Lexical Analysis

Outline

1. Scanning Tokens
2. Regular Expressions
3. Finite State Automata
4. Non-deterministic Versus Deterministic Finite State Automata
5. Regular Expressions to NFA
6. NFA to DFA
7. DFA to Minimal DFA
8. JavaCC

Scanning Tokens

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Example

HelloWorld.java

```
// Copyright 2012- Bill Campbell, Swami Iyer and Bahar Akbal-Delibas
//
// Writes to standard output the message "Hello, World".

import java.lang.System;

public class HelloWorld {
    // Entry point.
    public static void main(String[] args) {
        System.out.println("Hello, World");
    }
}
```

Tokens: `import, java, ., lang, ., System,;, public, class, HelloWorld, {, ..., ;, }, }`

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A scanner may be hand-crafted or generated from a specification consisting of regular expressions

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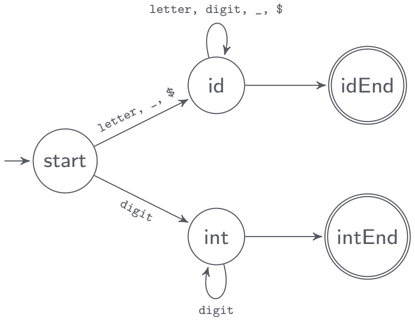
A state transition diagram for recognizing identifiers and integers



Scanning Tokens

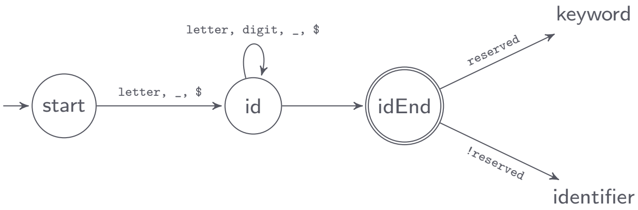
Scanning Tokens

Scanner.java

```java
    if (isLetter(ch) || ch == '_' || ch == '$') {
        buffer = new StringBuffer();
        do {
            buffer.append(ch);
            nextCh();
        } while (isLetter(ch) || isDigit(ch) || ch == '_' || ch == '$');
        return new TokenInfo(IDENTIFIER, buffer.toString(), line);
    } else if (isDigit(ch)){
        buffer = new StringBuffer();
        do {
            buffer.append(ch);
            nextCh();
        } while (isDigit(ch));
        return new TokenInfo(INT_LITERAL, buffer.toString(), line);
    }
```

Scanning Tokens

A state transition diagram for recognizing keywords



Scanning Tokens

Scanning Tokens

Scanner.java

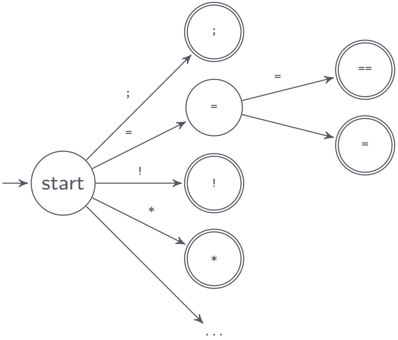
```
reserved = new Hashtable<String, Integer>();
reserved.put("abstract", ABSTRACT);
reserved.put("boolean", BOOLEAN);
reserved.put("char", CHAR);
...
reserved.put("while", WHILE);

...

if (isLetter(ch) || ch == '_' || ch == '$') {
    buffer = new StringBuffer();
    do {
        buffer.append(ch);
        nextCh();
    } while (isLetter(ch) || isDigit(ch) || ch == '_' || ch == '$');
    String identifier = buffer.toString();
    if (reserved.containsKey(identifier)) {
        return new TokenInfo(reserved.get(identifier), line);
    } else {
        return new TokenInfo(IDENTIFIER, identifier, line);
    }
}
```

