Compilation

TEACHING ASSISTANT: DAVID TRABISH

Administration

- Final grade:
  - Exam: 50%
  - Project: 50%
- For technical questions, please use the course forum
  - *Moodle*
- Reception time:
  - Wednesday 17:00 - 1800
  - davidtr1037@gmail.com
  - CheckPoint 246

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 3-4 students
- Constitutes **50%** of the final grade

Submission Guidelines

- Submission with **github**
  - Each group should create a private repository
- Exercises submissions will be tested on **nova**
- **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)

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

```
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, MSVC*
- *GCC* and *LLVM* are both open source
- Very useful as an implementation reference….
  - *LLVM* specially…

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…
- Machine code generation
  - Naive register allocation (as if we had infinitely many registers)
  - Finite register allocation (real world scenario)

Lexical Analysis

Lexical Analysis

- The code text consists of *tokens*
- We need to check the **validity** of these *tokens*

Valid Tokens in C

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

Examples

```
void f(int a) {
     6;
}
```

Examples

```
void f(int a) {
      6;
}
```

Valid

Examples

```
void f(int a) {
     6b;
}
```

Examples

```
void f(int a) {
      6b;
}
```

Valid

Examples

```
void f(int a) {
     0x;
}
```

Examples

```
void f(int a) {
      0x;
}
```

Valid

Examples

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

Examples

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

Valid

Examples

```
void f(int a) {
```

Examples

```
void f(int a) {
```

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Valid

Examples

```
void f(int a) {
      x 1
}
```

Examples

```
void f(int a) {
      x 1
}
```

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Invalid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Invalid

Examples

```
void f(int a) {
        123e;
}
```

Examples

```
void f(int a) {
      123e;
}
```

Valid

Examples

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

Examples

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

Valid

Examples

```
void f(int a) {
      int x = 0x00000000000000007;
}
```

Examples

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

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Invalid

Examples

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

Examples

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

Valid

Examples

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

Examples

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

Valid

Examples

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

Examples

```
void f(int a) {
      “1234”;
}
```

Valid

Examples

```
void f(int a) {
     ‶1234;
}
```

Examples

```
void f(int a) {
      "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

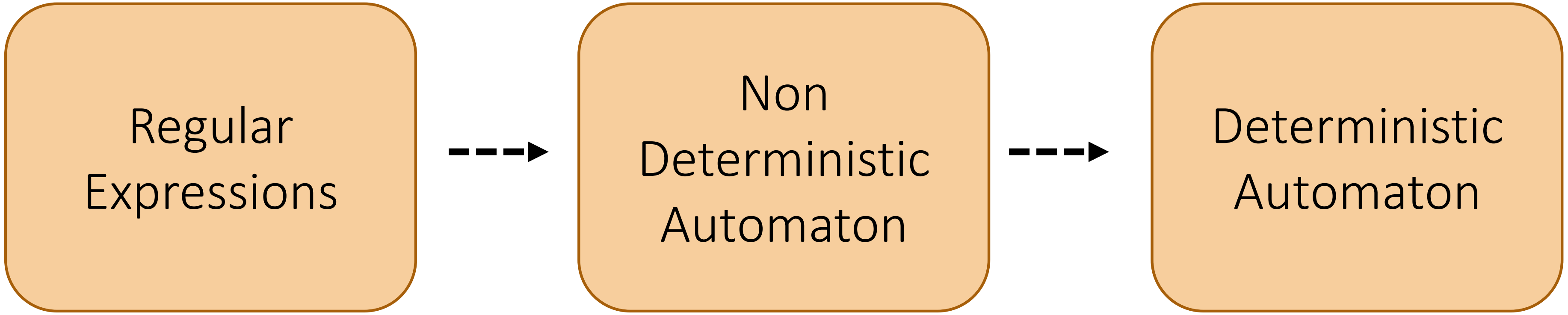
Using Regular Expressions

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

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 $s_0 s_1$ …:

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

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

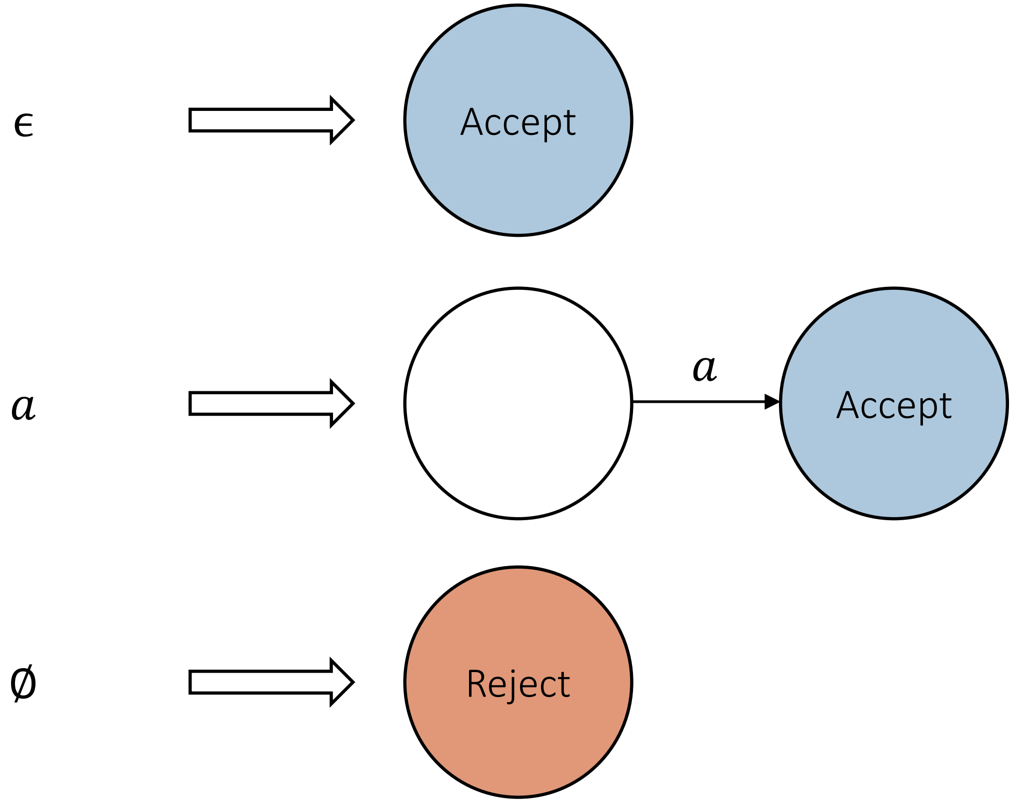
A string $a_1 a_2$ … is **accepted** by M if there is a state sequence $s_0 s_1$ …:

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

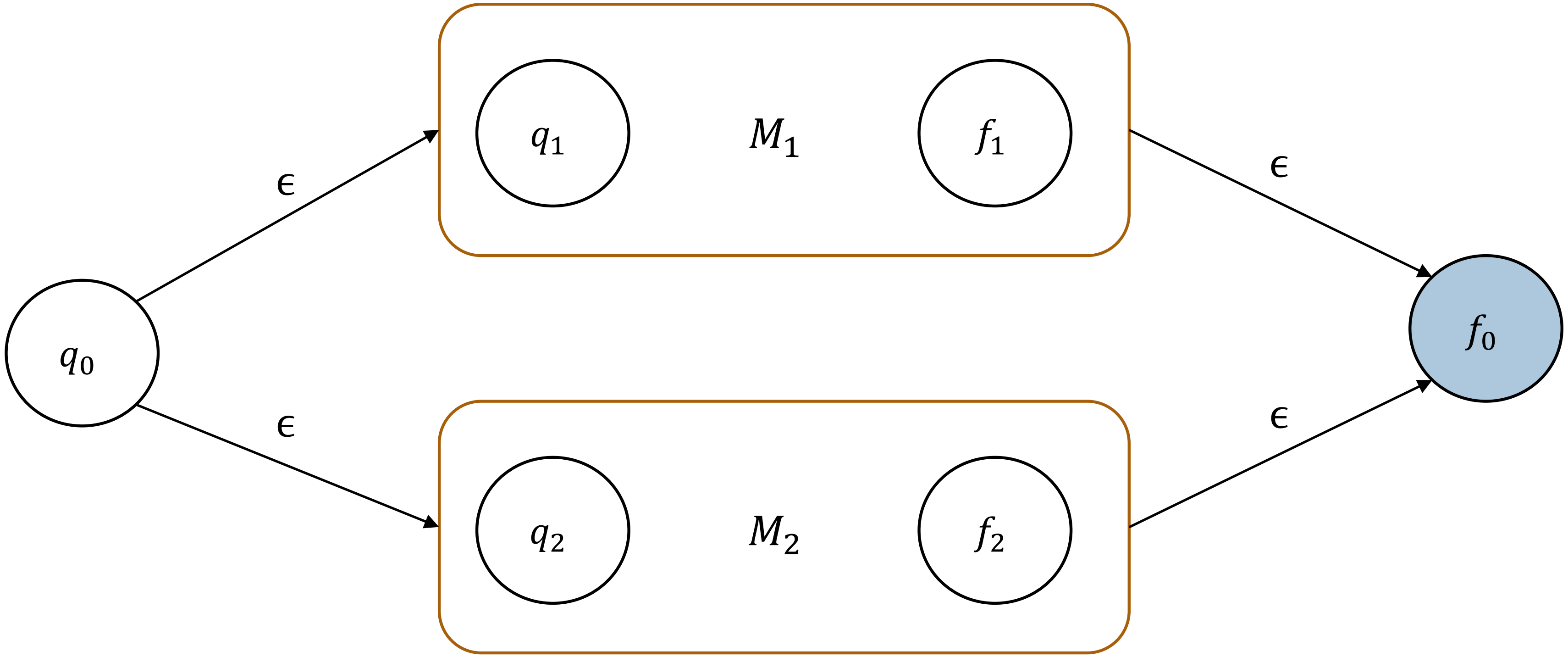
RE to DFA

- 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*

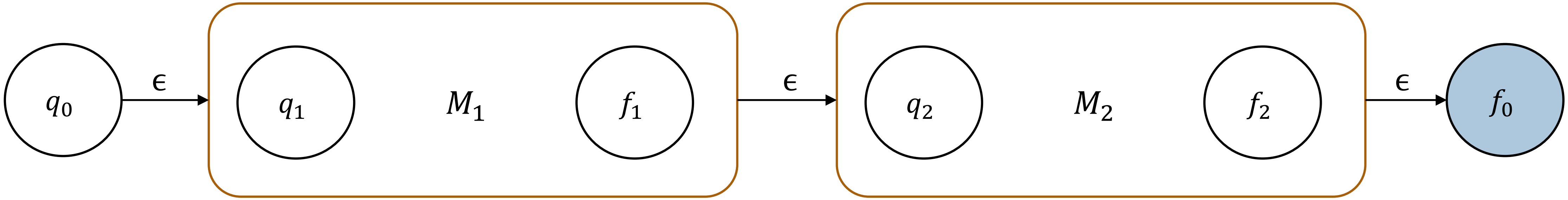
RE to NFA: Atomic Expressions



