Compilation

TEACHING ASSISTANT: DAVID TRABISH

Administration

- Final grade:
  - Exam: 50%
  - Project: 50%
- For technical questions, please use the course forum
  - *Moodle*
- Reception hour:
  - Sunday 18:00-19:00
  - 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
- Implement in Java
- Work in groups of 3 students
- Constitutes **50%** of the final grade

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

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() {
      900000000000000000000;
}
```

Examples

```
void f() {
      900000000000000000000;
}
```

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 = 0x000000000000000007;
}
```

Examples

```
void f() {
     int x = 0x000000000000000007;
}
```

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

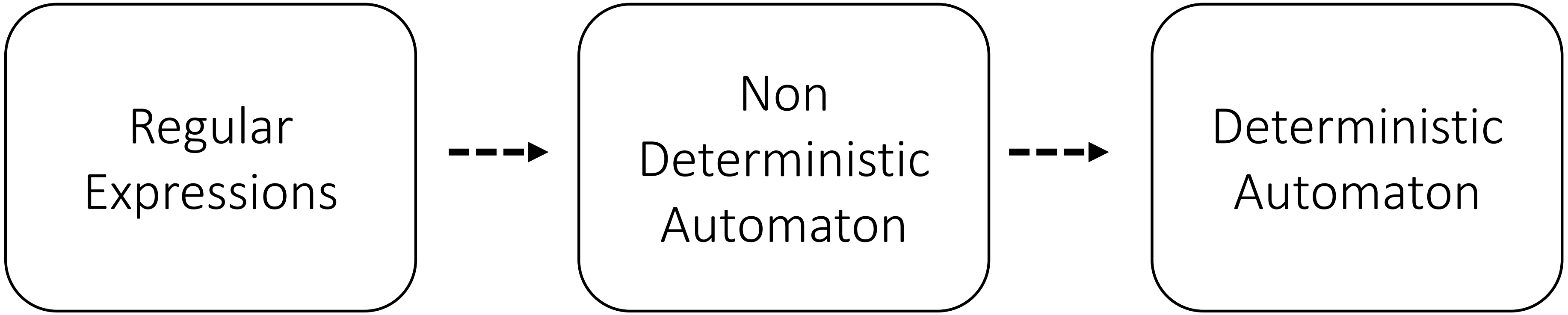
Using Regular Expressions

- 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 Σ, the regular expression R represents the language $L(R)$ as follows:

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

DFA: Reminder

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

- Q is a finite set of states
- Σ is a finite set of input symbols
- δ 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 $a_1 a_2$ … is **accepted** by M if there is a state sequence $s_0 s_1$ …:

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

NFA: Reminder

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

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

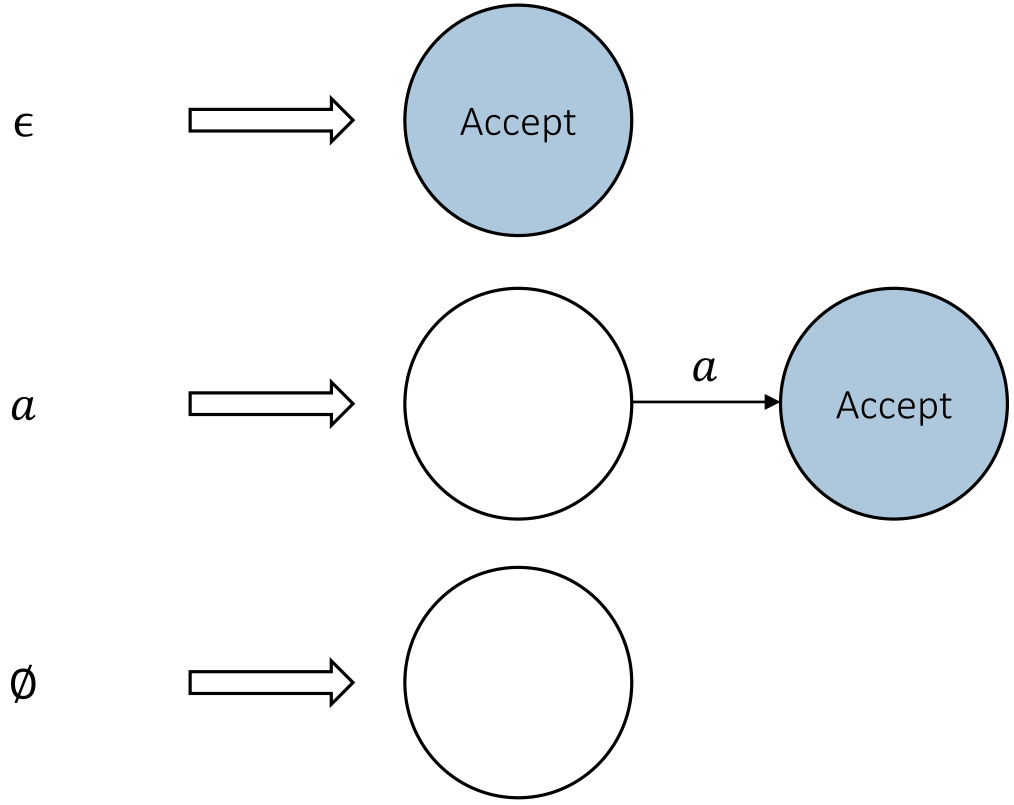
A string $a_1 a_2 \ldots$ is **accepted** by M if there is a state sequence $s_0 s_1 \ldots$:

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

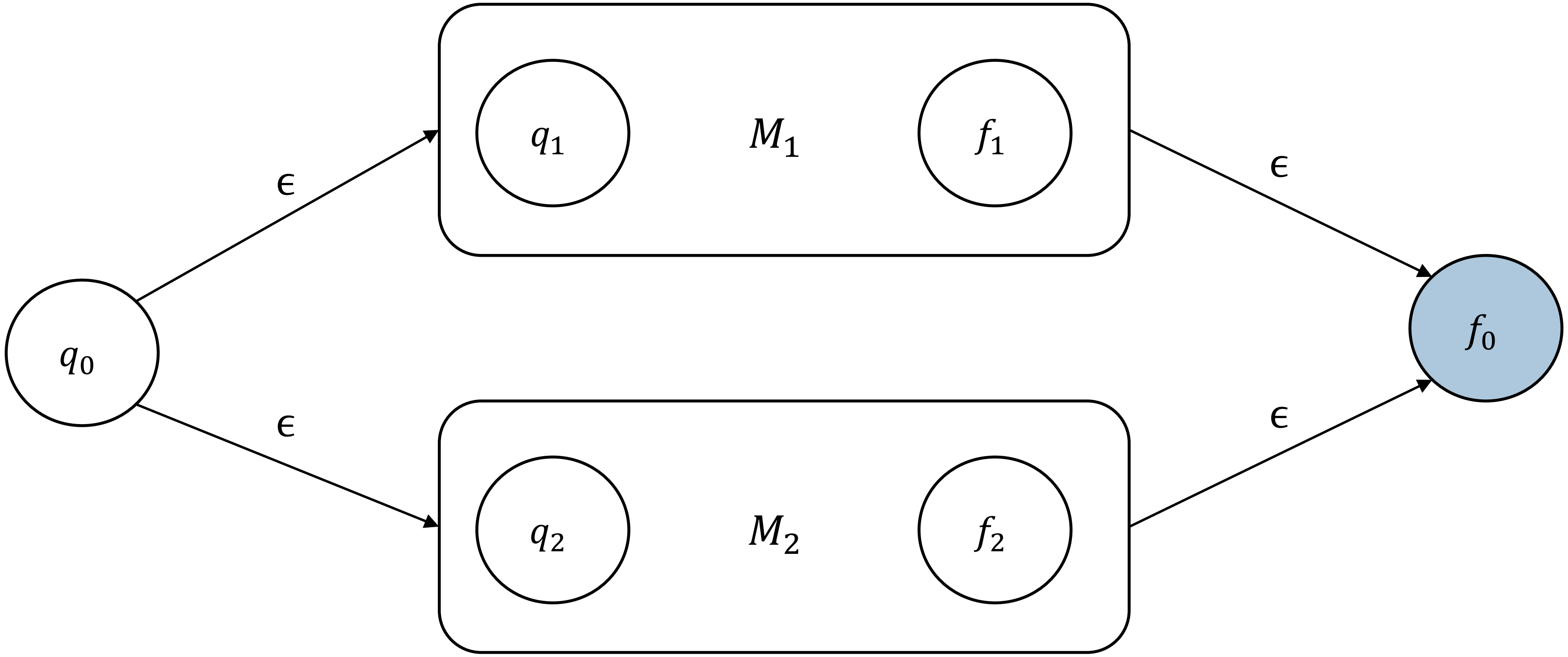
RE to DFA

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

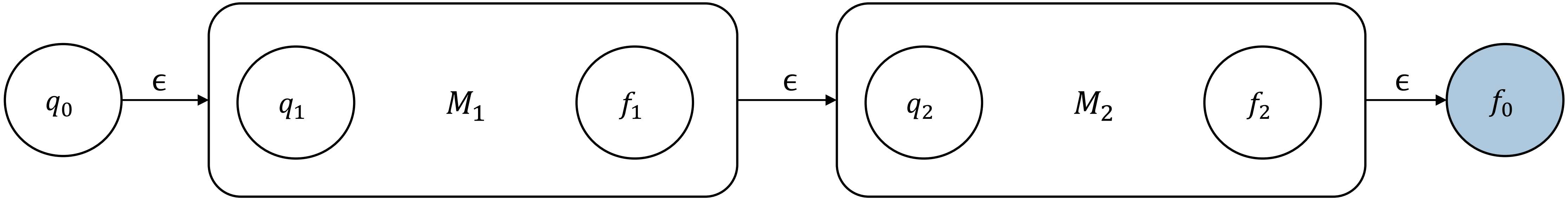
RE to NFA: Atomic Expressions