Scanning Tokens

A state transition diagram for recognizing separators and operators



Scanning Tokens

Scanning Tokens

Scanner.java

```
switch (ch) {
    case ';':
        nextCh();
        return new TokenInfo(SEMI, line);
    case '=':
        nextCh();
        if (ch == '=') {
            nextCh();
            return new TokenInfo(EQUAL, line);
        } else {
            return new TokenInfo(ASSIGN, line);
        }
    case '!':
        nextCh();
        return new TokenInfo(LNOT, line);
    case '*':
        nextCh();
        return new TokenInfo(STAR, line);
    ...
}
```

Scanning Tokens

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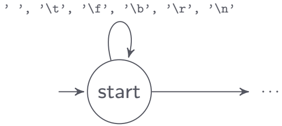
A state transition diagram for recognizing whitespace



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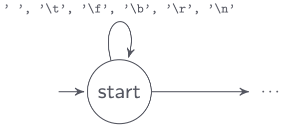
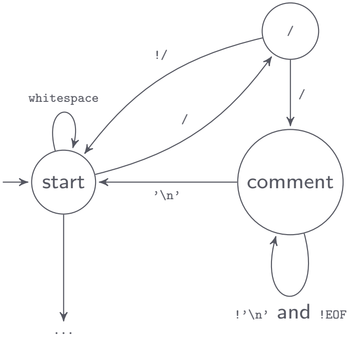


Scanner.java

```
while (isWhitespace(ch)) {
    nextCh();
}
```

Scanning Tokens

A state transition diagram for recognizing comments



Scanning Tokens

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Scanner.java

```
boolean moreWhiteSpace = true;
while (moreWhiteSpace) {
    while (isWhitespace(ch)) {
        nextCh();
    }
    if (ch == '/') {
        nextCh();
        if (ch == '/') {
            while (ch != '\n' && ch != EOFCH) {
                nextCh();
            }
        } else {
            reportScannerError("Operator / is not supported in j--.");
        }
    } else {
        moreWhiteSpace = false;
    }
}
```

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Both r and (r) describe the same language, ie, $L(r) = L((r))$

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5. M is a set of moves (aka transitions) of the form $m(r, a) = s$, where $r, s \in S$ and $a \in \Sigma$

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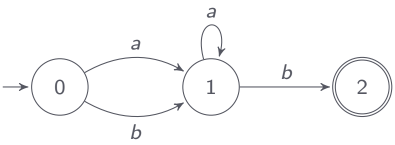

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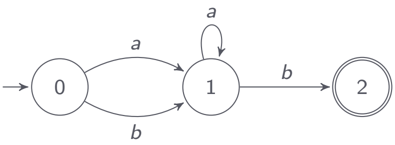

Formally, $F = (\Sigma, S, s_0, F, M)$, where $\Sigma = \{a, b\}$, $S = \{0, 1, 2\}$, $s_0 = 0$, $F = \{2\}$, and M is

r	a	$m(r, a)$
0	a	1
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A deterministic finite state automaton (DFA) is one in which:

- There are no ϵ-moves
- There is a unique move from any state r on an input symbol a, ie, if $m(r, a) = s$ and $m(r, a) = t$, then $s = t$

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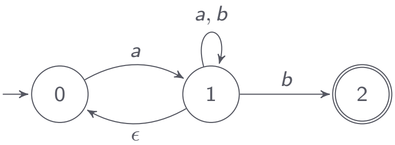
An NFA N that recognizes the language described by the regular expression



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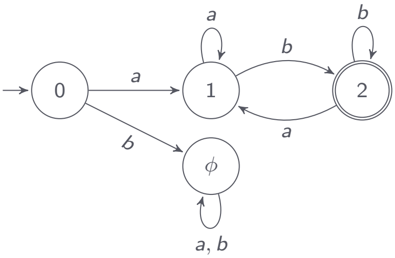
And a DFA D that recognizes the same language



$D = (\Sigma, S, s_0, F, M)$ where $\Sigma = \{a, b\}$, $S = \{0, 1, 2, \phi\}$, $s_0 = 0$, $F = \{2\}$, and M is

r	a	$m(r, a)$
0	a	1
0	b	ϕ
1	a	1
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2	b	2
ϕ	a, b	ϕ

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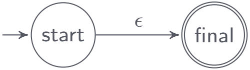