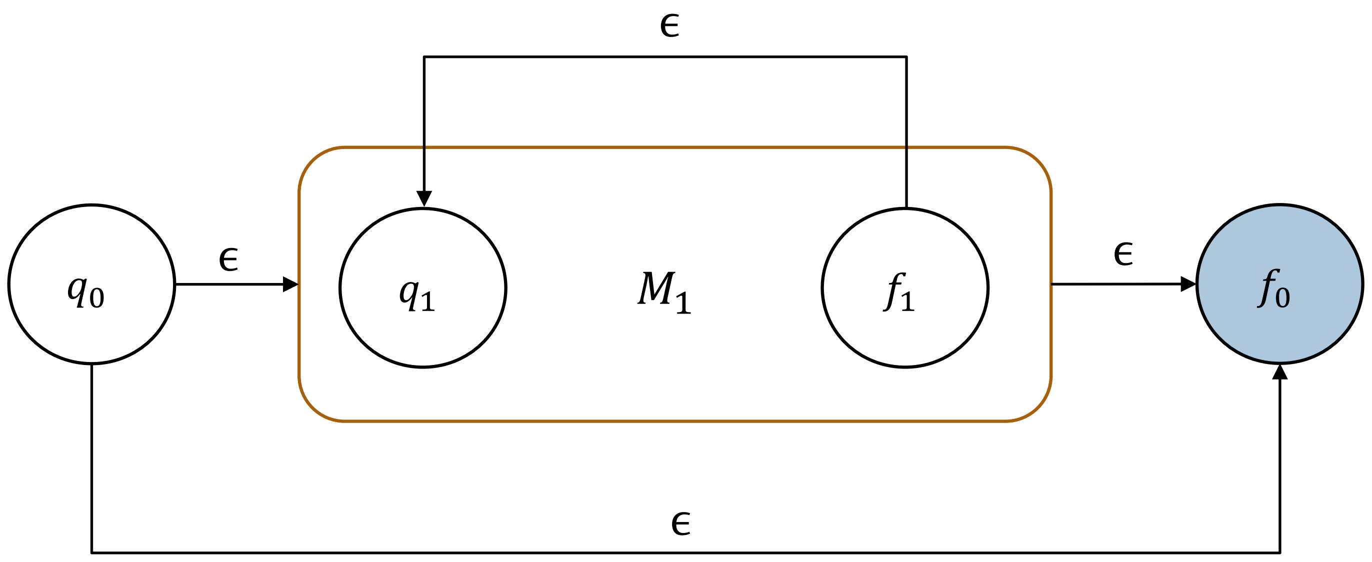
RE to NFA: Union



RE to NFA: Concatenation

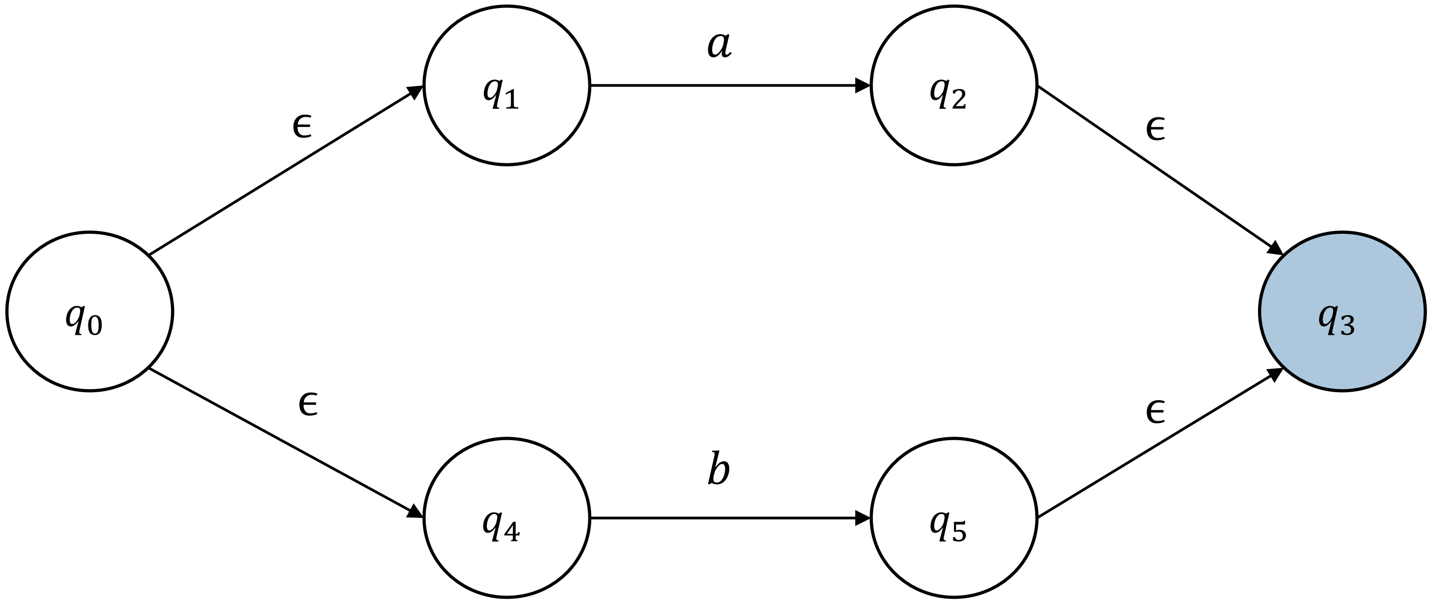


RE to NFA: Kleene Star



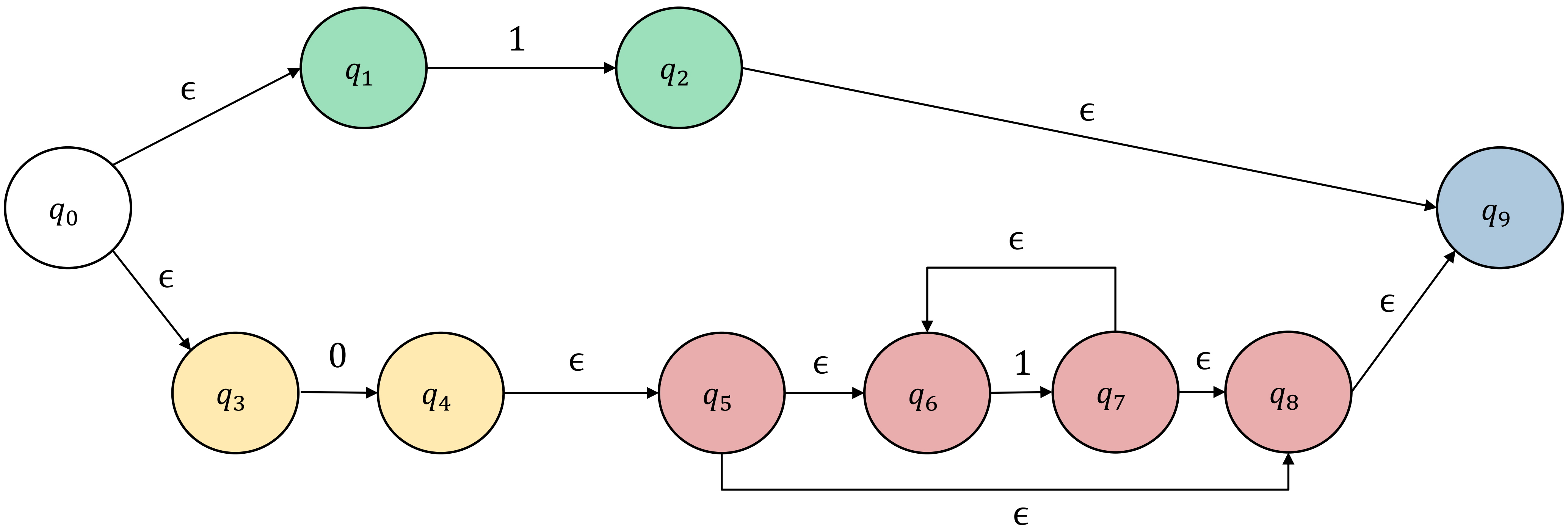
RE to NFA: Example

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