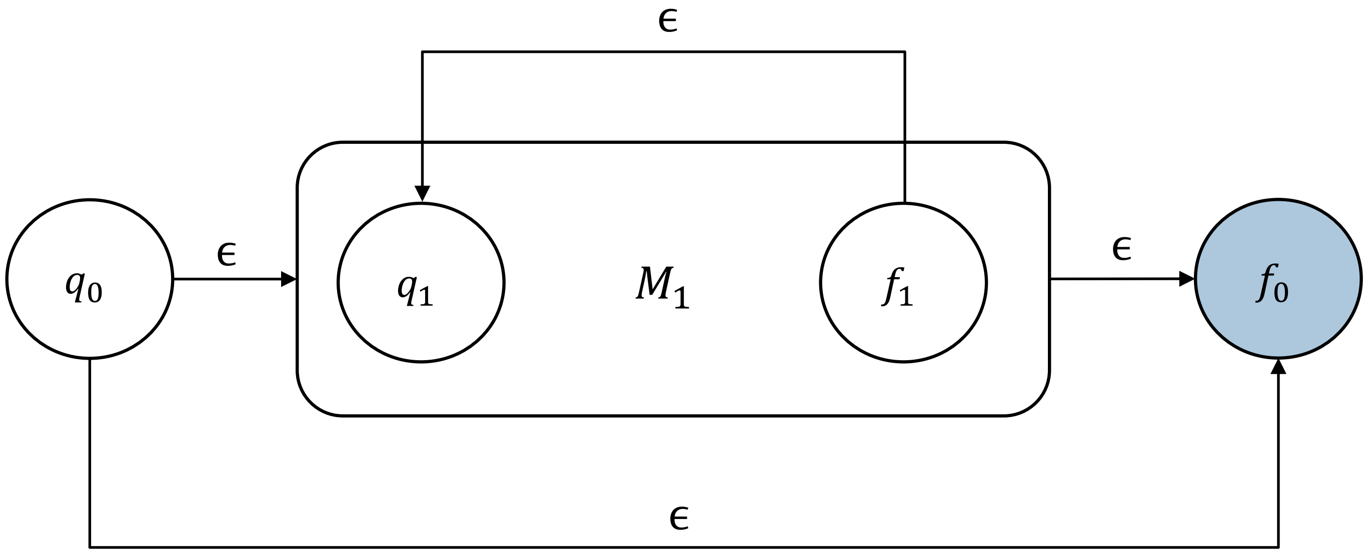
RE to NFA: Union



RE to NFA: Concatenation

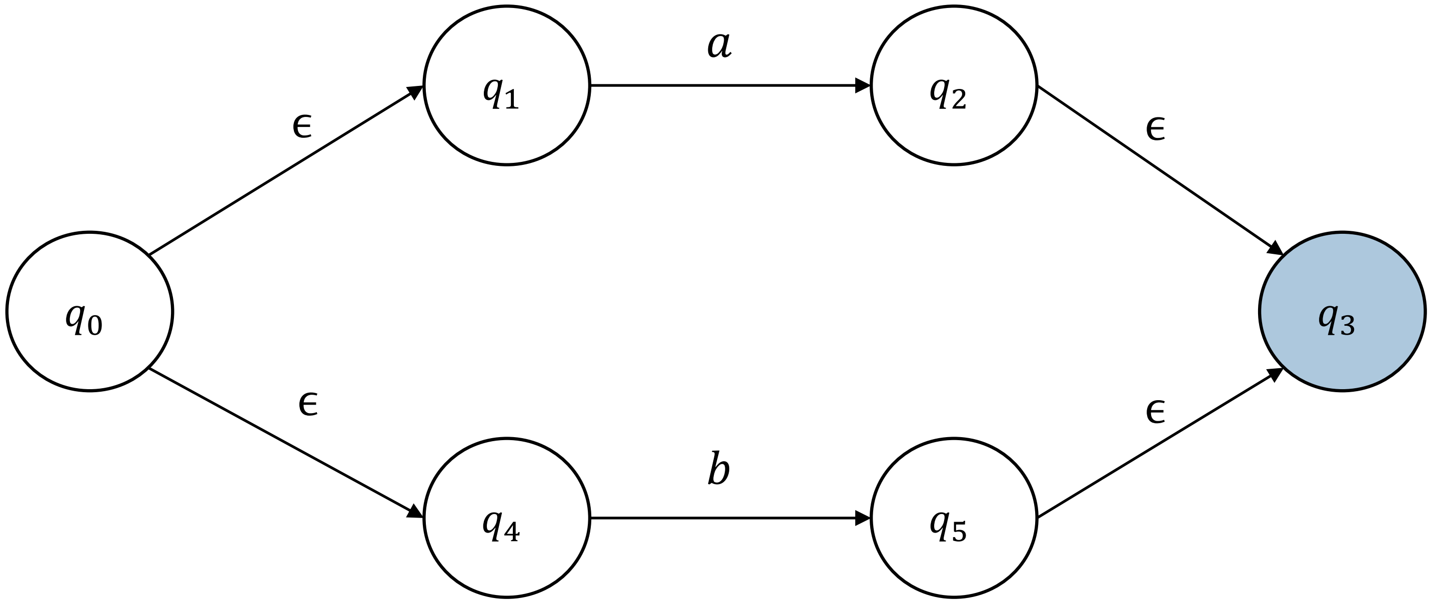


RE to NFA: Kleene Star



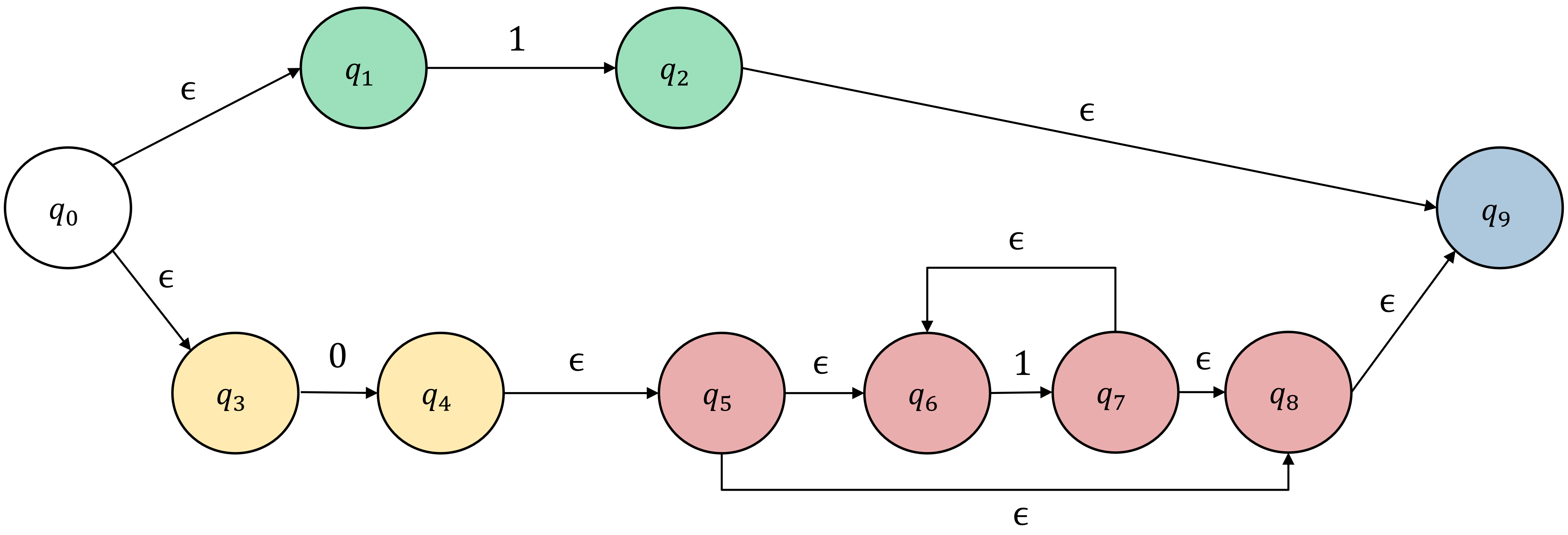
RE to NFA: Example

- NFA for $\mathrm{a} \mid \mathrm{b}$