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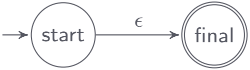
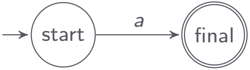


(Rule 2) NFA N_r for recognizing $L(r = a)$



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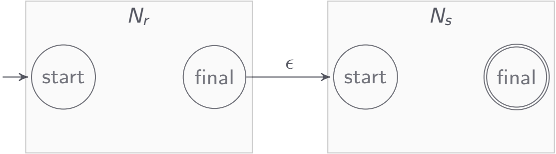
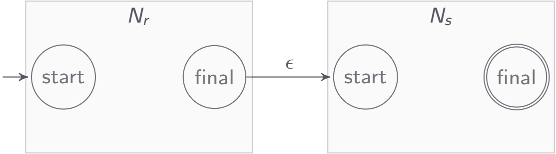
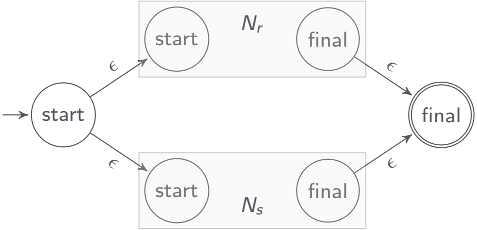


Regular Expressions to NFA

(Rule 3) NFA N_{rs} for recognizing $L(rs)$



(Rule 4) NFA $N_{r|s}$ for recognizing $L(r|s)$



Regular Expressions to NFA

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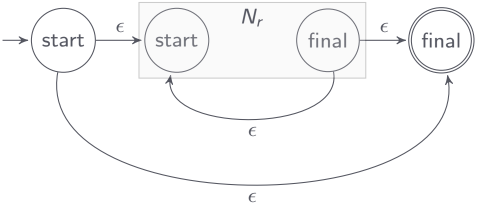
(Rule 5) NFA N_{r*} for recognizing $L(r*)$



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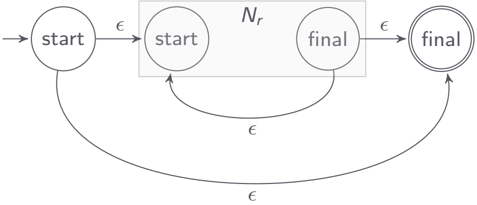

(Rule 6) NFA N_r for recognizing $L(r)$ also recognizes $L((r))$

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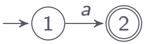

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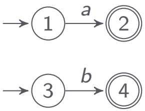

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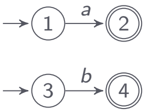

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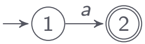

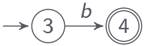

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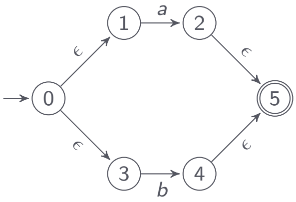

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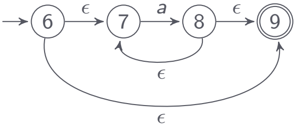

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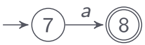

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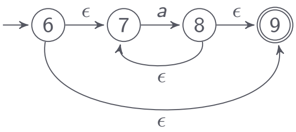

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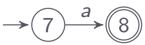

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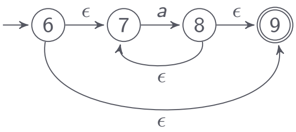

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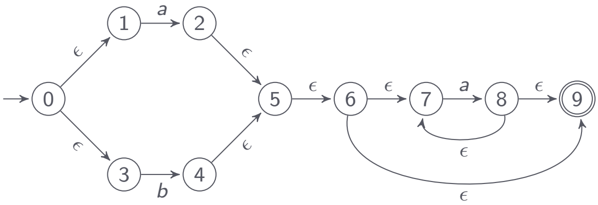

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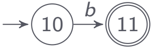

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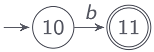

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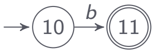

