

# Compilation

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# Administration

- Final grade:
  - Exam: 60%
  - Project: 40%
- For technical questions, please use the course forum
  - *Moodle*
- Reception hour:
  - Thursday 19:00-20:00
  - Coordinate by email (davidtr1037@gmail.com)

# Course Project

- Build a compiler for an OOP Programming Language
  - Simplified version of known programming languages
- Consists of 4 exercises
  - Exercise 1: 20 points
  - Exercise 2: 30 points
  - Exercise 3: 50 points
  - Exercise 4: 30 points (bonus)
- Implement in Java
- Work in groups of 3 students
- Constitutes **40%** of the final grade

# Course Project

Week #	Subject	Project
1	Lexical Analysis	
2	Lexical Analysis	Exercise 1 (3 weeks)
3	Syntactic Analysis	
4	<i>No new material</i>	
5	Syntactic Analysis	Exercise 2 (2 weeks)
6	Semantic Analysis	
7	IR	Exercise 3 (3 weeks)
8	AST Annotations	
9	Code Generation	Exercise 4 (3 weeks)
10	Code Generation	
11	Exam Questions	

# Submission Guidelines

- Submission with **github**
  - Each group should create a private repository
- **Recommended** development environment:
  - Ubuntu
  - Windows users can install a VM

# Books

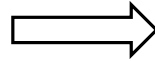
- Modern Compiler Implementation in C
  - *Andrew W Appel*
- Compilers: Principles, Techniques, and Tools
  - *Aho et al.*
- Modern Compiler Design
  - *Grune et al.*

# What is compilation?

Translation of code (text) to executable code (machine code)

source code

```
int foo(int x, int y) {  
    return x + y;  
}
```



machine code

```
push    %rbp  
mov     %rsp,%rbp  
mov     %edi,-0x4(%rbp)  
mov     %esi,-0x8(%rbp)  
mov     -0x4(%rbp),%edx  
mov     -0x8(%rbp),%eax  
add     %edx,%eax  
pop     %rbp  
retq
```

# Common compilers

- GCC, LLVM
  - *<https://gcc.gnu.org/>*
  - *<https://llvm.org/>*
- Useful as an implementation reference



# Compilation Steps: Frontend

- Lexical analysis
  - Check the validity of tokens
- Syntax analysis
  - Check the syntactic structure
- Semantic analysis
  - Make sure it makes sense

These steps **don't depend** on the compilation target!

# Compilation Steps: Backend

- Intermediate Code Generation
  - Can't be executed yet...
- Machine code generation
  - Executed on a real hardware

# Lexical Analysis

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# Lexical Analysis

- Input: **code text**
- Check if the input consists of valid tokens

High-level algorithm:

1. Set the current position to the beginning of the input
2. Scan
  - If reached end of input, **done**
  - Else, try to match with one of the defined tokens
    - If there is no match, **fail**
    - Otherwise
      - increment the current position
      - repeat step 2

# Valid Tokens in C

Token	Examples
Constants	12, 0x1234, 1.7, 2e+8
Identifiers	var, tmp1
Reserved Keywords	if, else, while, int, char
Parentheses	(,),{,}
Binary Operators	+, -, *, /
Unary Operators	-, *
Comments	/* ... */ , //

# Examples

```
void f() {  
    x = 1;  
}
```

# Examples

```
void f() {  
    x = 1;  
}
```

Valid

# Examples

```
void f() {  
    x = 1;  
}
```

Valid

tokens

void	ws	f	(	)	ws	{	ws	x	ws	=	ws	1	;	ws	}
------	----	---	---	---	----	---	----	---	----	---	----	---	---	----	---



# Examples

```
void f() {  
    1 = x;  
}
```

# Examples

```
void f() {  
    1 = x;  
}
```

Valid

# Examples

```
void f() {  
    x 1;  
}
```

# Examples

```
void f() {  
    x 1;  
}
```

Valid

# Examples

```
void f() {  
    x = 1  
}
```

# Examples

```
void f() {  
    x = 1  
}
```

Valid

# Examples

```
void f() {
```

# Examples

```
void f() {
```

Valid



# Examples

```
void f() {  
    a = 0x100;  
}
```

# Examples

```
void f() {  
    a = 0x100;  
}
```

Valid

# Examples

```
void f() {  
    a = 0u;  
}
```

# Examples

```
void f() {  
    a = 0u;  
}
```

Valid

# Examples

```
void f() {  
    a = 0y;  
}
```

# Examples

```
void f() {  
    a = 0y;  
}
```

Valid

# Examples

```
void f() {  
    90000000000000000000000000;  
}
```

# Examples

```
void f() {  
    9000000000000000000000000000;  
}
```

Valid



# Examples

```
void f() {  
    int @gmail = 0;  
}
```

# Examples

```
void f() {  
    int @gmail = 0;  
}
```

Invalid

# Examples

```
void f() {  
    127.0;  
}
```

# Examples

```
void f() {  
    127.0;  
}
```

Valid

# Examples

```
void f() {  
    127.0.0.1;  
}
```

# Examples

```
void f() {  
    127.0.0.1;  
}
```

Invalid

# Examples

```
void f() {  
    127.00.00.1;  
}
```

# Examples

```
void f() {  
    127.00.00.1;  
}
```

Invalid



# Examples

```
void f() {  
    0xcafecafe;  
}
```

# Examples

```
void f() {  
    0xcafecafe;  
}
```

Valid

# Examples

```
void f() {  
    int x = 0x0000000000000000000007;  
}
```

# Examples

```
void f() {  
    int x = 0x0000000000000000000007;  
}
```

Valid

# Examples

```
void f() {  
    void g() {};  
}
```

# Examples

```
void f() {  
    void g() {};  
}
```

Valid

# Examples

```
void f() {  
    /* @@@ */  
}
```

# Examples

```
void f() {  
    /* @@@ */  
}
```

Valid



# Examples

```
void f() {  
    /* @@@  
}
```

# Examples

```
void f() {  
    /* @@@  
}
```

Invalid

# Examples

```
void f() {  
    // bla  
}
```

# Examples

```
void f() {  
    // bla  
}
```

Valid

# Examples

```
void f() {  
    / bla  
}
```

# Examples

```
void f() {  
    / bla  
}
```

Valid

# Examples

```
void f() {  
    "1234";  
}
```

# Examples

```
void f() {  
    "1234";  
}
```

Valid



# Examples

```
void f() {  
    "1234";  
}
```

# Examples

```
void f() {  
    "1234;  
}
```

Invalid

# Detecting Numerical Constants

- We want an **efficient** algorithm for detecting numerical constants
- Can you use a dictionary?
  - Probably not...
  - Too many values to store

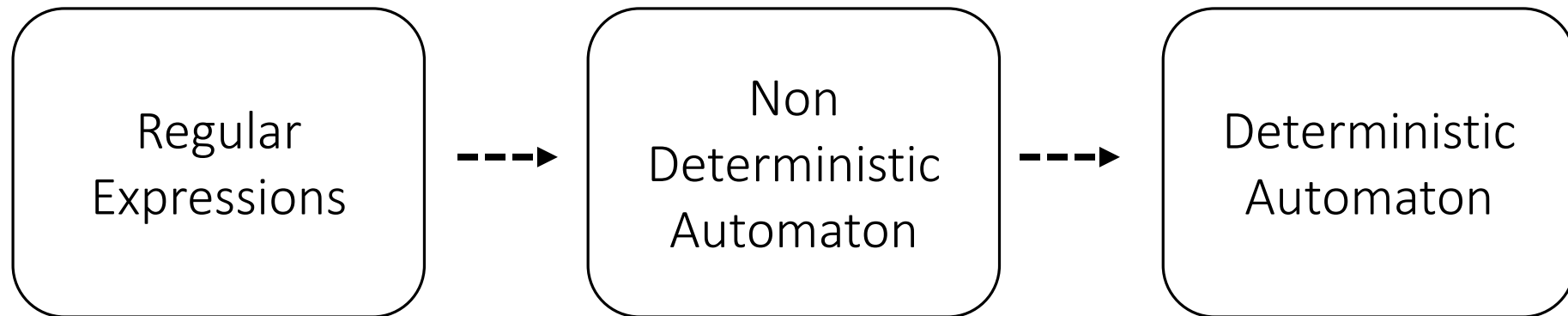
# Using Regular Expressions

- We can use regular expressions for that
- Identifiers:
  - $[a-zA-Z][a-zA-Z0-9]^*$
- Hex-decimal constants:
  - $[0][xX][0-9a-fA-F]^+$
- Floats
  - ...?

Every token can be represented using a regular expressions.

