

# **CSS125**

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## **notes and stuff**

*Petcham*

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# Racket Functional Programming

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## Data Types

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```
42, -5      ; integer
3.14        ; float
1/3         ; rational
#t, #f      ; boolean
"text"      ; string
'symbol     ; symbol
'(1 2 3)    ; list
#(1 2 3)    ; vector
```

## Variables

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- **Types:** Implicit
- **Typing:** Dynamic

```
(define x 10)          ; global binding
(let ([a 5] [b 10]) (+ a b)) ; local binding
```

## Control Structures

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```
; Branching
(if (> x 0) "pos" "neg")
(cond [(> x 0) "pos"] [(< x 0) "neg"] [else "zero"])

; Iteration
(define (countdown n)      ; recursion
  (if (= n 0) 'done (countdown (- n 1))))
(for ([i (range 1 6)]) (display i)) ; loop
```

# Functions

---

```
(define (name param1 param2) body)      ; definition
(lambda (x) (* x x))                    ; anonymous
```

## Exercises

---

### 1. Hello World

```
(display "Hello, World!")
```

### 2. Read/Echo Integer

```
(display "Enter an integer: ")
(define input (read))
(sprintf "You entered ~a~n" input)
```

### 3. Prime Checker

```
(define (is-prime? n)
  (cond [(<= n 1) #f] [(= n 2) #t] [(even? n) #f]
        [else (prime-helper n 3)]))

(define (prime-helper n div)
  (cond [(> (* div div) n) #t] [(= (remainder n div) 0) #f]
        [else (prime-helper n (+ div 2))]))

(display "Enter integer: ")
(define num (read))
(sprintf "~a is ~a prime~n" num (if (is-prime? num) "" "not"))
```

### 4. Math Expression: $x^2 + (\log_{10}(x) - \sin(x))/\sqrt{x}$

```
(define (calc x)
  (+ (expt x 2) (/ (- (log x 10) (sin x)) (sqrt x))))

(display "Enter float x: ")
(define x (read))
(if (<= x 0)
    (display "Error: x must be positive")
    (printf "Result: ~a~n" (calc x)))
```

# Lexical Analysis

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## Learning Objectives

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- Understand the role of the lexical analyzer in compilation
  - Learn about tokens, patterns, and lexemes
  - Explore lexical error handling
  - Master regular expressions for token specification
- 

## Guide Questions

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1. **What is the role of the lexical analyzer?**
  2. **Why should parsing be separated from lexical analysis?**
  3. **What are tokens, patterns, and lexemes and what are the differences between these three?**
  4. **What are lexical errors and how are they handled?**
  5. **How is a lexical definition of a language specified?**
- 

## The Role of the Lexical Analyzer

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The lexical analyzer serves as the **first phase of the compiler** and performs several crucial functions:

- **Converts raw text into tokens** - Transforms the source code from a stream of characters into meaningful units
- **Strips out whitespace and comments** - Removes unnecessary formatting and documentation that doesn't affect program logic
- **Correlates error messages** - Links compiler errors back to specific locations in the source code
- **Tracks position information** - Maintains line numbers and column numbers for debugging purposes

## Example Flow

---

```
Source Code: "int x = 42; // this is a variable"
↓
Lexical Analyzer
↓
Tokens: [INT_KEYWORD, IDENTIFIER(x), ASSIGN_OP, NUMBER(42), SEMICOLON]
```

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## Issues in Lexical Analysis

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### Why Separate Parsing from Tokenization?

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#### 1. Simplicity in Design

- Each phase has a single, well-defined responsibility
- Lexical analyzer focuses only on character-level recognition
- Parser focuses only on grammatical structure

#### 2. Improvement in Efficiency

- Specialized algorithms for each phase
- Better performance through focused optimization
- Reduced complexity in each component

#### 3. Compiler Portability Enhanced

- Easy to adapt lexical analyzer for different character sets
  - Grammar rules remain unchanged across platforms
  - Modular design allows independent updates
-

# Tokens, Patterns, and Lexemes

## Definitions

- **Token** - A category or label for lexical units (like a part of speech in grammar)
- **Pattern** - The rule or regular expression that defines how to recognize a token
- **Lexeme** - The actual text from source code that matches a token's pattern

