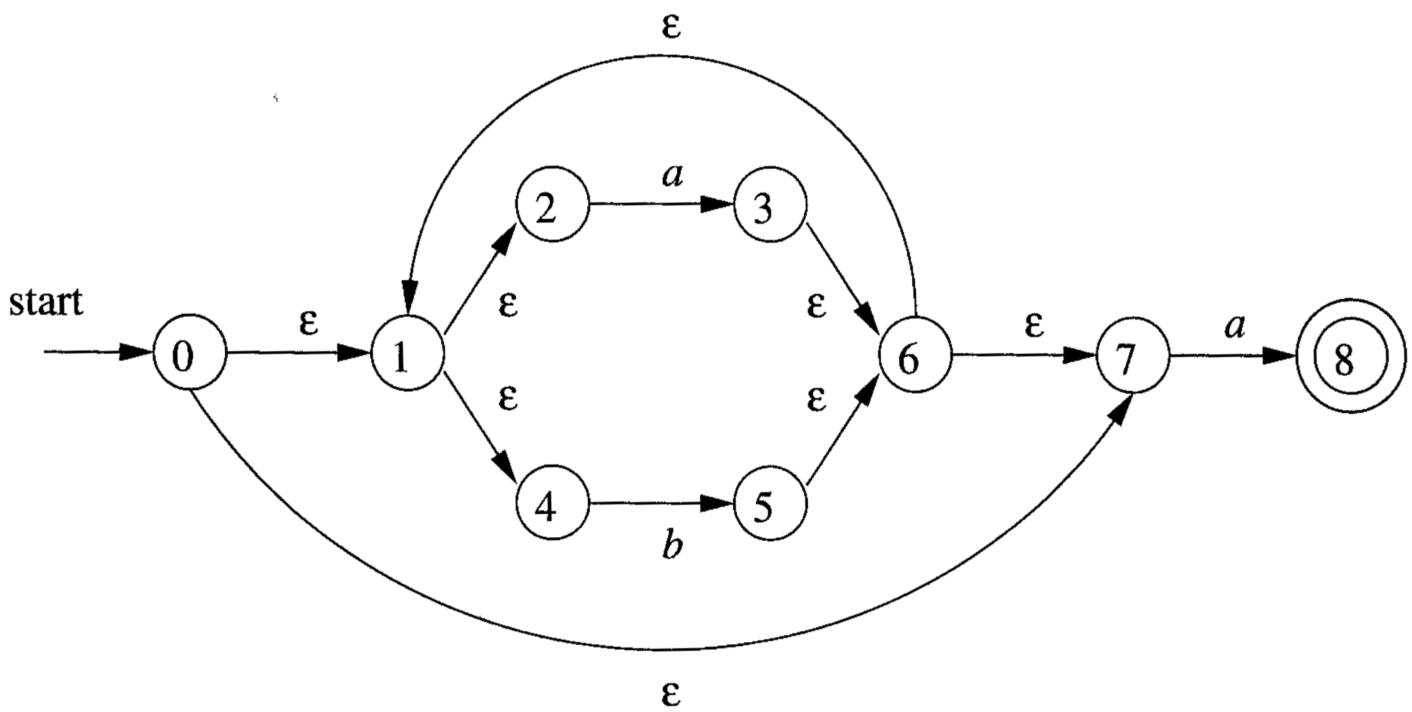
Example $r = (\mathbf{a} \mid \mathbf{b})^* \mathbf{a}$