# Using Regular Expressions

- But what is the actual algorithm?
- The plan is:



# Regular Expressions: Reminder

Given an alphabet  $\Sigma$ , the regular expression  $R$  represents the language  $L(R)$  as follows:

- Atomic expressions:
  - $L(a) = \{a\}, L(\epsilon) = \{\epsilon\}$
- Concatenation:
  - $L(R_1R_2) = \{w_1w_2 \mid w_1 \in L(R_1), w_2 \in L(R_2)\}$
- Union:
  - $L(R_1|R_2) = L(R_1) \cup L(R_2)$
- Kleene Star:
  - $L(R^*) = \{\epsilon\} \cup L(R) \cup L(RR) \cup \dots$

# DFA: Reminder

A deterministic finite automaton  $M$  is a tuple:  $(Q, \Sigma, \delta, q_0, F)$

- $Q$  is a finite set of states
- $\Sigma$  is a finite set of input symbols
- $\delta$  is the transition function:  $\delta: Q \times \Sigma \rightarrow Q$
- $q_0$  is the initial states
- $F$  is a set of accepting states

A string  $a_1 a_2 \dots$  is **accepted** by  $M$  if there is a state sequence  $s_0 s_1 \dots$ :

- $s_0 = q_0$
- $\delta(s_i, a_{i+1}) = s_{i+1} \ (i = 0, 1, \dots, n - 1)$
- $s_n \in F$

# NFA: Reminder

A non-deterministic finite automaton  $M$  is a tuple:  $(Q, \Sigma, \delta, q_0, F)$

- $Q$  is a finite set of states
- $\Sigma$  is a finite set of input symbols
- $\delta$  is the transition function:  $\delta: Q \times \Sigma \rightarrow P(Q)$
- $q_0$  is the initial states
- $F$  is a set of accepting states

A string  $a_1 a_2 \dots$  is **accepted** by  $M$  if there is a state sequence  $s_0 s_1 \dots$ :

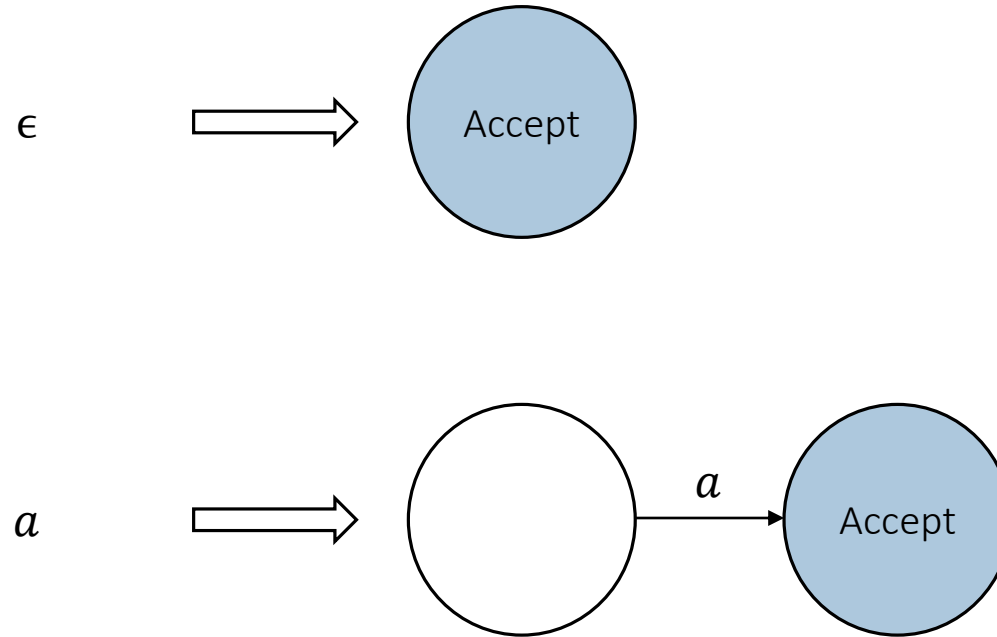
- $s_0 = q_0$
- $s_{i+1} \in \delta(s_i, a_{i+1})$  ( $i = 0, 1, \dots, n - 1$ )
- $s_n \in F$



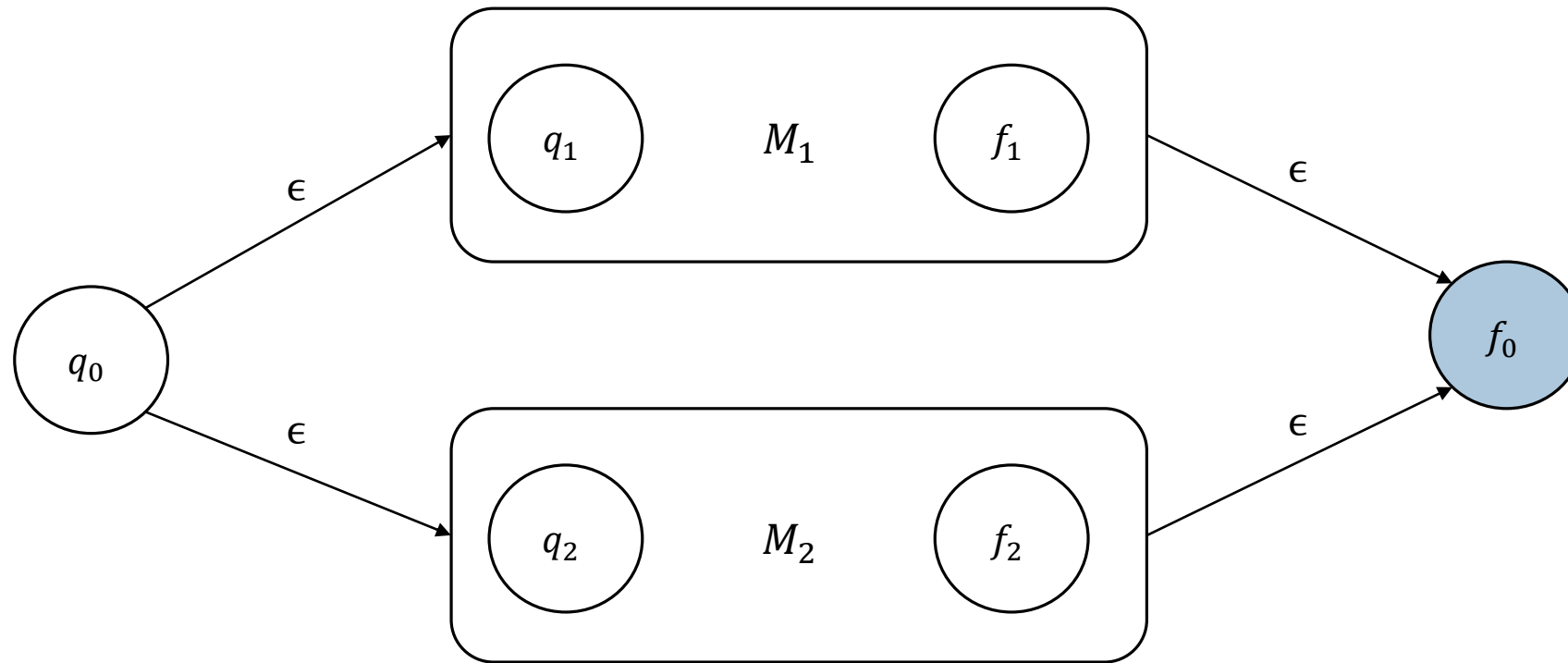
# RE to DFA

- For every regular expression, there is a deterministic finite automaton that accepts its language
  - Proof by construction
- Once we have the DFA, we can implement using a transition table
  - As done in *Flex*