## Example Breakdown

Component	Value	Description
Token	identifier	Category name
Pattern	/[A-Za-z_][A-Za-z0-9_]*	Rule for recognition
Lexeme	"nCount"	Actual text found

## Fortran Statement Example

For the statement: `E = M * C ** 2`

Lexeme	Token	Attributes
E	<id, pointer to symbol-table entry for E>	Variable identifier
=	<assign_op>	Assignment operator
M	<id, pointer to symbol-table entry for M>	Variable identifier
*	<mult_op>	Multiplication operator
C	<id, pointer to symbol-table entry for C>	Variable identifier
**	<exp_op>	Exponentiation operator
2	<number, integer value 2>	Numeric literal



# Important Notes

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- **Tokens serve as terminal symbols** in a language's grammar
  - **Reserved strings** are lexemes with specific meaning (keywords like `if`, `while`)
  - **Attributes** provide additional information when multiple lexemes match the same token pattern
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## Lexical Errors

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### What Are Lexical Errors?

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- Occur when **no pattern matches** the current sequence of characters
- Few errors are detectable at lexical level alone
- Example: `fi(a == f (x))` - `fi` might be a typo for `if`

### Error Recovery Strategies

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#### 1. Panic Mode

- Delete characters until a well-formed token can be created
- Simple but may skip over multiple errors

#### 2. Deletion

- Remove one character from the problematic lexeme
- Try to match again with shortened string

#### 3. Insertion

- Add a character to the current lexeme
- Attempt to create valid token

#### 4. Replacement

- Replace one character in the current lexeme
- Most common for typos

## 5. Transposition

- Swap adjacent characters
  - Handles common typing mistakes
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# Specifications of Tokens

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Tokens are specified using **regular expressions** - mathematical formulas that describe text patterns.

## Basic Concepts

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### Alphabet ( $\Sigma$ )

- Finite set of symbols
- Examples: ASCII (128 characters), Extended ASCII (256 characters)

### String

- Finite sequence of symbols from an alphabet
- Each symbol must be from the defined alphabet  $\Sigma$

### String Length

- Number of symbols in string  $S$
- Denoted by  $|S|$
- Empty string ( $\epsilon$ ) has length 0

### Language

- Set of strings defined over an alphabet
  - If language  $L$  is over alphabet  $\Sigma$ , then  $L \subseteq \Sigma^*$
  - $\Sigma^*$  = set of all possible strings from symbols in  $\Sigma$
-

# String Set Operations

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## Union ( $L_1 \cup L_2$ )

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- **Definition:** Set of strings in either  $L_1$  or  $L_2$  (or both)
- **Example:** If  $L_1 = \{\text{cat}, \text{dog}\}$  and  $L_2 = \{\text{bird}, \text{cat}\}$ , then  $L_1 \cup L_2 = \{\text{cat}, \text{dog}, \text{bird}\}$

## Concatenation ( $L_1 L_2$ )

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- **Definition:** Set of strings formed by concatenating each string in  $L_1$  with each string in  $L_2$
- **Example:** If  $L_1 = \{a, b\}$  and  $L_2 = \{c, d\}$ , then  $L_1 L_2 = \{ac, ad, bc, bd\}$

## Kleene Closure ( $L^*$ )

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- **Definition:** Set containing  $\epsilon$  and all strings formed by concatenating zero or more strings from  $L$
- **Example:** If  $L = \{a, b\}$ , then  $L^* = \{\epsilon, a, b, aa, ab, ba, bb, aaa, aab, \dots\}$

## Positive Closure ( $L^+$ )

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- **Definition:** Set of all strings formed by concatenating one or more strings from  $L$
  - **Example:** If  $L = \{a, b\}$ , then  $L^+ = \{a, b, aa, ab, ba, bb, aaa, aab, \dots\}$
  - **Note:**  $L^+ = LL$  ( $L$  concatenated with  $L$ )
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# Regular Expressions

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Regular expressions are patterns that match strings in a language. They use special symbols to describe text patterns.