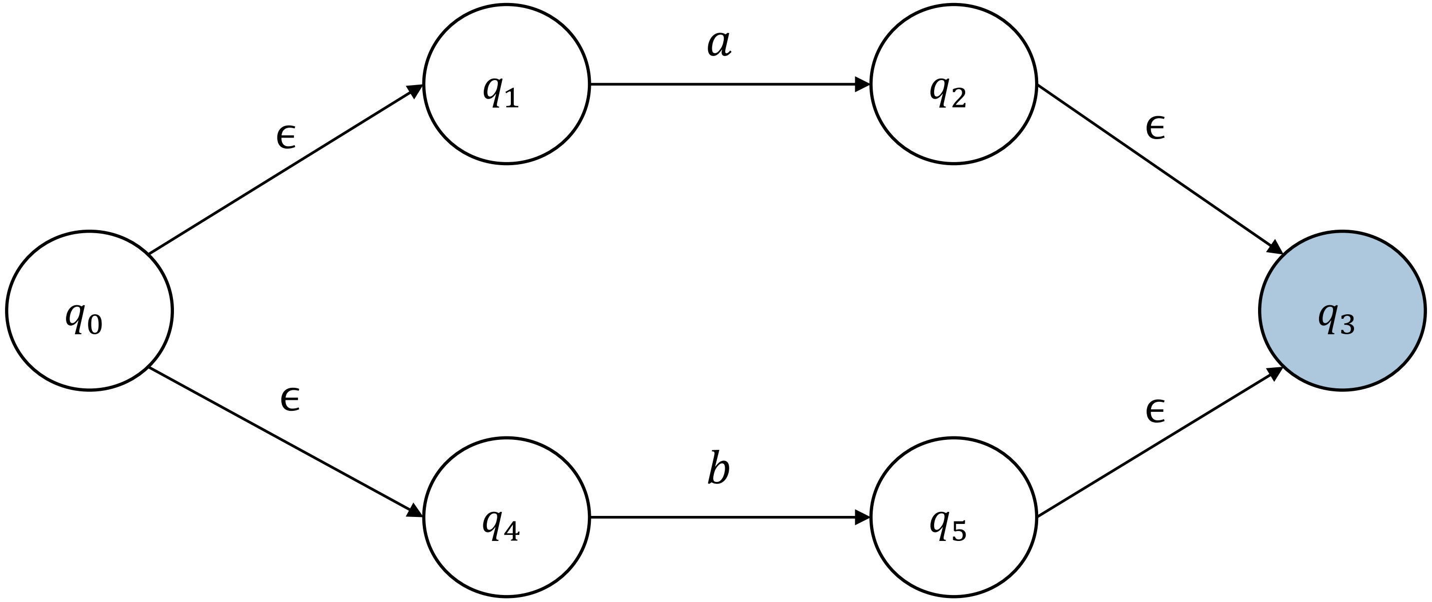
RE to NFA: Another Example

- NFA for $01^* \mid 1$



NFA to DFA: Example

- At the beginning, we may be at: $\mathrm{q}_0, \mathrm{q}_1, \mathrm{q}_4$
- 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: $\mathrm{q_0, q_1, q_4}$