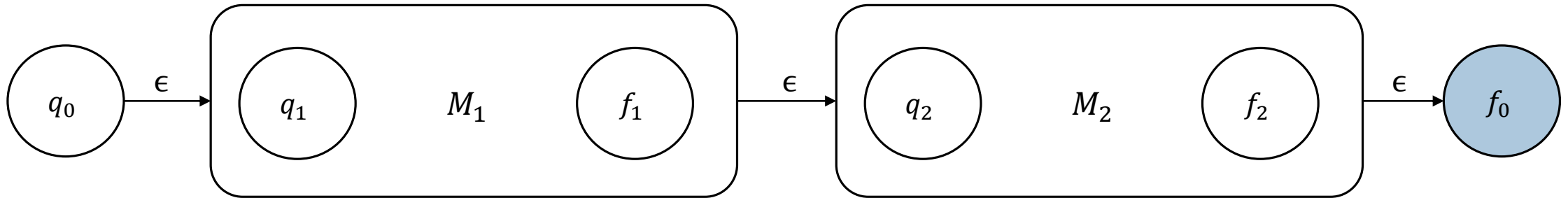
# RE to NFA: Atomic Expressions



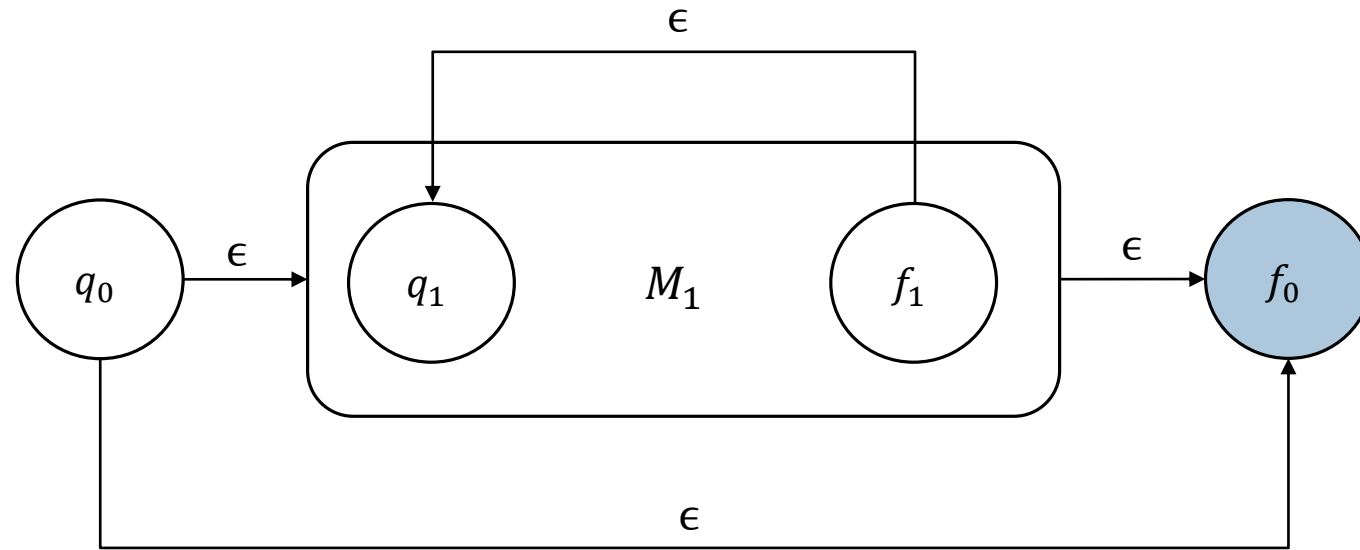
# RE to NFA: Union



# RE to NFA: Concatenation

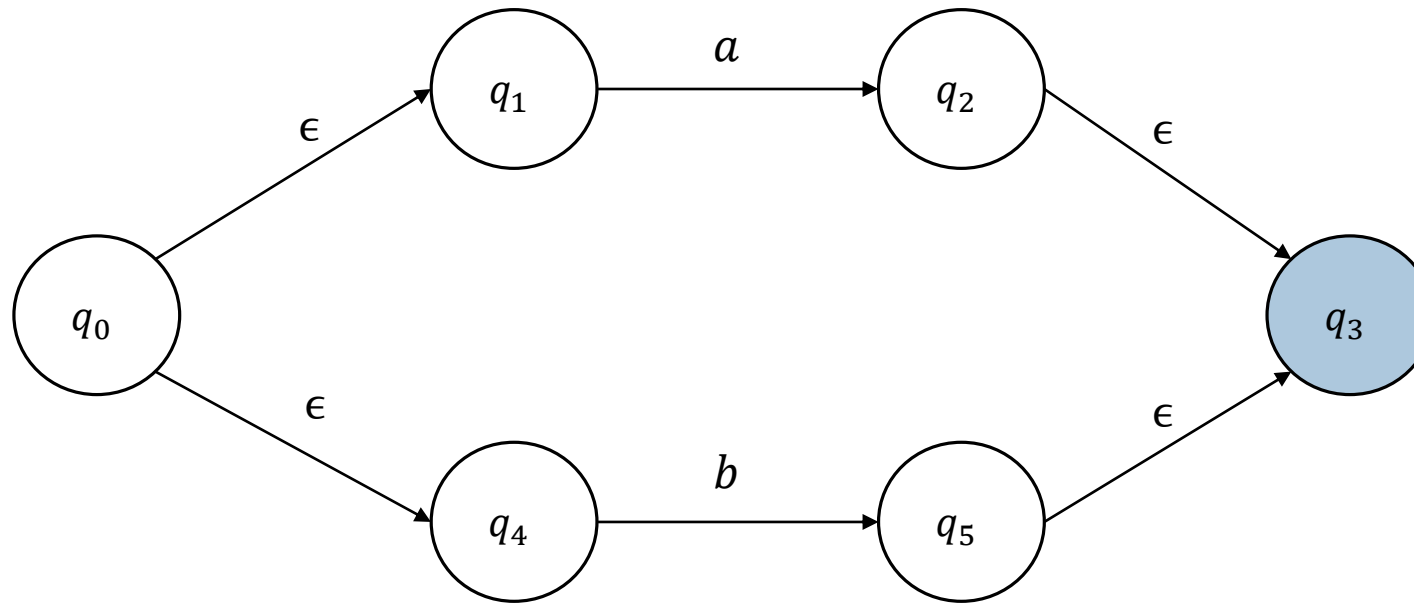


# RE to NFA: Kleene Star



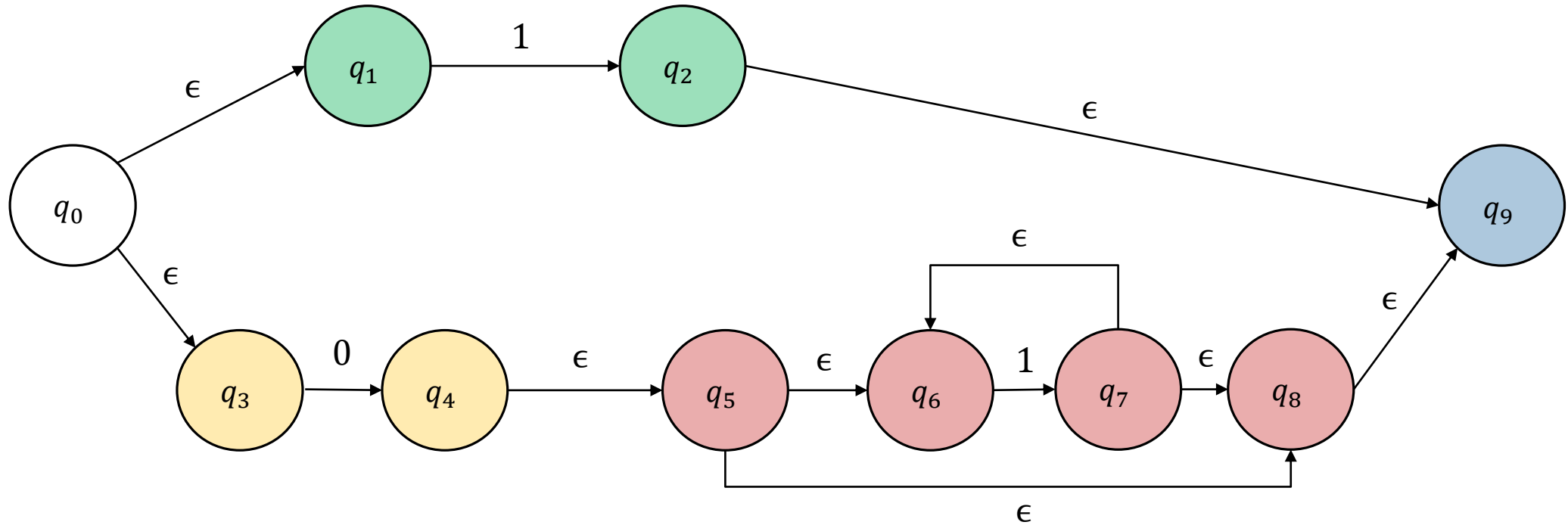
# RE to NFA: Example

- NFA for  $a \mid b$



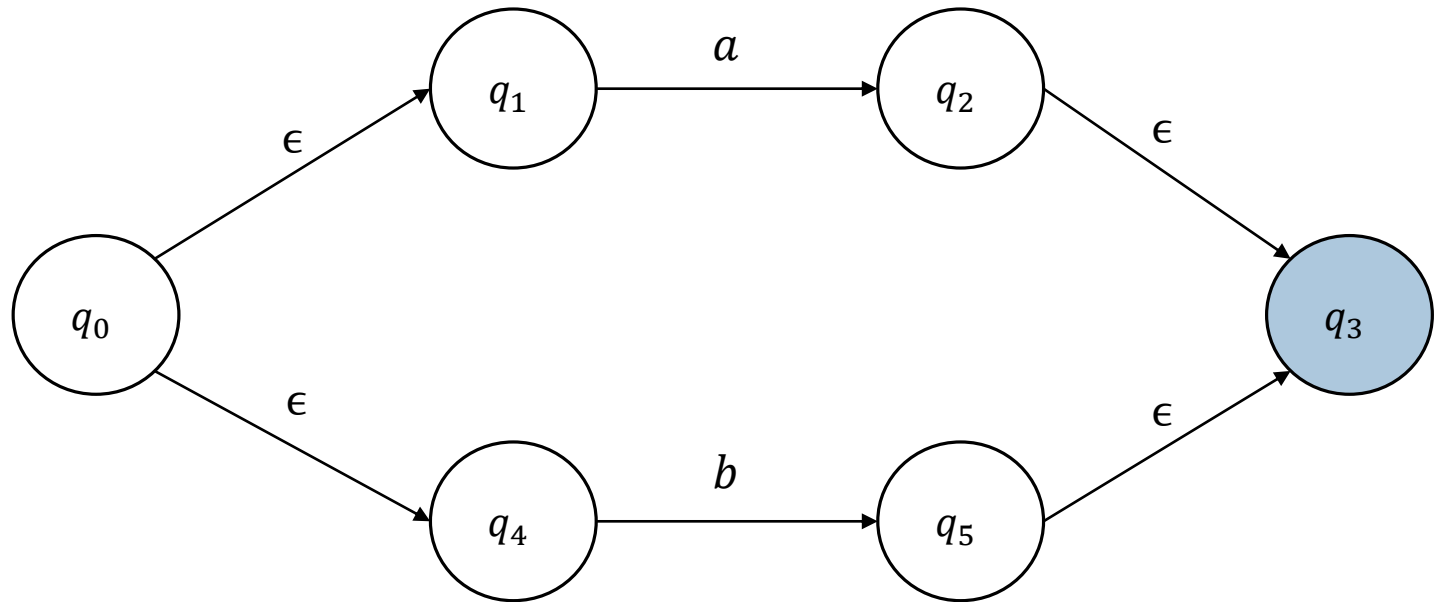
# RE to NFA: Another Example

- NFA for  $01^* | 1$



# NFA to DFA: Example

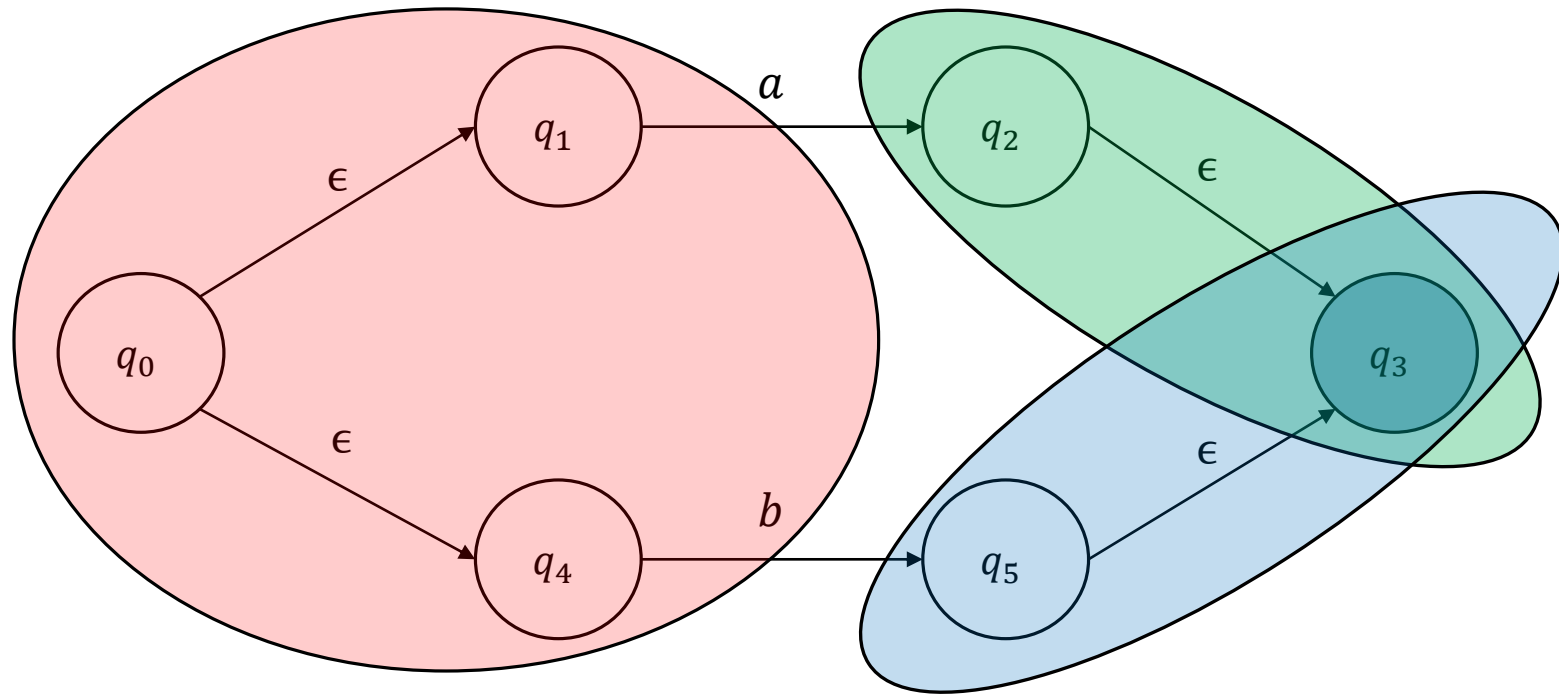