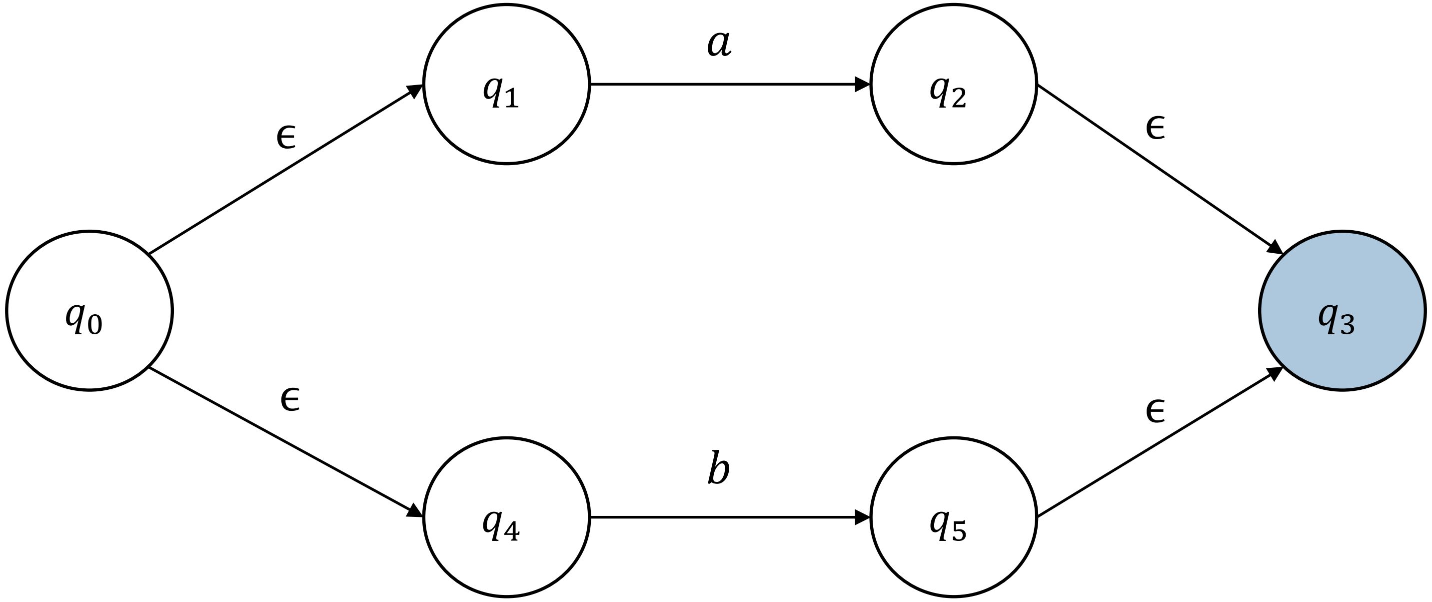
RE to NFA: Another Example

- NFA for $\mathbf{01^* \mid 1}$



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: $\mathrm{q}_0, \mathrm{q}_1, \mathrm{q}_4$
- If next token is a then we may be at: q_2, q_3