# Basic Symbols

Symbol	Meaning	Example
a	Literal character 'a'	Matches exactly 'a'
ε	Empty string	Matches nothing (zero length)
∅	Empty set	Matches no strings

# Operators

Operator	Name	Description	Example
	Union/OR	Either pattern	a   b matches 'a' or 'b'
• or concatenation	Concatenation	One after another	ab matches 'a' followed by 'b'
*	Kleene Star	Zero or more	a* matches "", 'a', 'aa', 'aaa'...
+	Plus	One or more	a+ matches 'a', 'aa', 'aaa'...
?	Question	Zero or one	a? matches "" or 'a'
[ ]	Character class	Any character inside	[abc] matches 'a', 'b', or 'c'
[ ^ ]	Negated class	Any character NOT inside	[^abc] matches any char except 'a', 'b', 'c'

# Common Patterns

Pattern	Regular Expression	Description
Identifier	[a-zA-Z_][a-zA-Z0-9_]*	Letter/underscore followed by letters/digits/underscores
Integer	[0-9]+	One or more digits
Float	[0-9]+\.[0-9]+	Digits, dot, digits
Whitespace	[\t\n\r]+	One or more space characters

## Examples in Action

```

Pattern: [0-9]+
Matches: "42", "123", "7"
Doesn't match: "abc", "12.5"

Pattern: [a-zA-Z][a-zA-Z0-9]*
Matches: "x", "variable1", "myVar"
Doesn't match: "123abc", "_private"

```

## Operator Precedence

When building regular expressions, operators have different precedence levels (like mathematical operations).

### Precedence Order (Highest to Lowest)

1. **Parentheses** `()` - Highest precedence
2. Used for grouping
3. Example: `(a|b)*` vs `a|b*`
4. **Closure operators** `*`, `+`, `?`
5. Apply to immediately preceding element
6. Example: `ab*` means `a` followed by zero or more `b` s
7. **Concatenation (implicit)**
8. Items next to each other are concatenated
9. Example: `abc` means `a` then `b` then `c`
10. **Union/OR** `|` - Lowest precedence
11. Separates alternative patterns
12. Example: `a|bc` means `a` OR `bc`

## Examples Showing Precedence

Expression	Interpretation	Matches
<code>a b*</code>	<code>a</code> OR (zero or more <code>b</code> s)	"a", "", "b", "bb", "bbb"...
<code>(a b)*</code>	Zero or more of ( <code>a</code> OR <code>b</code> )	"", "a", "b", "ab", "ba", "abb"...
<code>ab c</code>	( <code>ab</code> ) OR <code>c</code>	"ab", "c"
<code>a(b c)</code>	<code>a</code> followed by ( <code>b</code> OR <code>c</code> )	"ab", "ac"

## Best Practice

- **Use parentheses liberally** to make intentions clear
- **When in doubt, add parentheses** to avoid confusion
- Example: `(a|b)*(c|d)+` is clearer than `a|b*c|d+`

## Quick Reference

## Token Recognition Process

1. **Read characters** from source code
2. **Apply patterns** using regular expressions
3. **Match longest possible** lexeme
4. **Generate token** with attributes
5. **Handle errors** if no pattern matches
6. **Repeat** until end of input

## Common Token Types

- **Keywords:** `if`, `while`, `class`, `public`
- **Identifiers:** Variable and function names

- **Literals:** Numbers, strings, booleans
  - **Operators:** `+`, `-`, `*`, `/`, `==`, `!=`
  - **Delimiters:** `(`, `)`, `{`, `}`, `;`, `,`
  - **Whitespace:** Spaces, tabs, newlines (usually ignored)
- 

## Guide Questions - Complete Answers

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### 1. What is the role of the lexical analyzer?

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The lexical analyzer serves as the **first phase of the compiler** with four main roles:

- **Tokenization:** Converts raw source code text into meaningful tokens
- **Cleaning:** Strips out whitespace, comments, and other non-essential characters
- **Position tracking:** Maintains line and column numbers for error reporting
- **Error correlation:** Links compiler messages back to specific source code locations

### 2. Why should parsing be separated from lexical analysis?

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Separation provides three key benefits:

- **Simplicity in design:** Each phase has a single, focused responsibility - lexical analysis handles character recognition, parsing handles grammar structure
- **Improved efficiency:** Specialized algorithms can be optimized for each specific task
- **Enhanced portability:** The lexical analyzer can be easily adapted for different character sets while grammar rules remain unchanged across platforms

### 3. What are tokens, patterns, and lexemes and what are the differences between these three?

Concept	Definition	Example
<b>Token</b>	A category or label for lexical units (like grammatical parts of speech)	<code>identifier</code> , <code>number</code> , <code>operator</code>
<b>Pattern</b>	The rule or regular expression defining how to recognize a token	<code>/[A-Za-z_][A-Za-z0-9_]*/</code>
<b>Lexeme</b>	The actual text from source code that matches a token's pattern	<code>"count"</code> , <code>"42"</code> , <code>"+"</code>

**Key difference:** Tokens are categories, patterns are recognition rules, lexemes are actual text instances.

### 4. What are lexical errors and how

are they handled?