- At the beginning, we may be at:  $q_0, q_1, q_4$
- If next token is  $a$  then we may be at:  $q_2, q_3$
- If next token is  $b$  then we may be at:  $q_5, q_3$





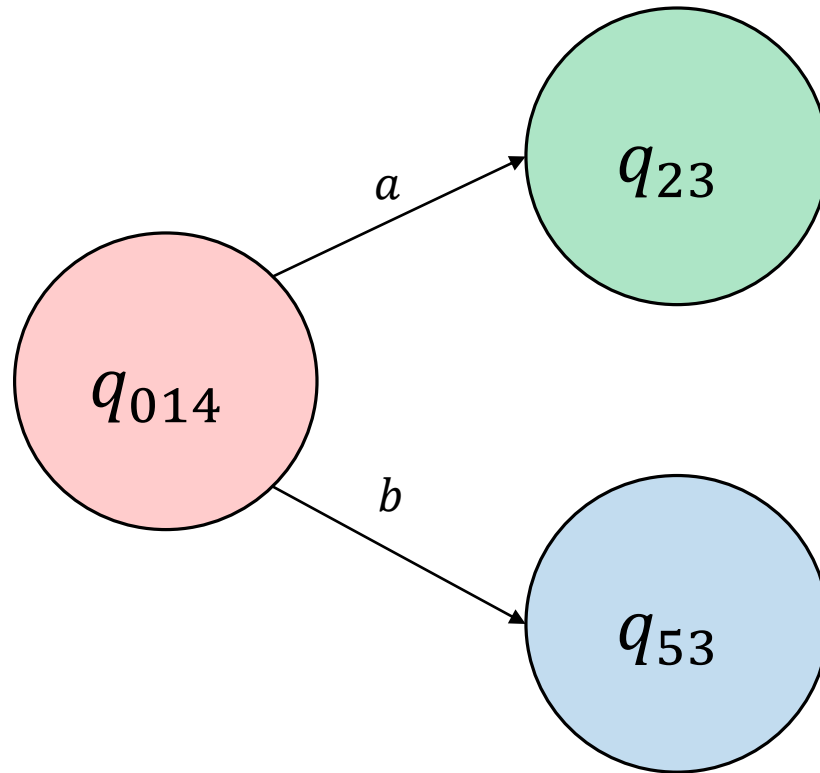
# NFA to DFA: Example

- At the beginning, we may be at:  $q_0, q_1, q_4$
- If next token is  $a$  then we may be at:  $q_2, q_3$
- If next token is  $b$  then we may be at:  $q_5, q_3$



# NFA to DFA: Example

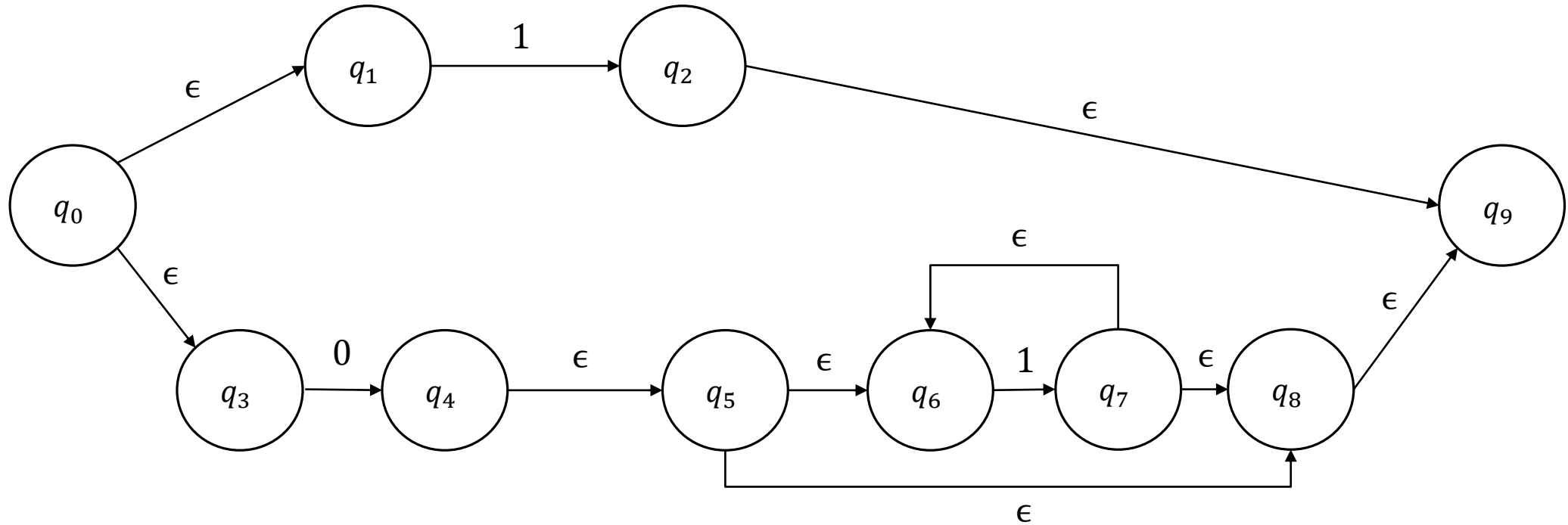
- So we can transform to the following DFA:



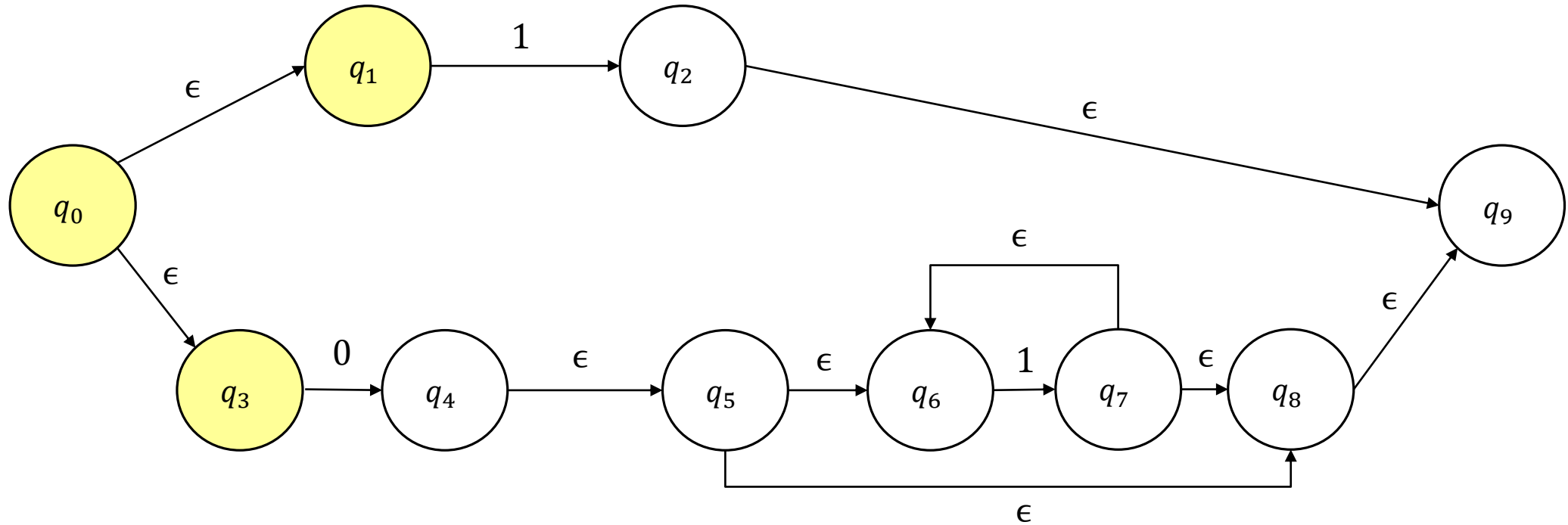
# NFA to DFA: Formal Details

- Let  $(Q, \Sigma, \delta, q_0, F)$  be a non-deterministic finite automaton
- The set of states is the  $P(Q)$
- The initial state is the  $\epsilon$ -closure of  $q_0$
- For every state in the set (now, a state is a ***set of states***):
  - Compute the union over the  $\epsilon$ -closure of the successor states
- A state is accepting if it contains a state from  $F$