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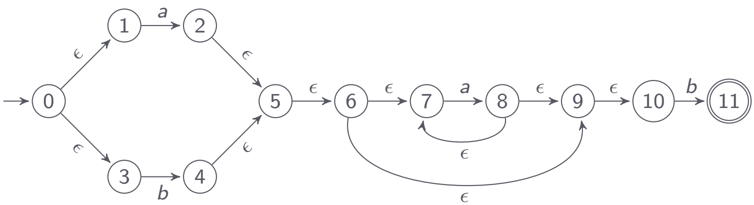

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The ϵ-closure(s) for a state s includes s and all states reachable from s using ϵ-moves alone, ie,
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The ϵ-closure(S) for a set of states S includes S and all states reachable from any state $s \in S$ using ϵ-moves alone

NFA to DFA

Algorithm ϵ-closure(S) for a set of states S

Input: a set of states S
Output: ϵ-closure(S)

```
P ← Stack(S)
C ← Set(S)
while not P.isEmpty() do
    r ← P.pop()
    for s ∈ m(r, ϵ) do
        if s ∉ C then
            P.push(s)
            C.add(s)
        end if
    end for
end while
return C
```

NFA to DFA

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Algorithm ϵ-closure(s) for a state s

Input: a state s

Output: ϵ-closure(s)

1: $S \leftarrow$ Set(s)

2: **return** ϵ-closure(S)

NFA to DFA

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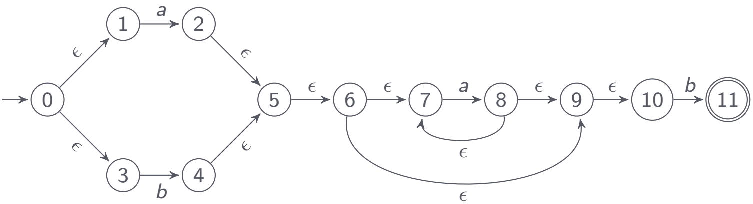
As an example, let's convert the NFA $N_{(a|b)a*b}$ to a DFA



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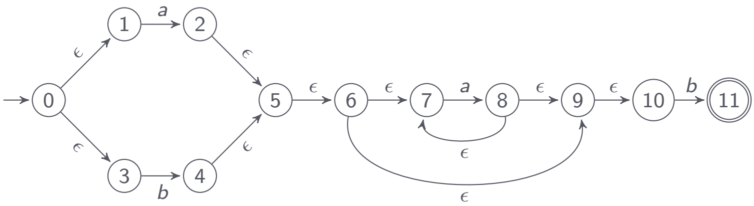
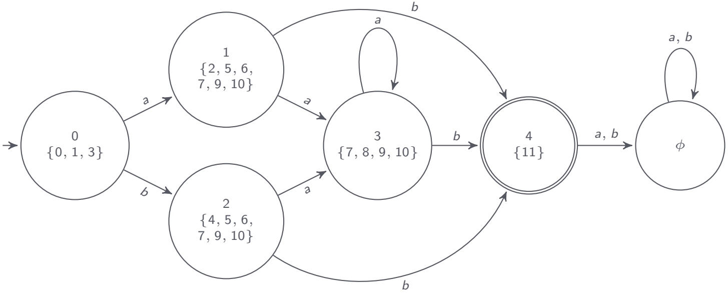


r	a	$m(r,a)$
$\{0,1,3\} = 0$ (start state)	a	$\{2,5,6,7,9,10\} = 1$
0	b	$\{4,5,6,7,9,10\} = 2$
1	a	$\{7,8,9,10\} = 3$
1	b	$\{11\} = 4$ (accept state)
2	a	3
2	b	4
3	a	3
3	b	4
4	a, b	ϕ
ϕ	a, b	ϕ

NFA to DFA

NFA to DFA

The DFA for recognizing $(a|b)a*b$



NFA to DFA

Algorithm NFA to DFA construction

Input: an NFA $N = (\Sigma, S, s_0, M, F)$
Output: an equivalent DFA $D = (\Sigma, S_D, s_{D0}, M_D, F_D)$