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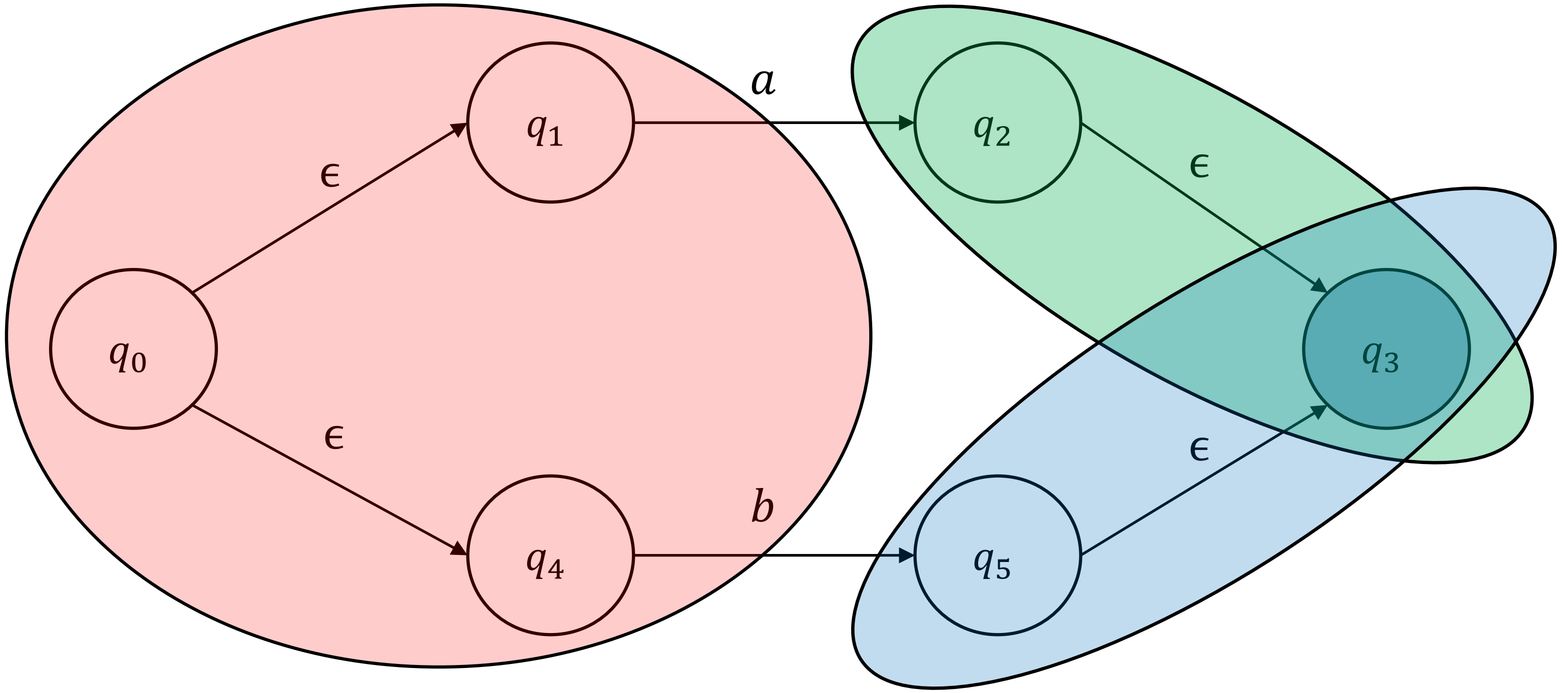
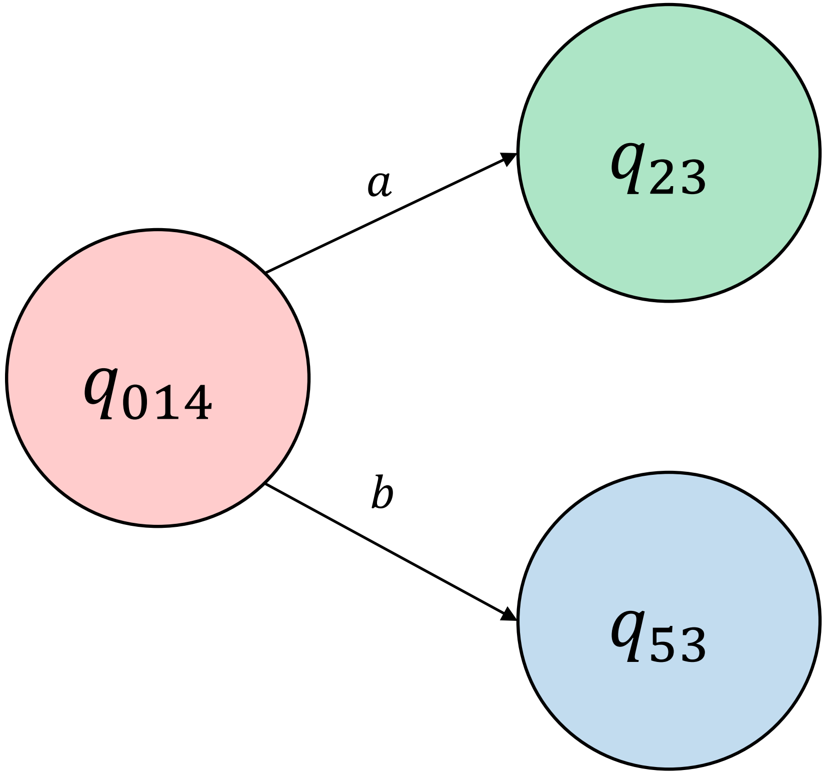


NFA to DFA: Example

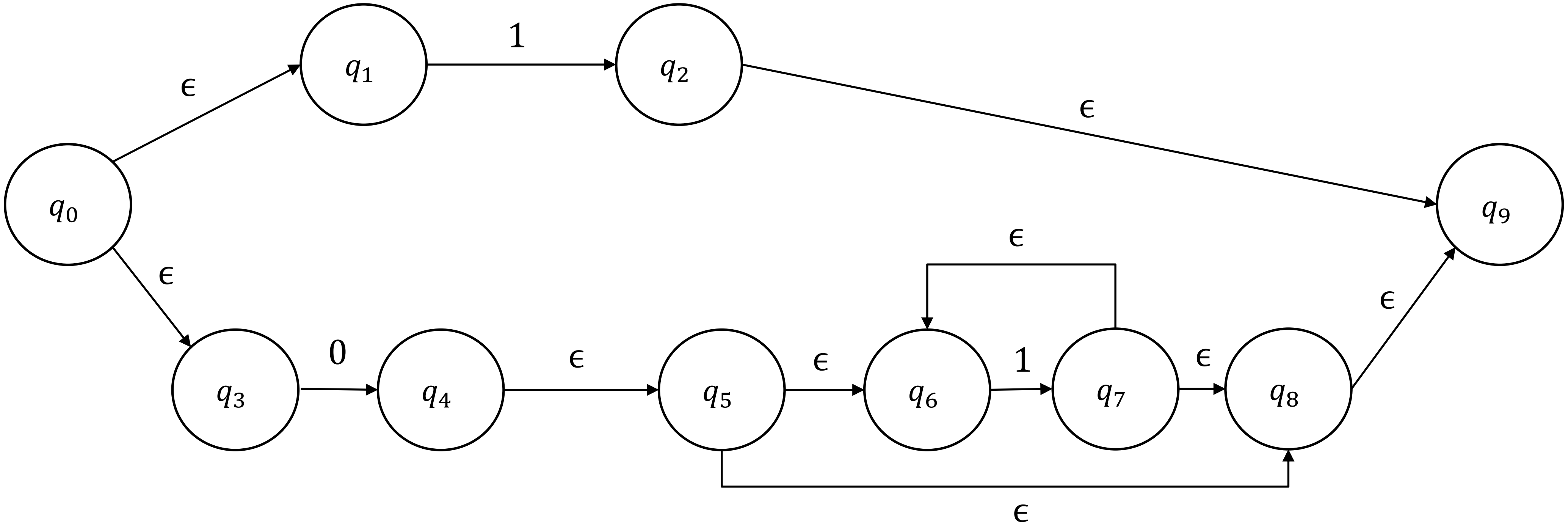
- So we can transform to the following DFA:



NFA to DFA: Formal Details

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

Another Example: NFA to DFA



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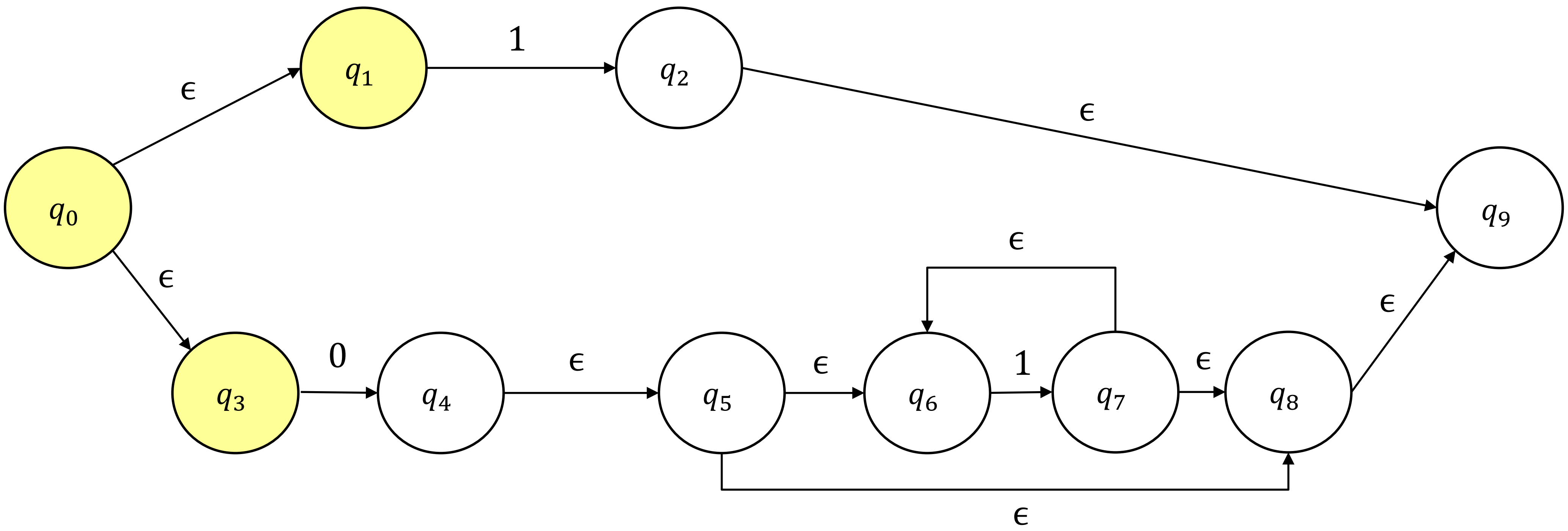

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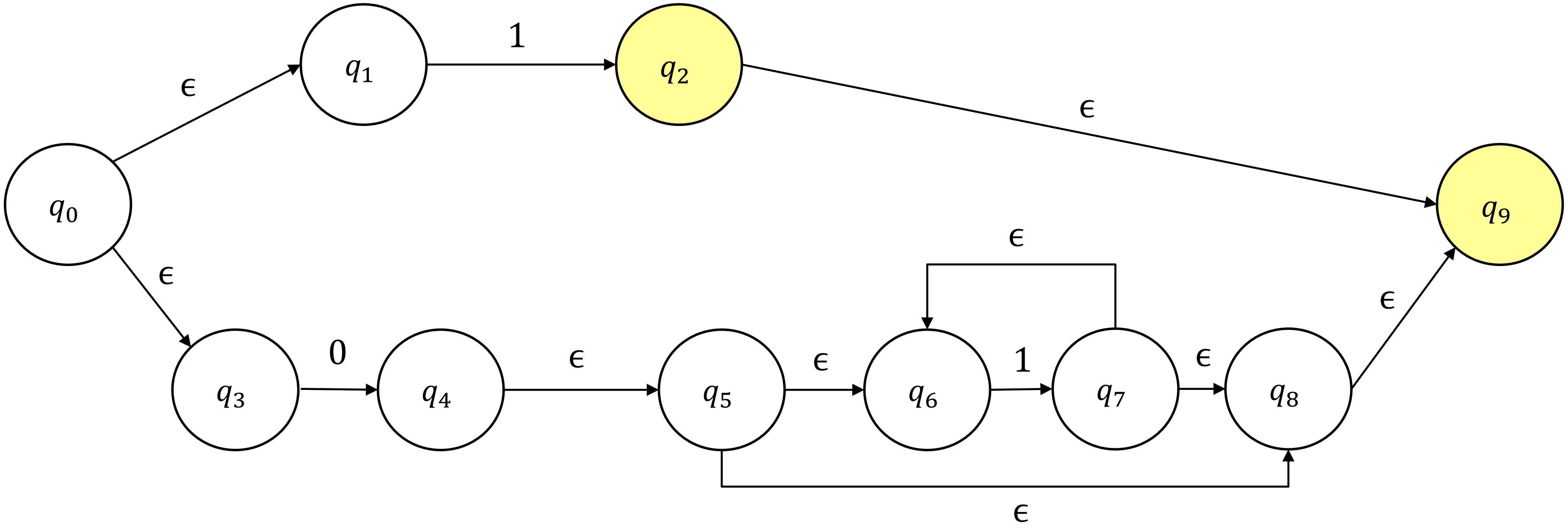