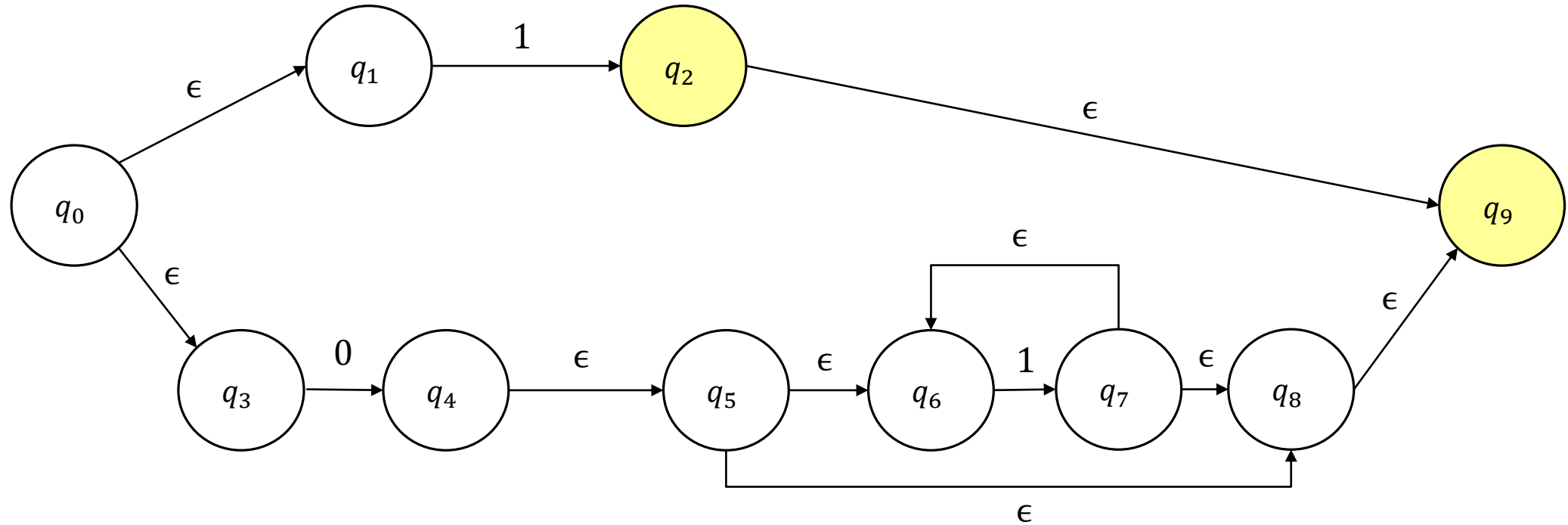
# Another Example: NFA to DFA



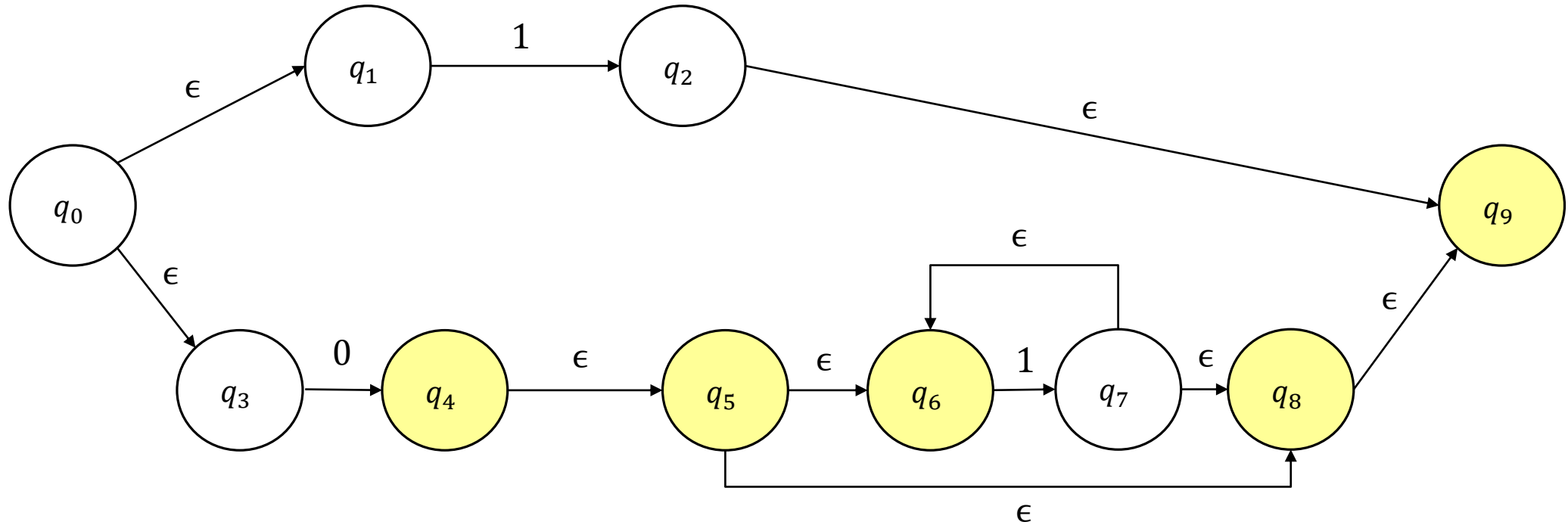
# Another Example: NFA to DFA



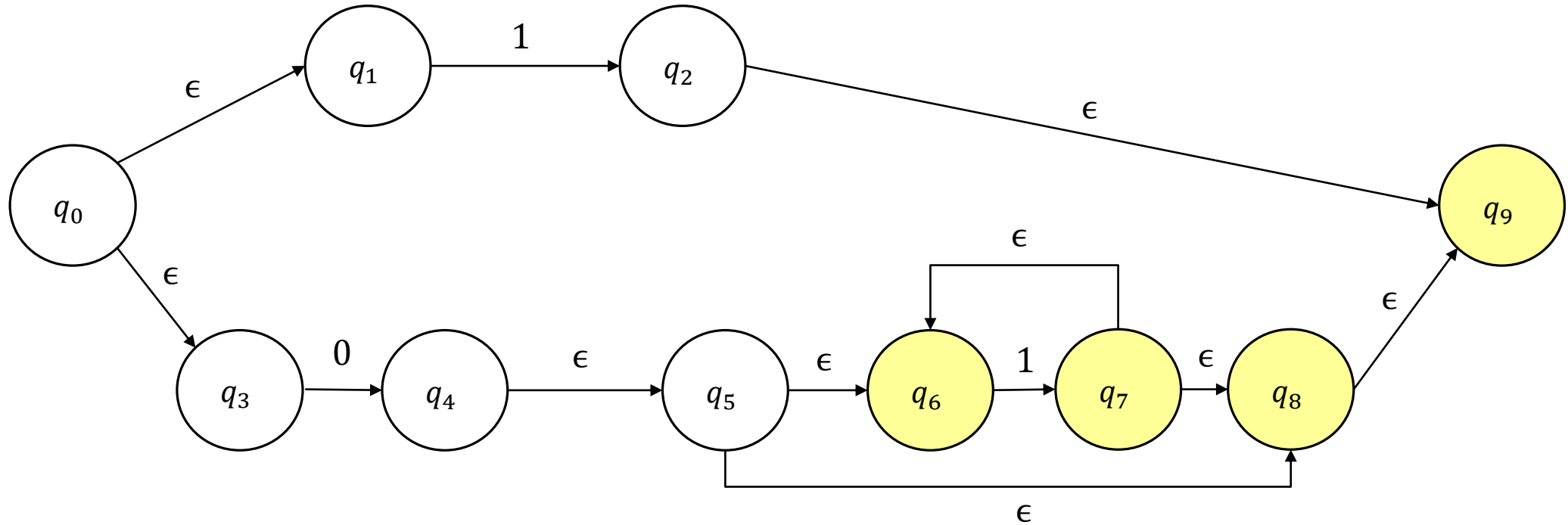
# Another Example: NFA to DFA



# Another Example: NFA to DFA

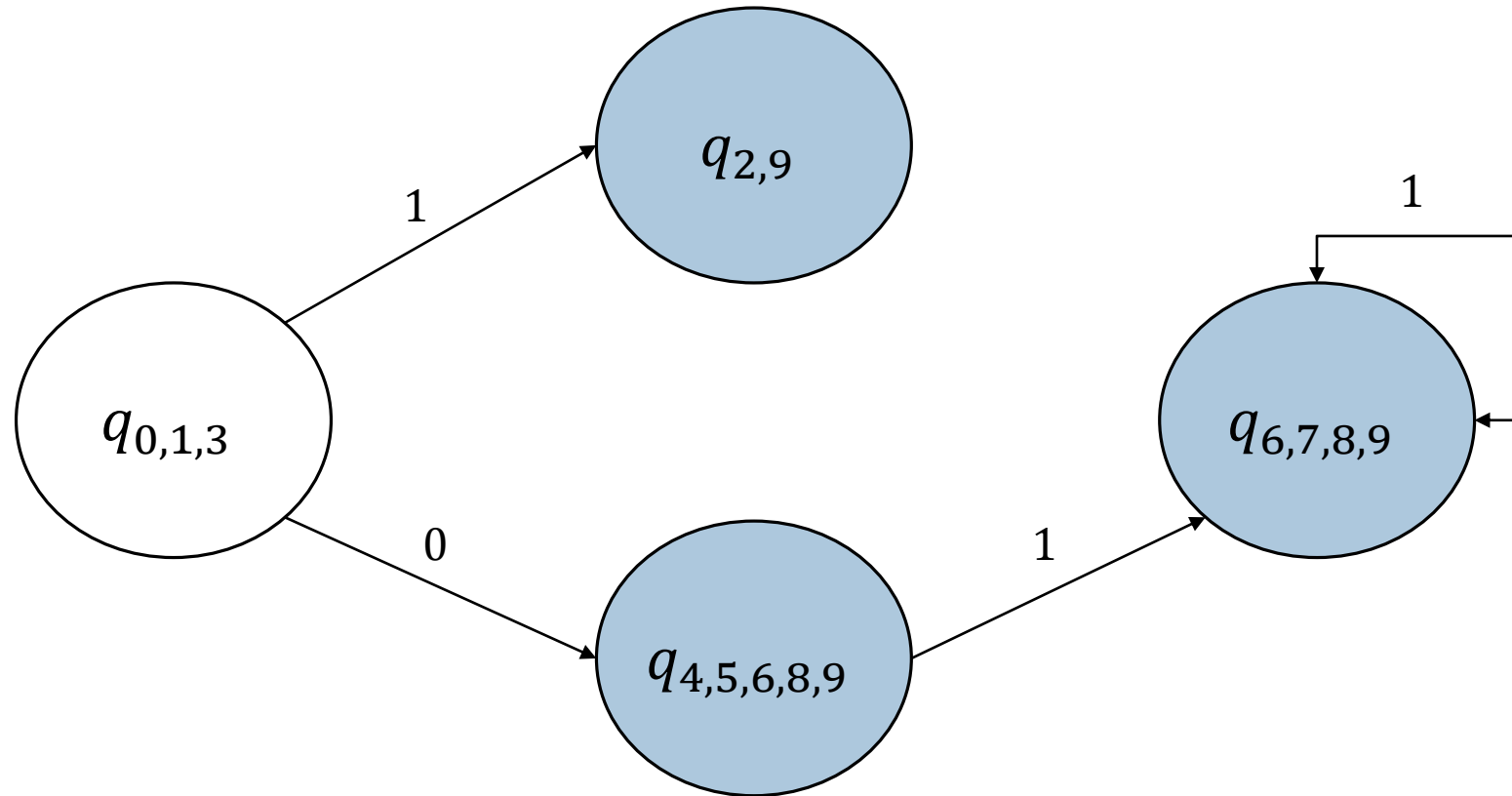


# Another Example: NFA to DFA





# Another Example: NFA to DFA



# Building a Lexical Analyzer

- Construct a regular expressions for token types:
  - Identifiers, numbers, reserved keywords
- If we have a collision (two or more matching tokens) :
  - Token with longest match wins
  - Order of definition

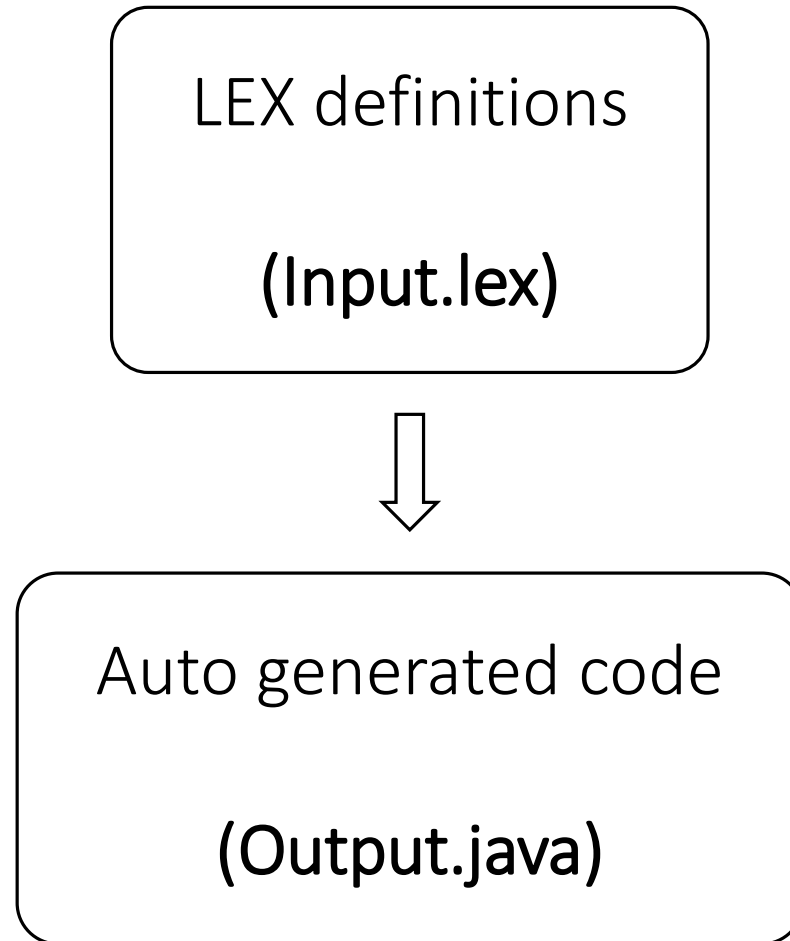
# Regular Expressions Definitions for C

- Here we can see the regular expression definitions:
  - <http://www.lysator.liu.se/c/ANSI-C-grammar-1.html>
  - Quite simple and modular...

# JFlex

- Java **F**ast **L**exical Analyzer
  - Inspired by the original **flex** project (written in C)
- Accepts an input file with tokens definitions
- Generates Java code with a scanning API
- This scanning API reads the input and returns:
  - The type of the read token
  - Or an error...