5. NFA for the second **a** (apply basic rule #1)



Example r = $(a|b)^*a$

6. NFA for $(\mathbf{a}|\mathbf{b})^*\mathbf{a}$ (apply inductive rule #2)



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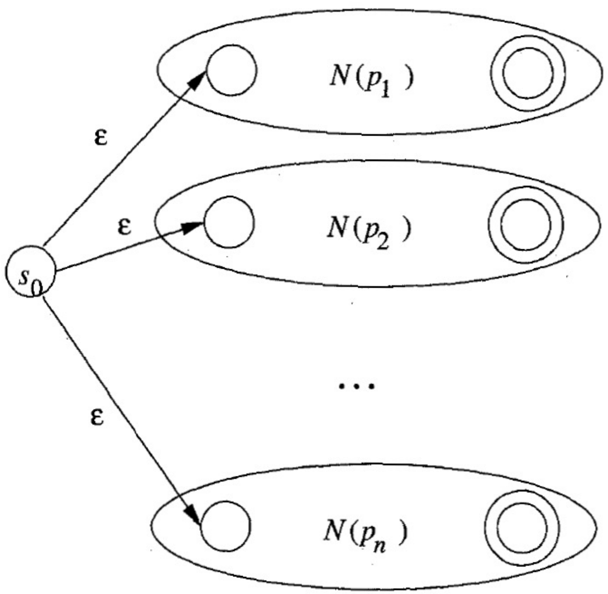
Combining NFAs

- **Why?** In the lexical analyzer, we need a single automaton to recognize lexemes matching any pattern
- **How?** Introduce a new start state with ϵ-transitions to each of the start states of the NFAs for pattern p_i



- The language that can be accepted by the big NFA is the union of the languages that can be accepted by the small NFAs
- Different accepting states correspond to different patterns

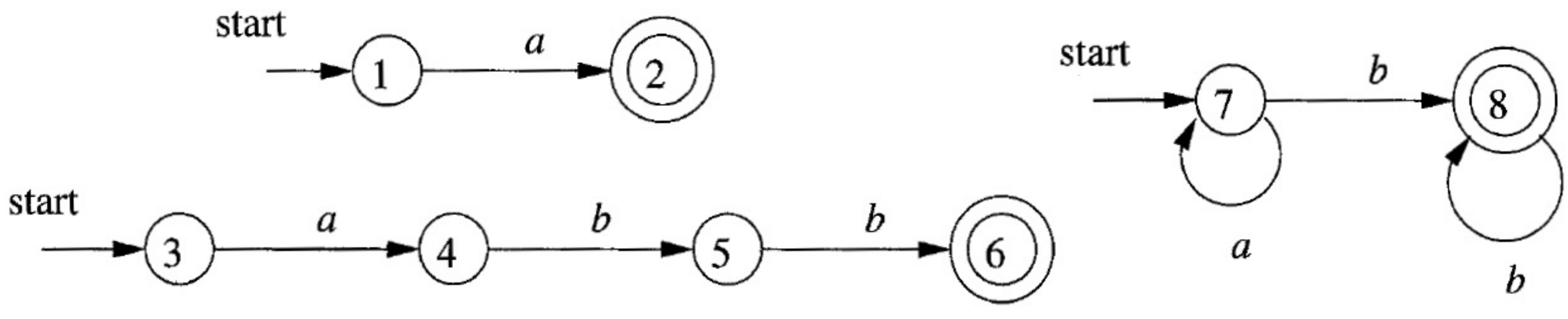
DFAs for Lexical Analyzers

- Convert the NFA for all the patterns into an equivalent DFA, using the subset construction algorithm

- An accepting state of the DFA corresponds to a subset of the NFA states, in which at least one is an accepting NFA state
  - If there are more than one accepting NFA state, this means that conflicts arise (the prefix of the input string matches multiple patterns)
  - Upon conflicts, find the first pattern whose accepting state is in the set and make that pattern the output of the DFA state