**Lexical errors** occur when no defined pattern matches the current sequence of characters in the source code.

**Five handling strategies:**

1. **Panic mode:** Delete characters until a valid token can be formed
2. **Deletion:** Remove one character from the problematic lexeme
3. **Insertion:** Add a character to create a valid token
4. **Replacement:** Replace one character (common for typos)
5. **Transposition:** Swap adjacent characters (handles typing mistakes)



## 5. How is a lexical definition of a language specified?

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Lexical definitions use **regular expressions** built on these foundations:

- **Alphabet ( $\Sigma$ )**: Finite set of symbols (e.g., ASCII characters)
- **Strings**: Finite sequences of symbols from the alphabet
- **Languages**: Sets of strings defined over an alphabet
- **Regular expressions**: Mathematical patterns using operators like `*` (zero or more), `+` (one or more), `|` (union), and `[]` (character classes)

**Example specification:**

```
identifier: [a-zA-Z_][a-zA-Z0-9_]*  
number: [0-9]+  
whitespace: [ \t\n\r]+
```

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*Remember: The lexical analyzer is your first line of defense in compilation - it transforms messy text into clean, categorized tokens that the parser can work with!*

# Lexical Analysis Implementation

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## Overview

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**Lexical Analysis** is the first phase of a compiler that breaks down source code into meaningful tokens. Think of it as reading a sentence and identifying each word, punctuation mark, and symbol.

## Key Concepts:

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- **Token:** A meaningful unit (like keywords, identifiers, operators)
  - **Lexeme:** The actual string that forms a token (e.g., "if", "x", "+")
  - **Pattern:** Rules that describe how tokens are formed
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## Recognition of Tokens

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### Basic Assumptions

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#### 1. Reserved words cannot be used as identifiers

- Example: You can't name a variable "if" or "while"

#### 2. Whitespace is ignored

- Spaces, tabs, and newlines don't affect token recognition

## Token Recognition Process

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#### 1. Order token patterns by precedence

- Keywords before identifiers
- Longer operators before shorter ones (">=" before ">")

## 2. Use two pointers:

- **Lexeme-beginning pointer:** Marks start of current token
- **Forward pointer:** Scans ahead through input

## 3. Recognition steps:

Input: "if (x >= 10)"

Step 1: Scan "if" → Recognized as KEYWORD  
Step 2: Skip whitespace  
Step 3: Scan "(" → Recognized as LEFT\_PAREN  
Step 4: Skip whitespace  
Step 5: Scan "x" → Recognized as IDENTIFIER  
Step 6: Skip whitespace  
Step 7: Scan ">=" → Recognized as GTE\_OPERATOR  
Step 8: Skip whitespace  
Step 9: Scan "10" → Recognized as NUMBER  
Step 10: Scan ")" → Recognized as RIGHT\_PAREN

---

# Transition Diagrams

A **transition diagram** is a visual representation of how a lexical analyzer recognizes tokens.

## Elements of a Transition Diagram:

1. **States** (circles): Represent current position in recognition
2. **Edges/Transitions** (arrows): Show movement between states
3. **Symbols** (labels on arrows): Characters that trigger transitions
4. **Start state**: Where recognition begins
5. **Accepting states**: Where valid tokens are recognized
6. **Determinism**: Each state has at most one transition for each input symbol

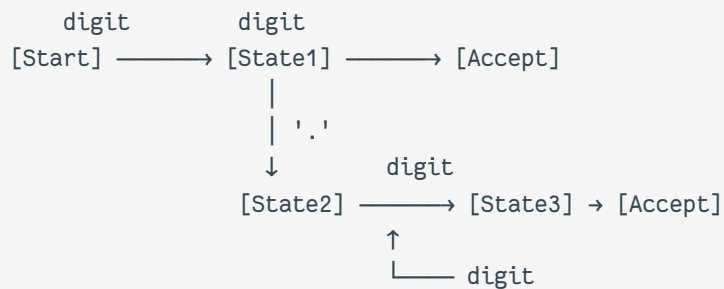
## Example: Recognizing Identifiers

Input: Letters followed by letters/digits



## Example: Recognizing Numbers

Input: Digits, possibly with decimal point



## Implementation Details

### Core Functions:

- `nextchar()` : Reads next character, advances forward pointer
- **State management**: Each state has its own code segment
- **Backtracking**: When recognition fails, return to beginning