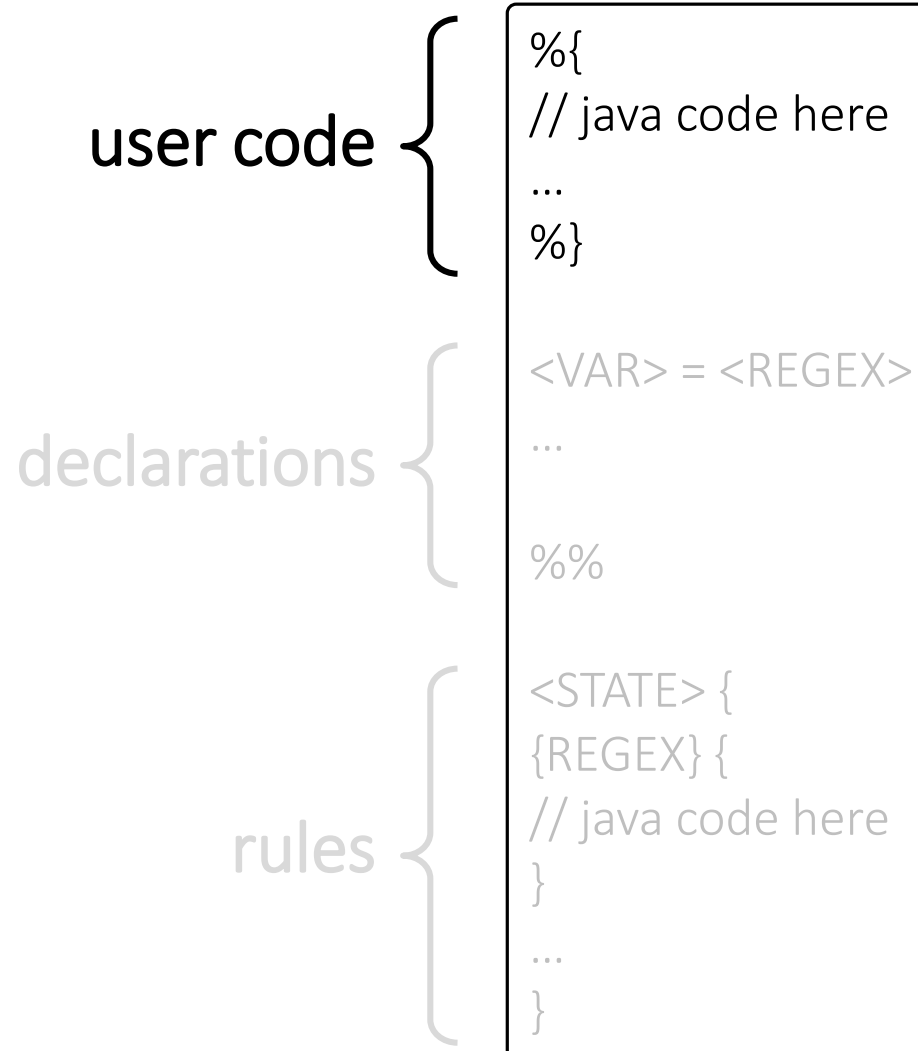
# JFlex



# LEX Format

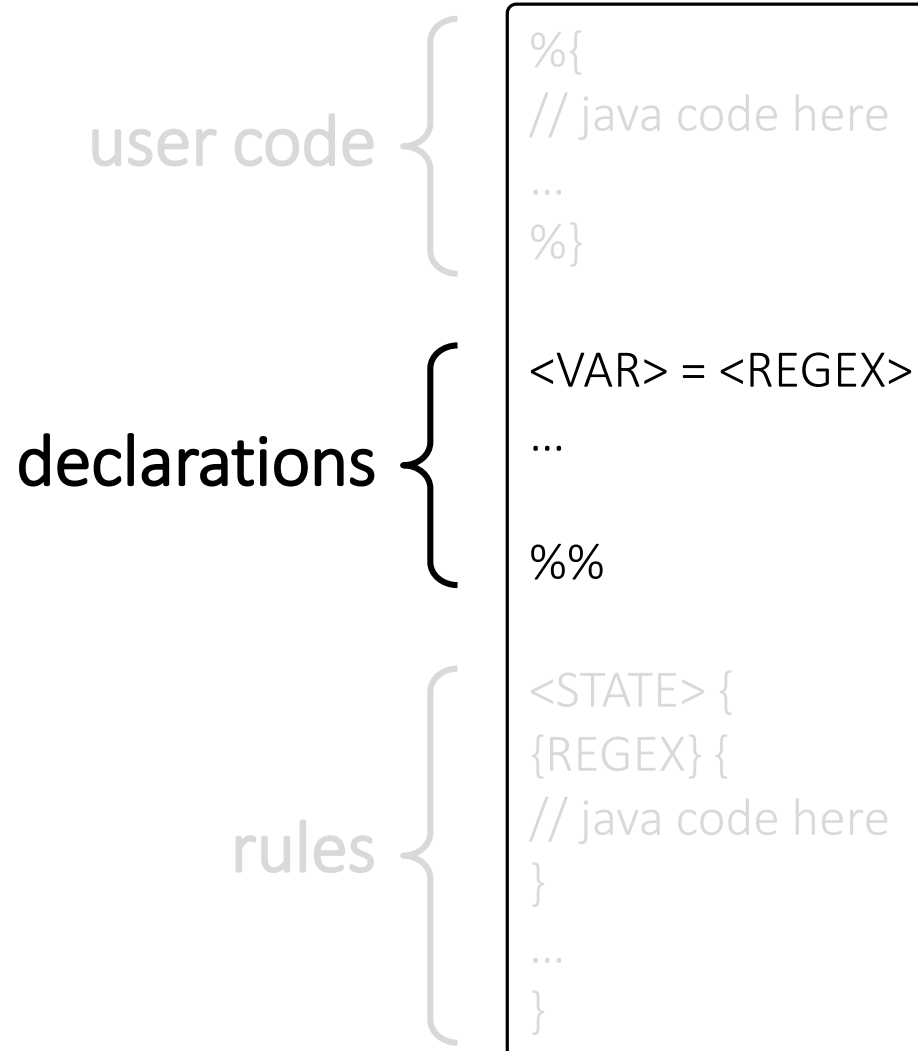
user code	{	%{ // java code here ... %}
declarations	{	<VAR> = <REGEX> ... %%
rules	{	<STATE> { {REGEX} { // java code here } ... }

# LEX Format



- Regular Java code
- Pasted to the generated file

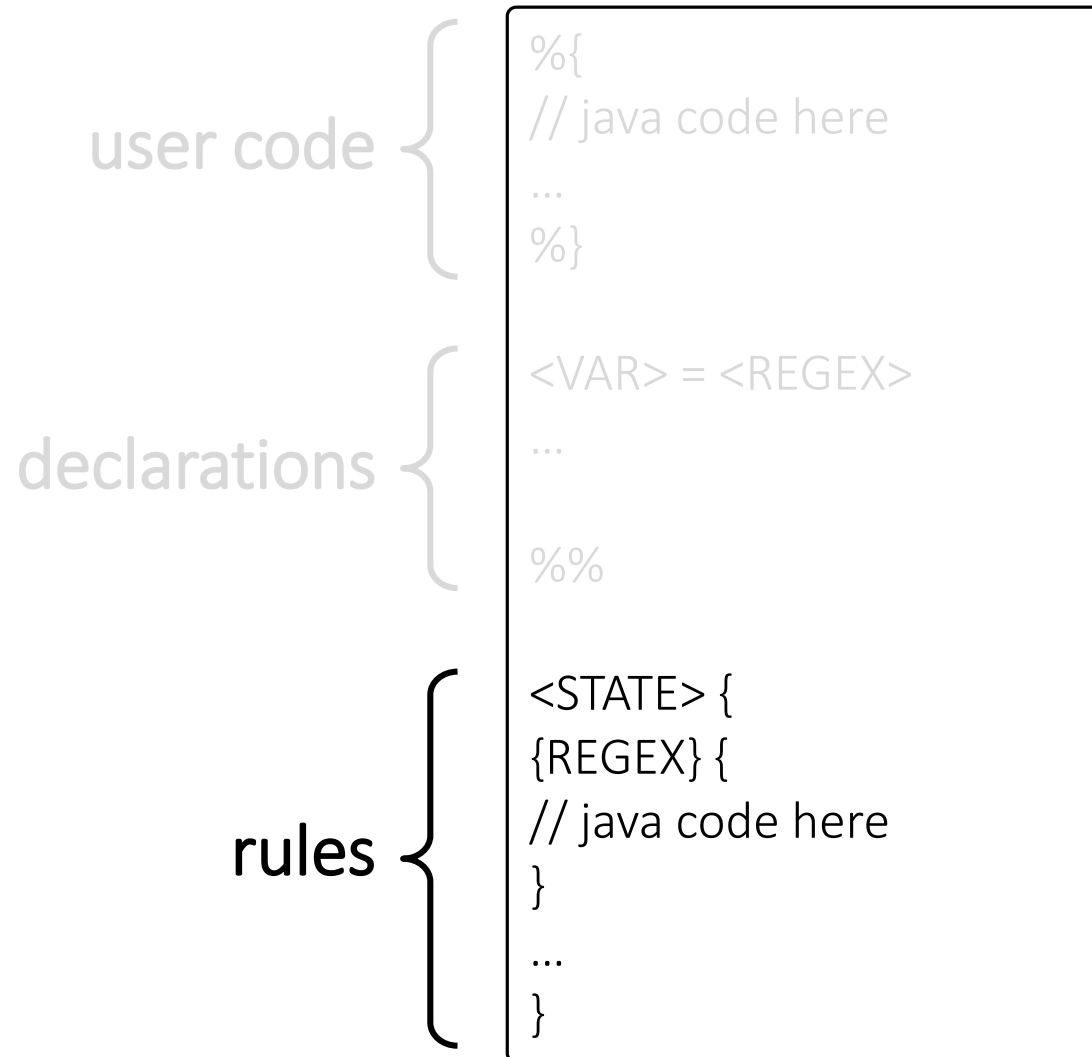
# LEX Format



- Regular Java code
- Pasted to the generated file
- Macro definitions
- Define a regex for each token



# LEX Format



- Regular Java code
- Pasted to the generated file
- Macro definitions
- Define a regex for each token
- If the following holds:
  - Current lexical state is `<STATE>`
  - `<REGEX>` is matched
- Then execute the action code

# Example 1

- We want 2 kind of tokens:
  - $a$
  - $b^*$
  - Everything else is rejected...