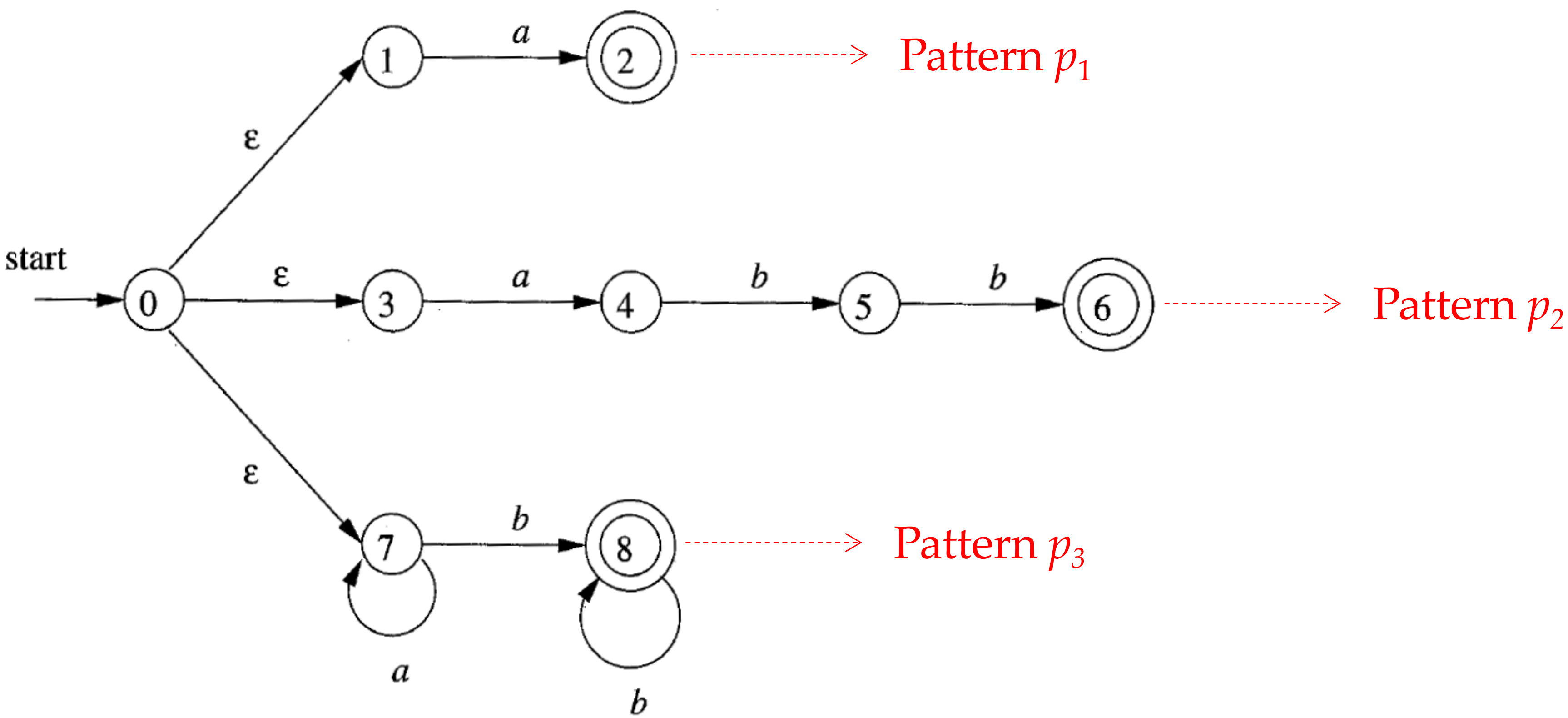
Example

- Suppose we have three patterns: p_1, p_2, and p_3
  - **a** {action A_1 for pattern p_1}
  - **abb** {action A_2 for pattern p_2}
  - $\mathbf{a^*b^+}$ {action A_3 for pattern p_3}
- We first construct an NFA for each pattern