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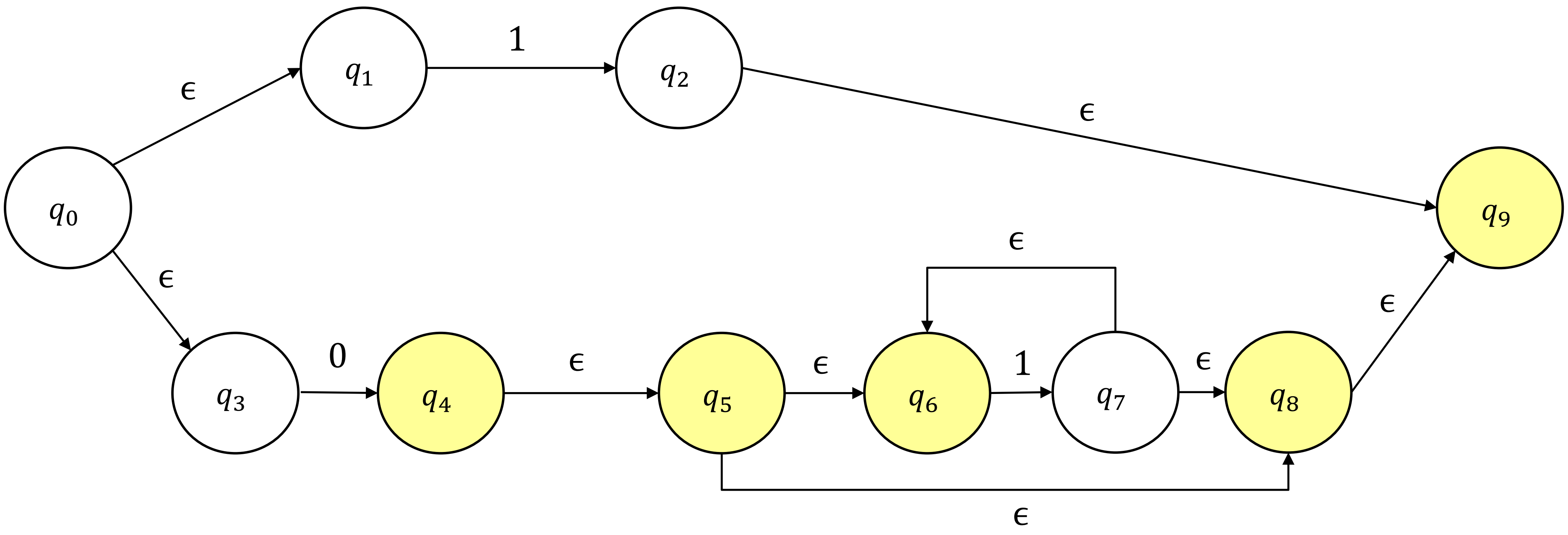

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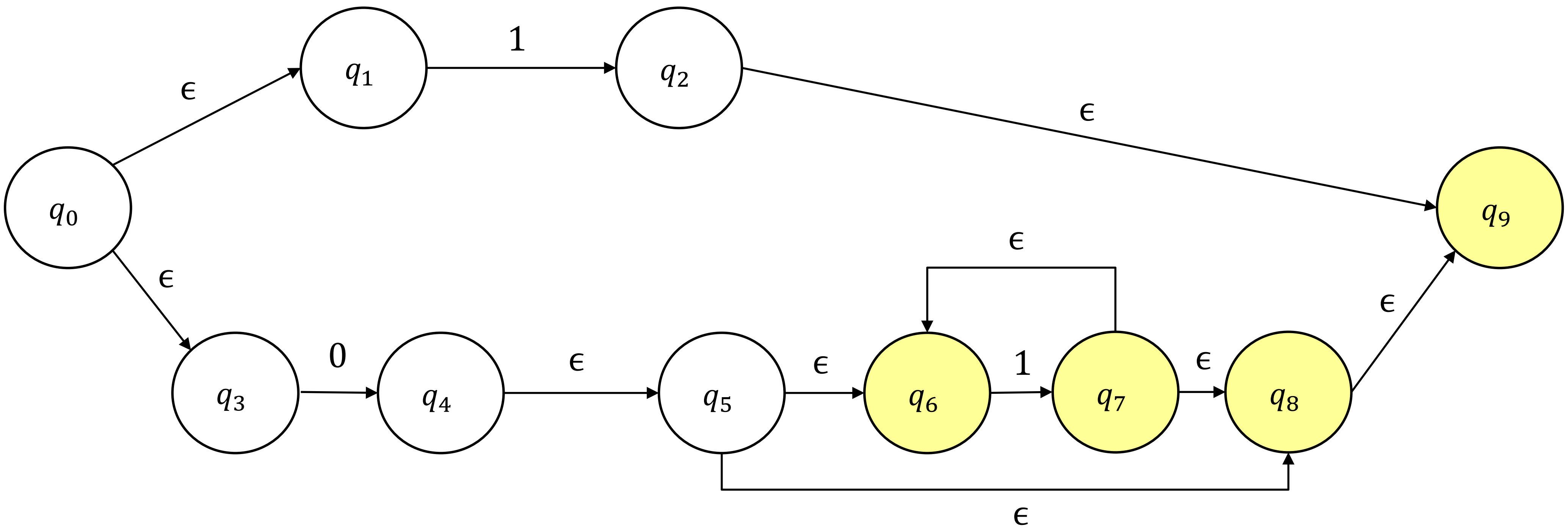