## Implementation Algorithm:

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```
function getNextToken():
    lexeme_begin = forward_pointer

    while (not end_of_input):
        current_char = nextchar()

        if (valid_transition_exists):
            move_to_next_state()
        else:
            if (current_state_is_accepting):
                retract_one_character()
                return create_token(current_lexeme)
            else:
                reset_to_beginning()
                try_next_pattern()

    return END_OF_FILE_TOKEN
```

## Symbol Table Integration:

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- **Identifiers** must be stored in symbol table during lexical analysis
  - **Keywords** can be stored in a hash table for quick lookup
  - This reduces the number of states needed in transition diagrams
- 

## Finite State Automata (FSA)

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An **FSA** is a mathematical model for recognizing patterns in input.

## Components:

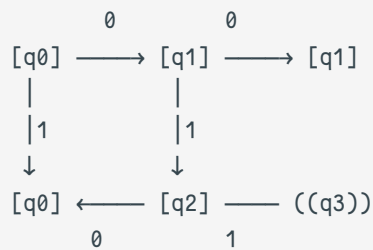
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1. **States**: Finite set of conditions
2. **Alphabet**: Set of input symbols
3. **Transition function**: Maps (state, symbol) → state
4. **Start state**: Initial state

5. **Accepting states:** States that recognize valid input

## Example: Binary strings ending with "01"

Input alphabet: {0, 1}



- q0: Start state
- q3: Accepting state (double circle)
- Accepts: "01", "001", "101", "1001", etc.

## Guide Questions Answered

### 1. How are tokens recognized by a lexical analyzer?

Tokens are recognized through a **pattern matching process** using:

- **Transition diagrams** or **finite state automata** that define valid token patterns
- **Two-pointer technique** (lexeme-beginning and forward pointers) to scan input
- **Priority-based matching** where patterns are tried in order of precedence
- **Backtracking** when invalid patterns are encountered

**Example Process:**

Input: "count = 42"

1. Scan "count" → matches identifier pattern → TOKEN: ID("count")
2. Skip whitespace
3. Scan "=" → matches assignment operator → TOKEN: ASSIGN
4. Skip whitespace
5. Scan "42" → matches number pattern → TOKEN: NUM(42)

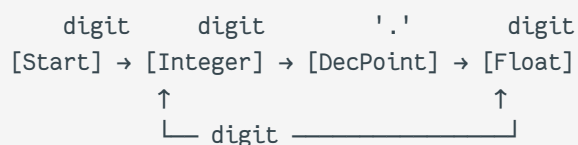
## 2. What are the elements of a transition diagram?

The key elements are:

1. **States** (nodes/circles): Represent current position in pattern recognition
2. **Edges/Transitions** (arrows): Show valid moves between states based on input
3. **Symbols** (edge labels): Characters or character classes that trigger transitions
4. **Start state**: Initial state where recognition begins
5. **Accepting states**: Final states that indicate successful token recognition
6. **Determinism**: Property ensuring unique transitions (no ambiguity)

**Visual Example:**

Recognizing floating-point numbers:



## 3. How are lexical analyzers implemented?

Lexical analyzers are implemented using:

**A. State-driven approach:**

- Each state corresponds to a code segment
- Transitions change program state
- `nextchar()` function advances through input

**B. Table-driven approach:**

- Transition table maps (current\_state, input\_symbol) → next\_state
- Generic driver reads table and processes input

**C. Key implementation strategies:**

- **Error handling:** Backtrack when invalid patterns are found
- **Symbol table integration:** Store identifiers as they're recognized
- **Keyword handling:** Pre-populate reserved words to distinguish from identifiers
- **Buffer management:** Efficiently handle large input files

**Sample Implementation Structure:**