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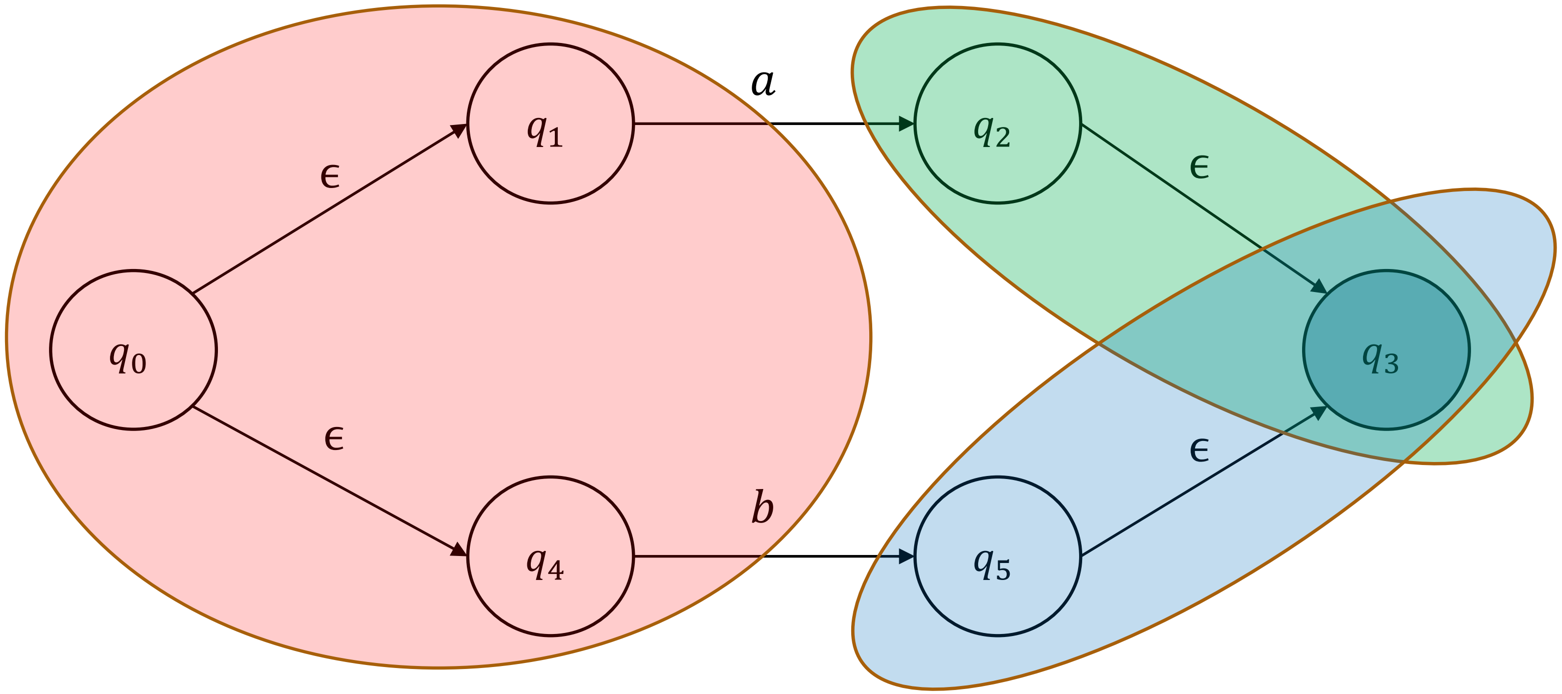
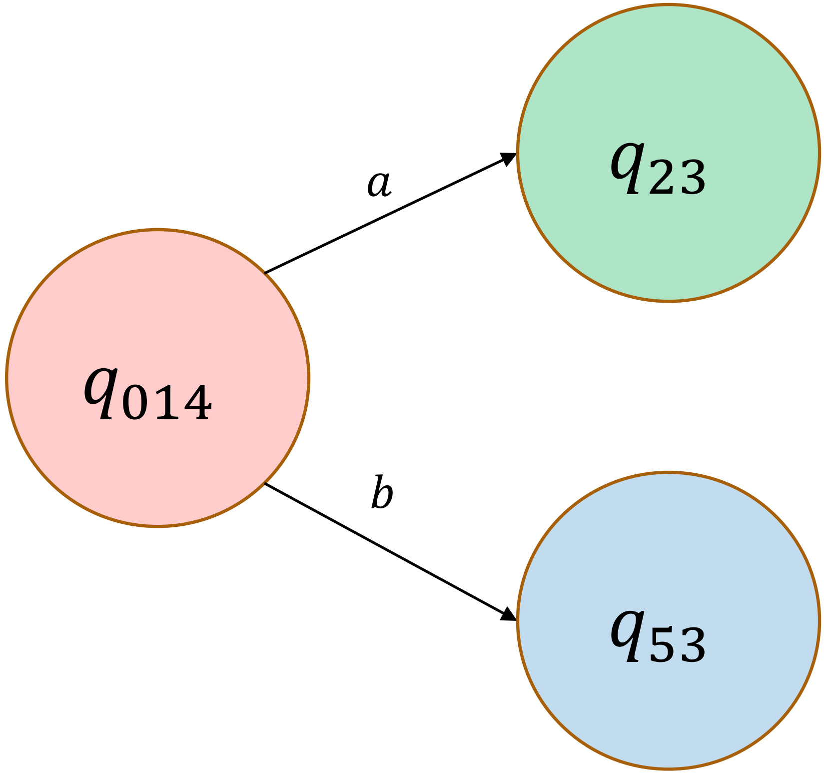


NFA to DFA: Example

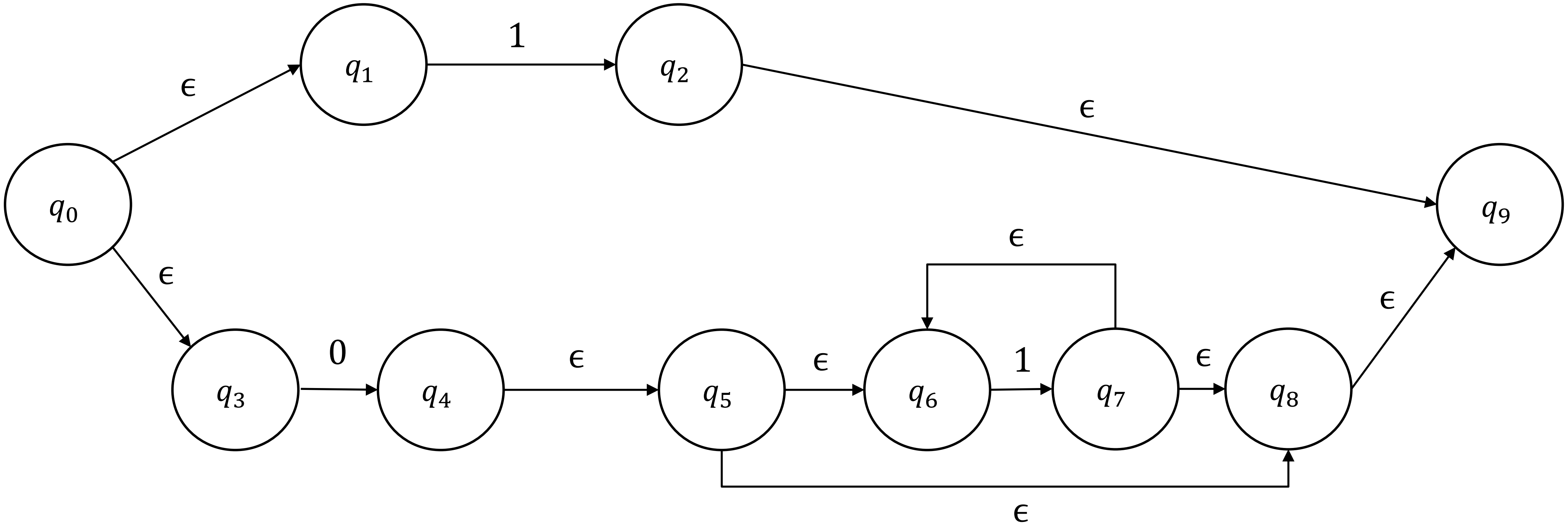
- So we can transform to the following DFA:



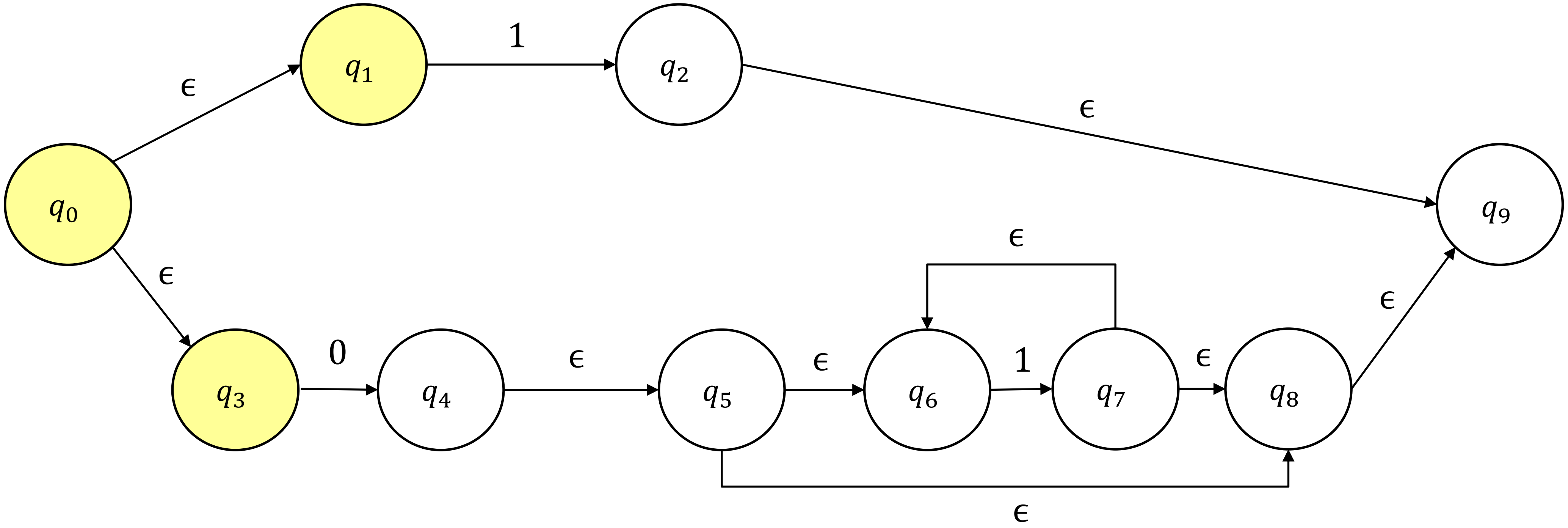
NFA to DFA: Formal Details

- Let $(Q, \Sigma, \Delta, q_0, F)$ be a non-deterministic finite automaton
- The set of states is the $\mathrm{P}(\mathrm{Q})$
- The initial state is the *ϵ-closure* of $\mathbf{q_0}$
- 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 set from F