$s_{D0} \leftarrow \epsilon\text{-closure}(s_0)$
$S_D \leftarrow \text{Set}(s_{D0})$
$M_D \leftarrow Moves()$
$stk \leftarrow \text{Stack}(s_{D0})$
$i \leftarrow 0$
while not stk.isEmpty() **do**
    $r \leftarrow stk$.pop()
    for $a \in \Sigma$ **do**
        $s_{Di+1} \leftarrow \epsilon\text{-closure}(m(r, a))$
        if $s_{Di+1} \neq \{\}$ **then**
            if $s_{Di+1} \notin S_D$ **then**
                S_D.add(s_{Di+1})
                stk.push(s_{Di+1})
                $i \leftarrow i + 1$
                M_D.add($(r, a) \rightarrow s_{Di+1}$)
            else if $\exists s_j \in S_D$ such that $s_{Di+1} = s_j$ **then**
                M_D.add($(r, a) \rightarrow s_j$)
            end if
        end if
    end for
end while
$F_D \leftarrow \text{Set}()$
for $s_D \in S_D$ **do**
    for $s \in s_D$ **do**
        if $s \in F$ **then**
            F_D.add(s_D)
        end if
    end for
end for
return $D = (\Sigma, S_D, s_{D0}, M_D, F_D)$

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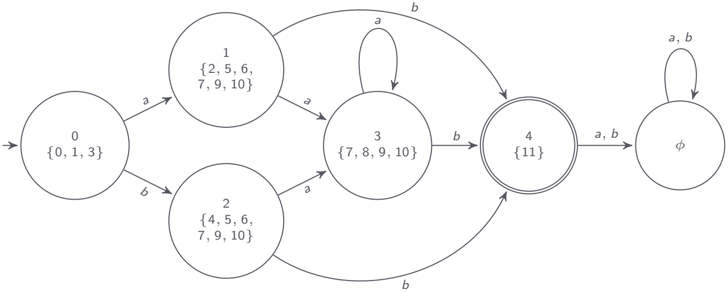

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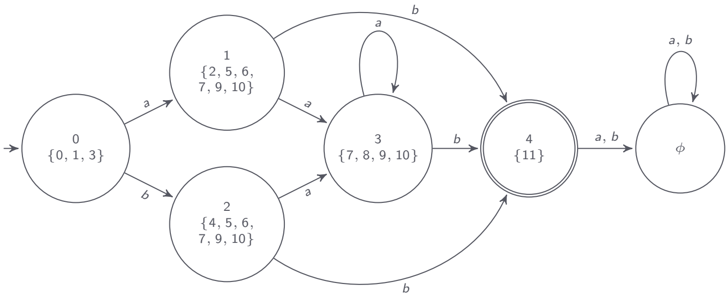

The initial partition contains the subsets $\{0, 1, 2, 3, \phi\}$ and $\{4\}$

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The symbol *a* does not split the subset $\{0, 1, 2, 3, \phi\}$, since

$$
\begin{aligned}
m(0, a) &= 1 \\
m(1, a) &= 3 \\
m(2, a) &= 3 \\
m(3, a) &= 3 \\
m(\phi, a) &= \phi
\end{aligned}
$$

DFA to Minimal DFA

Make sure that from a particular subset, on each input symbol, you transition into an identical subset; if not, split the subset

The symbol a does not split the subset $\{0, 1, 2, 3, \phi\}$, since

$$m(0, a) = 1$$
$$m(1, a) = 3$$
$$m(2, a) = 3$$
$$m(3, a) = 3$$
$$m(\phi, a) = \phi$$

The symbol b splits the subset $\{0, 1, 2, 3, \phi\}$ into subsets $\{0, \phi\}$ and $\{1, 2, 3\}$, since

$$m(0, b) = 2$$
$$m(1, b) = 4$$
$$m(2, b) = 4$$
$$m(3, b) = 4$$
$$m(\phi, b) = \phi$$