# Example 1: LEX Definitions

User code:

```
%{  
private Symbol symbol(int type) {  
    return new Symbol(type, yyline, yycolumn);  
}  
public int getLine() { return yyline + 1; }  
public int getTokenStartPosition() { return yycolumn + 1; }  
%}
```

# Example 1: LEX Definitions

Declarations

A = a

B\_STAR = b\*

# Example 1: LEX Definitions

Rules:

```
<YYINITIAL> {  
  {A} { return symbol(TokenNames.A); }  
  {B_STAR} { return symbol(TokenNames.B_STAR); }  
  <<EOF>> { return symbol(TokenNames.EOF);}  
}
```

# Example 1: LEX Definitions

```
%{  
private Symbol symbol(int type) { return new Symbol(type, yyline, yycolumn); }  
public int getLine() { return yyline + 1; }  
public int getTokenStartPosition() { return yycolumn + 1; }  
%}  
A = a  
B_STAR = b*  
%% // separator...  
<YYINITIAL> {  
{A} { return symbol(TokenNames.A); }  
{B_STAR} { return symbol(TokenNames.B_STAR); }  
<<EOF>> { return symbol(TokenNames.EOF); }  
}
```

# Example 1: Tokens Definitions

```
public interface TokenNames {  
    /* terminals */  
    public static final int EOF = 0;  
    public static final int A = 1;  
    public static final int B_STAR = 2;  
}
```

# Example 1: Main

```
Lexer l = new Lexer(fileReader); // auto-generated lexer
Symbol s = l.next_token();
while (s.sym != TokenNames.EOF) {
    System.out.print("[");
    System.out.print(l.getLine() + ", " + l.getTokenStartPosition);
    System.out.print("]:");
    System.out.print(s.sym + "\n");
    s = l.next_token();
}
```



# Example 1: Output

What will be the output for the following input?

- *ababbbb*

# Example 1: Output

What will be the output for the following input?

- *ababbbb*

[1,1]:1

[1,2]:2

[1,3]:1

[1,4]:2

*Format:*

[line,column]:<token\_type>

# Example 1: Output

What will be the output for the following input?

- *ab abbbb*

# Example 1: Output

What will be the output for the following input?

- *ab abbbb*

```
[1,1]:1  
[1,2]:2  
Exception in ...
```

# Example 1: The EOF Token

- Why do we need the EOF token?

## Example 2: Counting Words

- How can we use JFlex to count words for a given input file?
  - Assume only letters

# Example 2: LEX Definitions

```
%{  
private Symbol symbol(int type) { return new Symbol(type, yyline, yycolumn); }  
public int getLine() { return yyline + 1; }  
public int getTokenStartPosition() { return yycolumn + 1; }  
public int words_count = 0;  
%}  
WORD = [a-zA-Z]+  
ANY = [^a-zA-Z]+  
%% // separator...  
<YYINITIAL> {  
  {WORD} { words_count++; }  
  {ANY} { }  
  <<EOF>> { return symbol(TokenNames.EOF); }  
}
```

## Example 2: Tokens Definitions

```
public interface TokenNames {  
    /* terminals */  
    public static final int EOF = 0;  
}
```



# Example 2: Counting Words

Other definitions instead of **ANY**?

# Example 2: Counting Words

Other definitions instead of **ANY**?

- $|n|$ .

# Example 3: Calculator

- How can we use JFlex to detect calculator tokens?
  - Numbers, parentheses, operators, ...
  - 1+1, (9), 1+(0000, ...

# Example 3: LEX Definitions

Declarations:

PLUS = "+"

L\_PAREN = "("

R\_PAREN = ")"

NUMBER = [0-9]+

# Example 3: LEX Definitions

Rules:

```
<YYINITIAL> {  
  {PLUS} { return symbol(TokenNames.PLUS); }  
  {L_PAREN} { return symbol(TokenNames.L_PAREN); }  
  {R_PAREN} { return symbol(TokenNames.R_PAREN); }  
  {NUMBER} {  
    return symbol(TokenNames.NUMBER, new Integer(yytext()));  
  }  
  <<EOF>> { return symbol(TokenNames.EOF); }  
}
```

# Example 3: Tokens Definitions

```
public interface TokenNames {  
    /* terminals */  
    public static final int EOF = 0;  
    public static final int PLUS = 1;  
    public static final int L_PAREN = 2;  
    public static final int R_PAREN = 3;  
    public static final int NUMBER = 4;  
}
```

# Example 3: Output

What will be the output for:

- 1(+2345

```
[1,1]:4 1  
[1,2]:2 null  
[1,3]:1 null  
[1,4]:4 2345
```

# Example 4: Definition Order

```
%{  
private Symbol symbol(int type) { return new Symbol(type, yyline, yycolumn); }  
public int getLine() { return yyline + 1; }  
public int getTokenStartPosition() { return yycolumn + 1; }  
%}  
T1 = a  
T2 = ab*  
%% // separator...  
<YYINITIAL> {  
{T1} { return symbol(TokenNames.T1); }  
{T2} { return symbol(TokenNames.T2); }  
<<EOF>> { return symbol(TokenNames.EOF); }  
}
```



# Example 4: Definition Order

What will be the output for:

- *aabbbba*

T1 = a

T2 = ab\*

```
<YYINITIAL> {  
  {T1} { return symbol(TokenNames.T1); }  
  {T2} { return symbol(TokenNames.T2); }  
  <<EOF>> { return symbol(TokenNames.EOF); }  
}
```

# Example 4: Definition Order

What will be the output for:

- *aabbbba*

[1,1]:1

[1,2]:2

[1,7]:1

T1 = a

T2 = ab\*

<YYINITIAL> {

{T1} { return symbol(TokenNames.T1); }

{T2} { return symbol(TokenNames.T2); }

<<EOF>> { return symbol(TokenNames.EOF); }

}

# Example 4: Definition Order

If the order is swapped?

- *aabbbba*

T1 = a

T2 = ab\*

```
<YYINITIAL> {
```

```
{T2} { return symbol(TokenNames.T2); }
```

```
{T1} { return symbol(TokenNames.T1); }
```

```
<<EOF>> { return symbol(TokenNames.EOF); }
```

```
}
```

# Example 4: Definition Order

If the order is swapped?

- *aabbbba*

[1,1]:2

[1,2]:2

[1,7]:2

T1 = a

T2 = ab\*

<YYINITIAL> {

{T2} { return symbol(TokenNames.T2); }

{T1} { return symbol(TokenNames.T1); }

<<EOF>> { return symbol(TokenNames.EOF); }

}

# Exam Questions

- Consider the following flex-like definition:
  - `a*b { print "1" }`
  - `ca { print "2" }`
  - `a*ca* { print "3" }`
- What will the lexer print for the input:
  - **`abcaacacaaabbbaabcaaca`**

# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

**abcaacacaaabbbaaabcaaca**

# Exam Questions

- Consider the following flex-like definition:
  - `a*b` { print "1" }
  - `ca` { print "2" }
  - `a*ca*` { print "3" }

**ab** | caacacaaabbbaaabcaaca

# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

**ab | caa | cacaaabbbaabcaaca**



# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

$ab$  |  $caa$  |  $ca$  | caaabbaaabcaaca

# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

$ab$  |  $caa$  |  $ca$  |  $caaa$  |  $bbaaaabcaaca$

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- Consider the following flex-like definition:
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$ab|caa|ca|caaa|b|baaabcaaca$

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- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

$ab$  |  $caa$  |  $ca$  |  $caaa$  |  $b$  |  $b$  |  $aaab$  |  $caaca$

# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

$ab \mid caa \mid ca \mid caaa \mid b \mid b \mid aaab \mid caa \mid ca$

# Exam Questions

- Consider the following flex-like definition:
  - $a^*b$  { print "1" }
  - $ca$  { print "2" }
  - $a^*ca^*$  { print "3" }

$ab \mid caa \mid ca \mid caaa \mid b \mid b \mid aaab \mid caa \mid ca$

Answer:

- 132311132

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i--+-j;  
}
```



# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i--+-j;  
}
```

tokens

i	--	+	--	j
---	----	---	----	---

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i--+-j;  
}
```

Valid

tokens

i	--	+	--	j
---	----	---	----	---

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i-----j;  
}
```

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i-----j;  
}
```

tokens

i	--	--	-	j
---	----	----	---	---

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i-----j;  
}
```

(i--) --

tokens

i	--	--	-	j
---	----	----	---	---

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    i-----j;  
}
```

Invalid

(i--) --

tokens

i	--	--	-	j
---	----	----	---	---

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    (i--) - (--j) ;  
}
```

# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    (i--) - (--j) ;  
}
```

tokens

(	i	--	)	-	(	--	j	)
---	---	----	---	---	---	----	---	---



# Exam Questions: Will Compile?

```
void f(int a) {  
    int i = 8;  
    int j = 3;  
    (i--) - (--j) ;  
}
```

Valid

tokens

(	i	--	)	-	(	--	j	)
---	---	----	---	---	---	----	---	---

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    int i = 8;  
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tokens

i	--	-	(	--	j	)
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Valid

tokens

i	--	-	(	--	j	)
---	----	---	---	----	---	---