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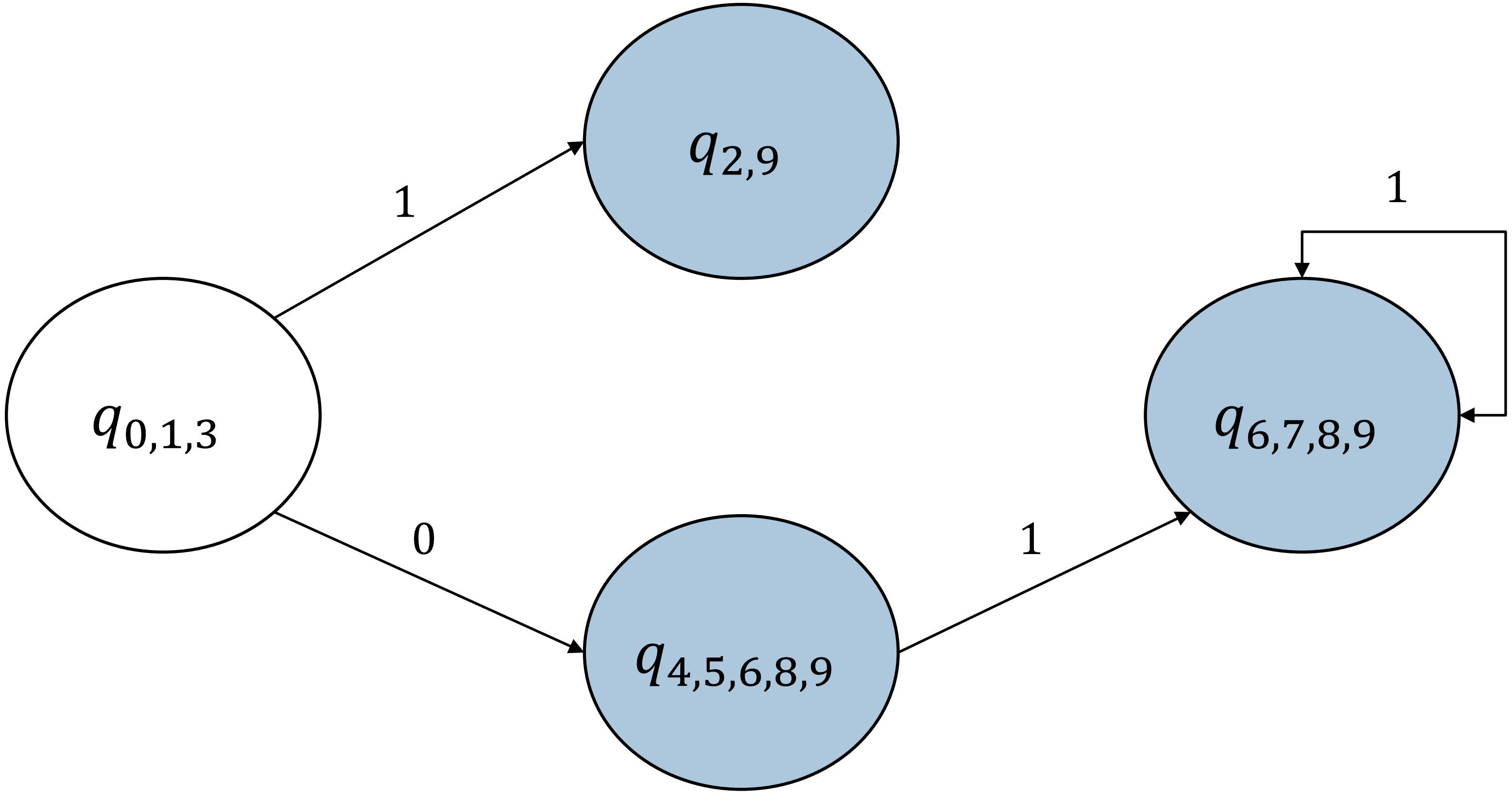


Building a Lexical Analyzer

- 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

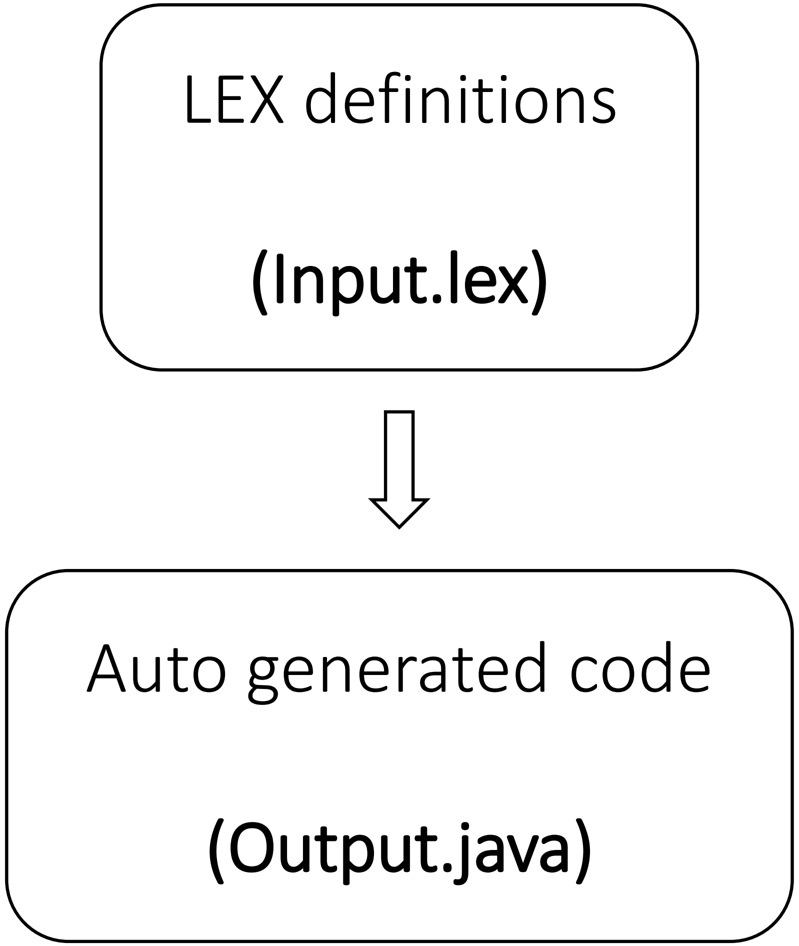
Regular Expressions Definitions for C

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

JFlex

- **J**ava **F**ast **Lex**ical 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

user code

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- Regular Java code
- Pasted to the generated file

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- Macro definitions
- Define a regex for each token

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```
<VAR> = <REGEX>
…

%%
```

- Macro definitions
- Define a regex for each token

rules

```
<STATE> {
{REGEX} {
// java code here
}
…
}
```

- 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:
  - **abcaacacaaabbaaabcaaca**

Exam Questions

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

abcaacacaaabbaaabcaaca

Exam Questions

- Consider the following flex-like definition:
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ab|caacacaaabbaaabcaaca

Exam Questions

- Consider the following flex-like definition:
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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;
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}
```

tokens

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

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```
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;
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```
void f(int a) {
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`(i--)--`

tokens

i	--	--	-	j

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```
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      int i = 8;
      int j = 3;
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```

Invalid

`(i--)--`

tokens

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tokens

(	i	--	)	-	(	--	j	)

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tokens

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tokens

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