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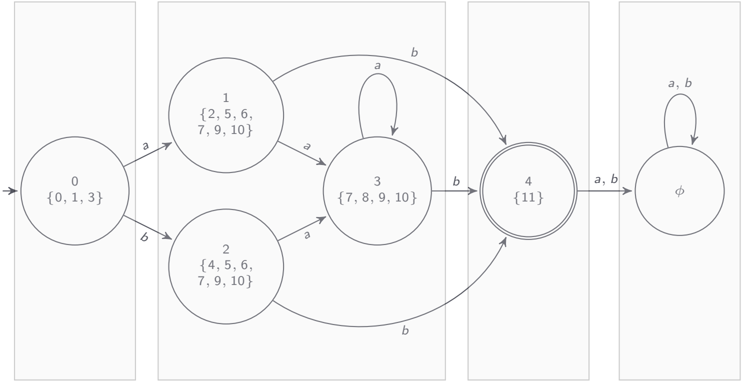
Neither a nor b splits the subset $\{1, 2, 3\}$

The final partition is therefore $\{\{0\}, \{1, 2, 3\}, \{4\}, \{\phi\}\}$



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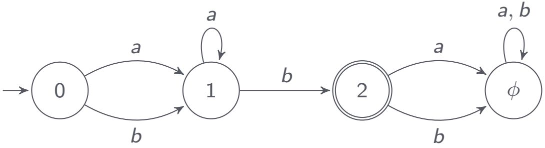
Minimal DFA for recognizing $(a|b)a*b$



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Algorithm Minimizing a DFA

Input: a DFA $D = (\Sigma, S, s_0, M, F)$

Output: a partition of S

$partition \leftarrow \{S - F, F\}$
while splitting occurs **do**
  for $subset \in partition$ **do**
    if $subset$.size() > 1 **then**
      for $a \in \Sigma$ **do**
        $r \leftarrow$ a state chosen from $subset$
        $targetSet \leftarrow$ the subset in the partition containing $m(r, a)$
        $set1 \leftarrow \{s \in subset | m(s, a) \in targetSet\}$
        $set2 \leftarrow \{s \in subset | m(s, a) \notin targetSet\}$
        if $set2 \neq \{\}$ **then**
          replace $subset$ in $partition$ by $set1$ and $set2$
          break
        end if
      end for
    end if
  end for
end while

JavaCC

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After a match, the scanner goes into a specified state or stays in the current state

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JavaCC generates a scanner for *j--* from regular expressions defined in `$j/j--/src/jminusminus/j--.jj`

`j--.jj` → JavaCC → `TokenManager.java`

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Scanning whitespace

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SKIP: { " " | "\t" | "\n" | "\r" | "\f" }
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Scanning single-line comments

```
SKIP: { <BEGIN_COMMENT: "//">: IN_SINGLE_LINE_COMMENT }
<IN_SINGLE_LINE_COMMENT>
SKIP: { <END_COMMENT: "\n" | "\r" | "\r\n">: DEFAULT }
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Alternative way of scanning single-line comments

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SPECIAL_TOKEN: {
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}
```

Scanning reserved words, separators, and operators

```
TOKEN: {
  <ABSTRACT: "abstract">
| <BOOLEAN: "boolean">
...
| <COMMA: ",">
| <DOT: "." >
...
| <ASSIGN: "=">
| <DEC: "--">
...
}
```

JavaCC

Scanning identifiers

```
TOKEN: {
  <IDENTIFIER: ( <LETTER> | "_" | "$" ) ( <LETTER> | <DIGIT> | "_" | "$" )*>
| <#LETTER: [ "a"-"z", "A"-"Z" ]>
| <#DIGIT: [ "0"-"9" ]>
}
```

Scanning identifiers

```
TOKEN: {
  <IDENTIFIER: ( <LETTER> | "_" | "$" ) ( <LETTER> | <DIGIT> | "_" | "$" )*>
| <#LETTER: [ "a"-"z", "A"-"Z" ]>
| <#DIGIT: [ "0"-"9" ]>
}
```

Scanning literals

```
TOKEN: {
  <INT_LITERAL: <DIGIT> ( <DIGIT> )*>
| <CHAR_LITERAL: "'" ( <ESC> | ~[ "'", "\\" ]) "'">
| <STRING_LITERAL: "\"" ( <ESC> | ~[ "\"", "\\" ] )* "\"">
| <#ESC: "\\" [ "n", "t", "b", "r", "f", "\\", "'", "\"" ]>
}
```