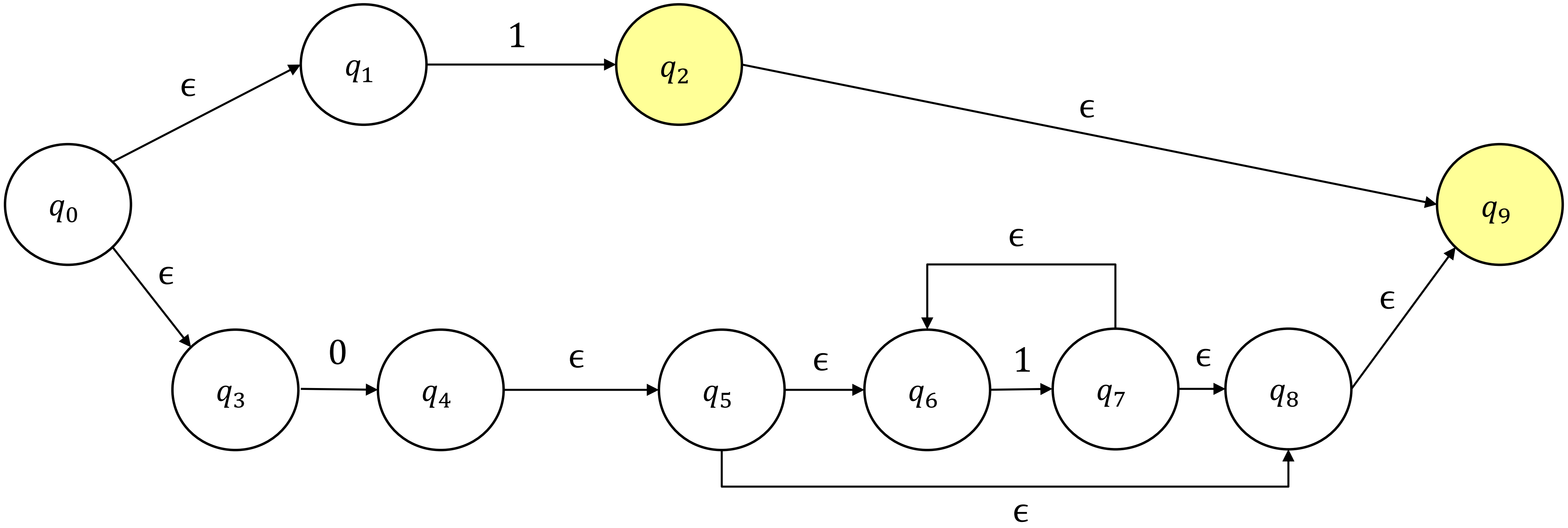
Another Example: NFA to DFA



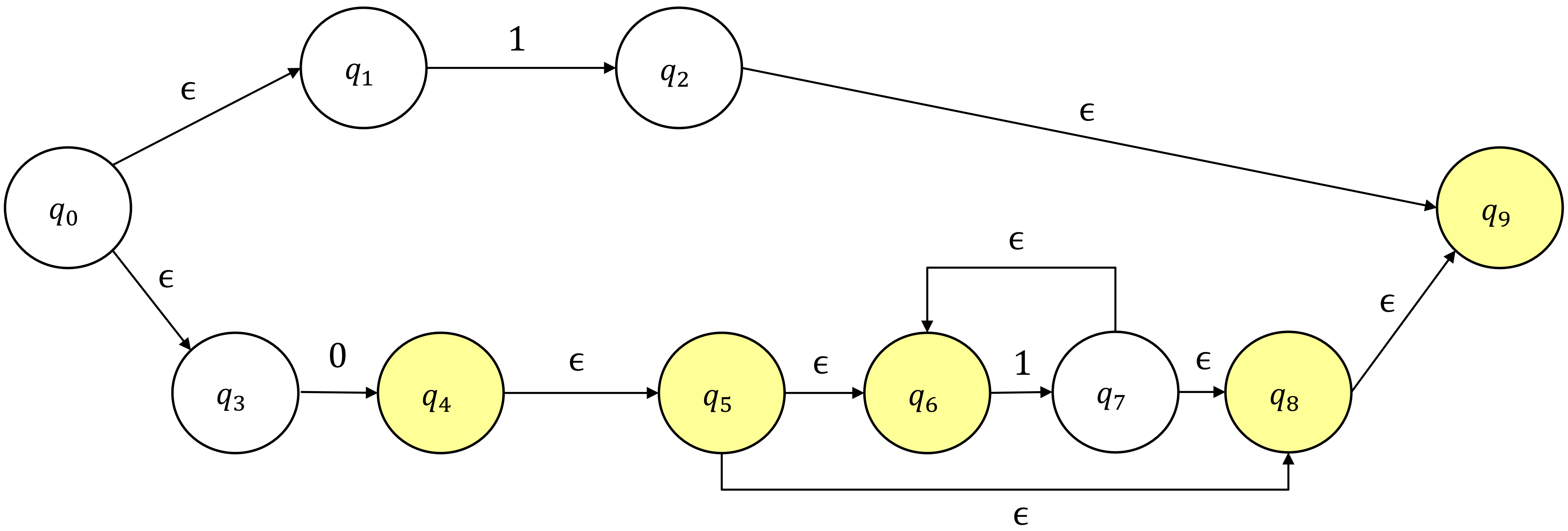
Another Example: NFA to DFA



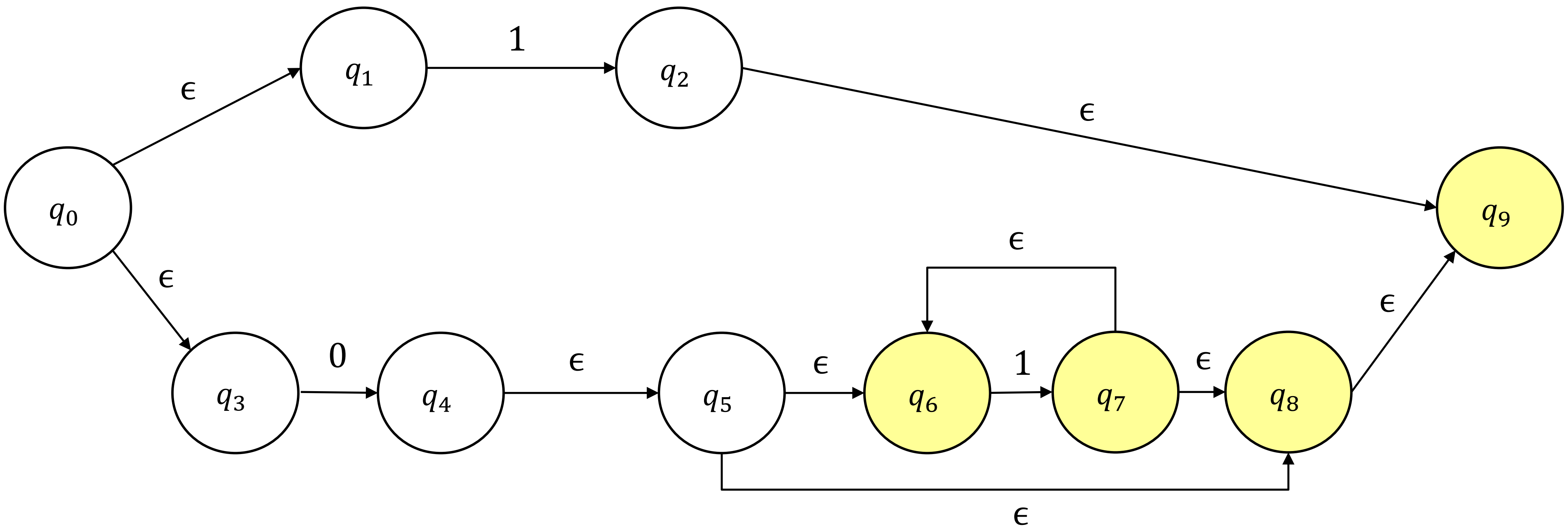
Another Example: NFA to DFA



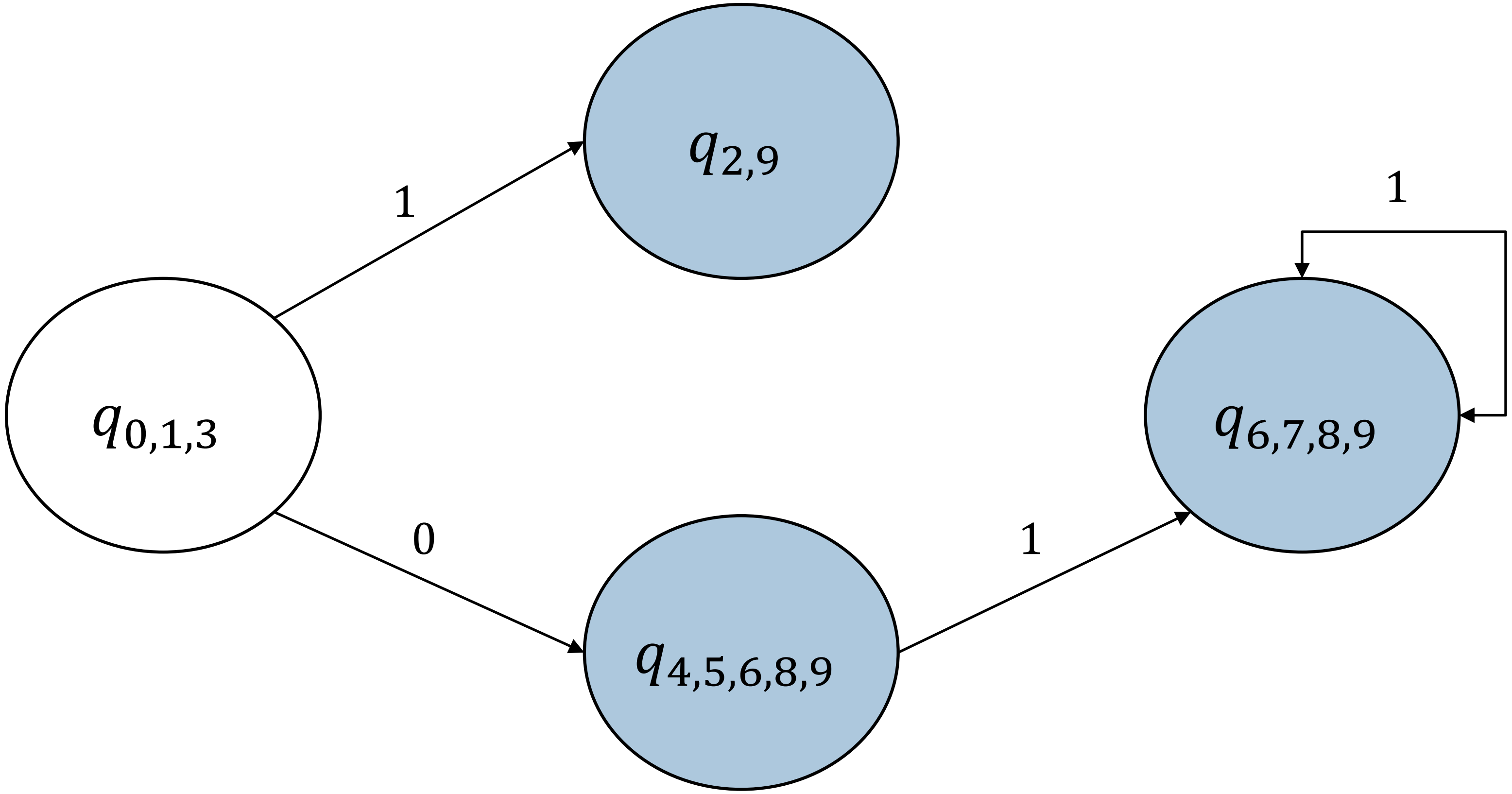
Another Example: NFA to DFA



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 (a token is accepted in more than one DFA):
  - Define priority
  - Token with longest match wins
  - If more than one matching token:
    - The token that was defined earlier will take advantage

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 Definitions
(Def.lex)

→

Auto generated
Code
(Lexer.java)

Example 1

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

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: 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: Lex Definitions

User define code/handlers:

```
%{
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

Regular expressions definitions:

A = a
B_STAR = b*

Example 1: Lex Definitions

Putting it all together:

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

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?
- What will happened without it?

Example 2: Counting Words

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

Counting Words: Tokens Definitions

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

Counting Words: 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 = \n|.
%%  // separator…
<YYINITIAL> {
{WORD} { words_count++; }
{ANY} { }
<<EOF>> { return symbol(TokenNames.EOF); }
}
```

Example 2: Counting Words

Other definitions instead of **ANY**?

Example 2: Counting Words

Other definitions instead of **ANY**?

- [^a-zA-Z]+

Example 3: Calculator

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