```
class LexicalAnalyzer:
    input_buffer
    forward_pointer
    lexeme_begin
    symbol_table
    keyword_table

    function getToken():
        skip_whitespace()
        lexeme_begin = forward_pointer

        # Try each token pattern in priority order
        if (try_keyword_pattern()):
            return keyword_token
        elif (try_identifier_pattern()):
            return identifier_token
        elif (try_number_pattern()):
            return number_token
        # ... other patterns
        else:
            return error_token
```



# FSA Activities Solutions

## Activity 1: FSA that accepts strings ending with "01"

States: {q0, q1, q2, q3}

Start state: q0

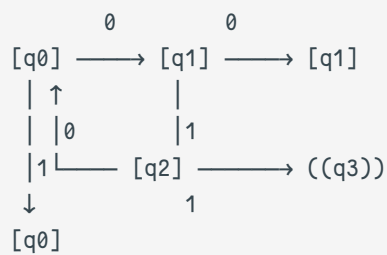
Accepting state: q3

Alphabet: {0, 1}

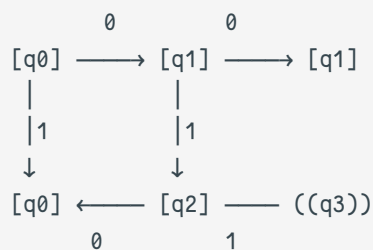
Transitions:

	0	1
q0 → q1,	q0 → q0	
q1 → q1,	q1 → q2	
q2 → q1,	q2 → q0	
q3 → q1,	q3 → q0 (q3 is accepting)	

Diagram:



Actually, let me correct this:



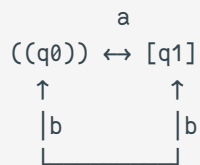
**Test cases:** - "01" ✓ (accepts) - "001" ✓ (accepts) - "101" ✓ (accepts) - "10" ✗ (rejects) - "11" ✗ (rejects)

## Activity 2: FSA that accepts strings with an even number of a's

States: {q0, q1}  
 Start state: q0 (also accepting - 0 is even)  
 Accepting state: q0  
 Alphabet: {a, b}

Transitions:  
 q0 → q1 (on 'a'), q0 → q0 (on 'b')  
 q1 → q0 (on 'a'), q1 → q1 (on 'b')

Diagram:



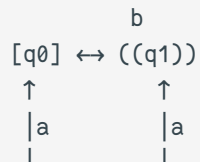
**Test cases:** - "" ✓ (0 a's - even) - "aa" ✓ (2 a's - even) - "bab" ✗ (1 a - odd) - "baab" ✓ (2 a's - even)

## Activity 3: FSA that accepts strings with an odd number of b's

States: {q0, q1}  
 Start state: q0  
 Accepting state: q1  
 Alphabet: {a, b}

Transitions:  
 q0 → q0 (on 'a'), q0 → q1 (on 'b')  
 q1 → q1 (on 'a'), q1 → q0 (on 'b')

Diagram:



**Test cases:** - "b" ✓ (1 b - odd) - "bb" ✗ (2 b's - even) - "aba" ✓ (1 b - odd) - "abab" ✗ (2 b's - even)

## Activity 4: FSA that accepts strings containing "ab" as a substring

States: {q0, q1, q2}

Start state: q0

Accepting state: q2

Alphabet: {a, b}

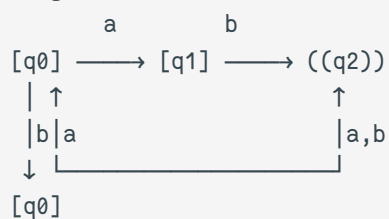
Transitions:

q0 → q1 (on 'a'), q0 → q0 (on 'b')

q1 → q1 (on 'a'), q1 → q2 (on 'b')

q2 → q2 (on 'a'), q2 → q2 (on 'b')

Diagram:



**Test cases:** - "ab" ✓ (contains "ab") - "aab" ✓ (contains "ab") - "abbb" ✓ (contains "ab") - "ba" ✗ (doesn't contain "ab") - "a" ✗ (doesn't contain "ab")

## Summary

Lexical analysis is the foundation of compilation, transforming raw source code into meaningful tokens through:

- **Pattern matching** using FSAs and transition diagrams
- **Systematic scanning** with pointer-based techniques
- **Priority-based recognition** to handle conflicts
- **Integration with symbol tables** for identifier management