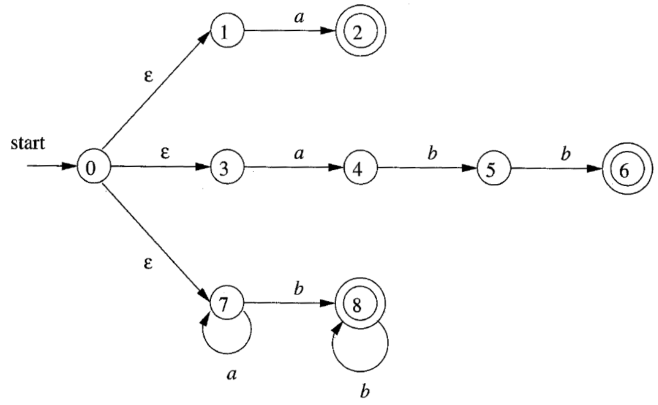


Example

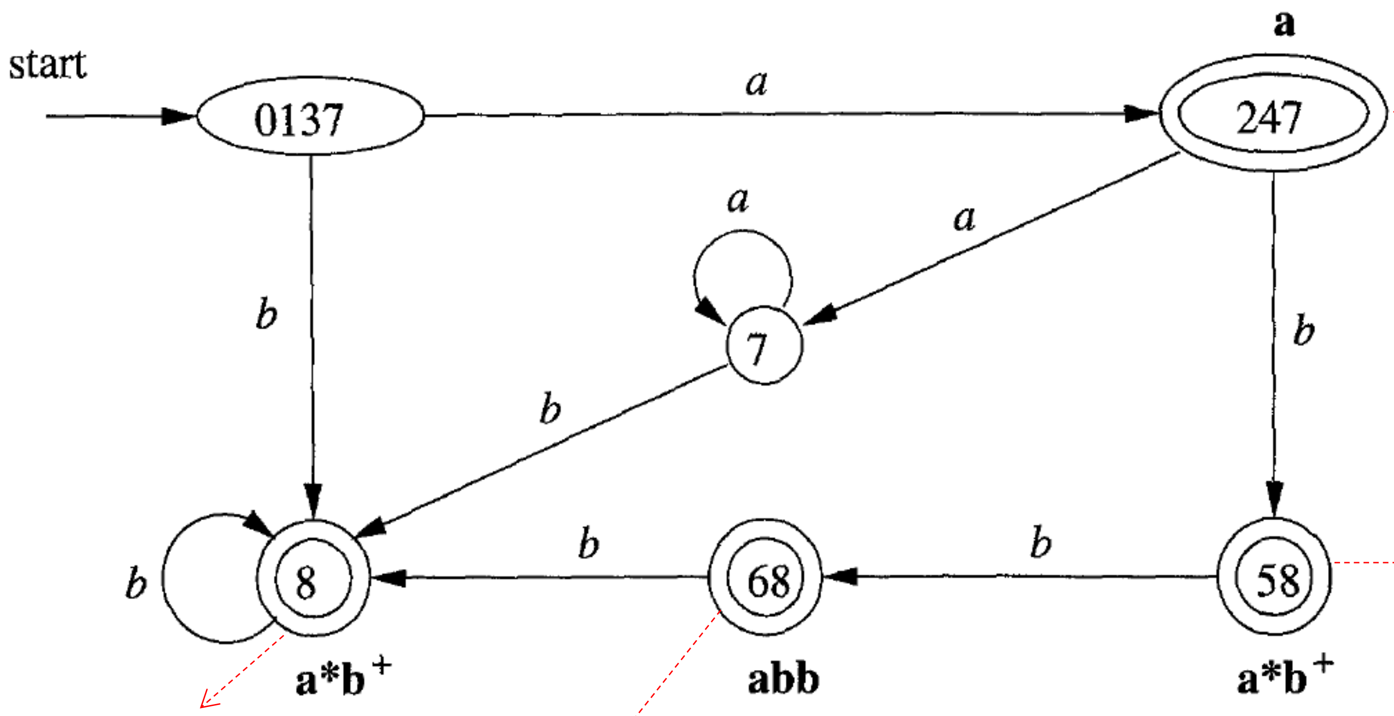
- Combining the three NFAs



Example



- Converting the big NFA to a DFA



Pattern p_1

Pattern p_3

Pattern p_3

6 and 8 are two accepting NFA states corresponding to two patterns. We choose Pattern p2, which is specified before p3

Reading Tasks

- Chapter 3 of the dragon book
  - 3.1 The role of the lexical analyzer
  - 3.3 Specification of tokens
  - 3.4 Recognition of tokens (lab content)
  - 3.5 The lexical-analyzer generator Lex (lab content)
  - 3.6 Finite automata
  - 3.7 From regular expressions to automata
  - 3.8 Design of a lexical analyzer generator
    - 3.8.1 – 3.8.3, the remaining can be skipped