Example 3: Calculator

```
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: Calculator

Regular expressions definitions:

PLUS = "+“
L_PAREN = "(“
R_PAREN = ")“
NUMBER = [0-9]+

Example 3: Calculator

Putting it all together:

```
<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: Calculator

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:

- $aabbbba$

Example 4: Definition Order

What will be the output for:

- $aabbbba$

[1,1]:1
[1,2]:2
[1,7]:1

Example 4: Definition Order

What will be the output if we swap the order (same input)?

```
{T2} { return symbol(TokenNames.T2); }
{T1} { return symbol(TokenNames.T1); }
```

Example 4: Definition Order

What will be the output if we swap the order (same input)?

```
{T2} { return symbol(TokenNames.T2); }
{T1} { return symbol(TokenNames.T1); }
```

[1,1]:2
[1,2]:2
[1,7]:2

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

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ab|caacacaaabbaaabcaaca

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ab|caa|cacaaabbaaabcaaca

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ab|caa|ca|caaa|b|b|aaabcaaca

Exam Questions

- Consider the following flex-like definition:
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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|caa|ca|caaa|b|b|aaab|caa|ca

Exam Questions

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

ab | caa | ca | caaa | b | b | aaab | caa | 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;
}
```

Valid

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;
}
```

Invalid

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);
}
```

Valid

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);
}
```

Valid