Compiler

Scanning

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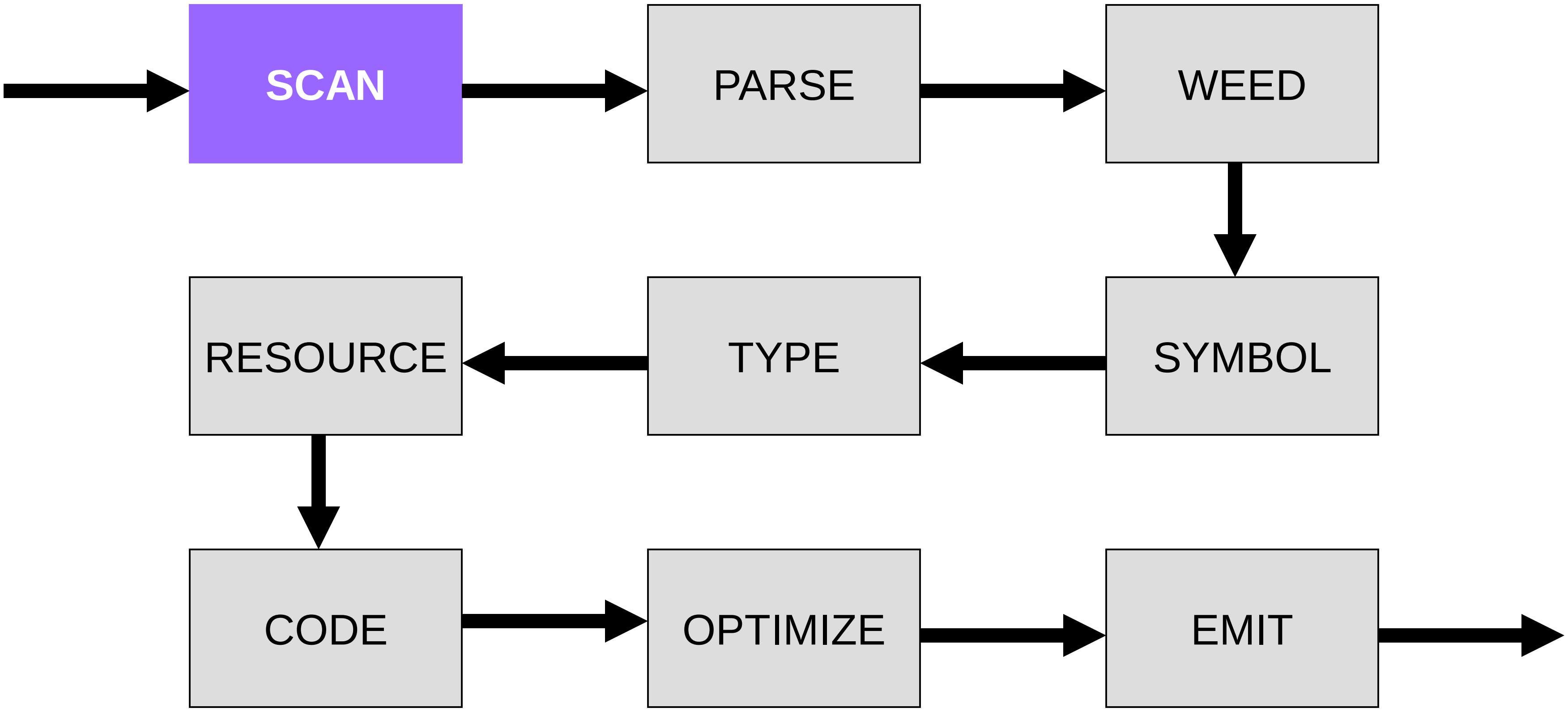
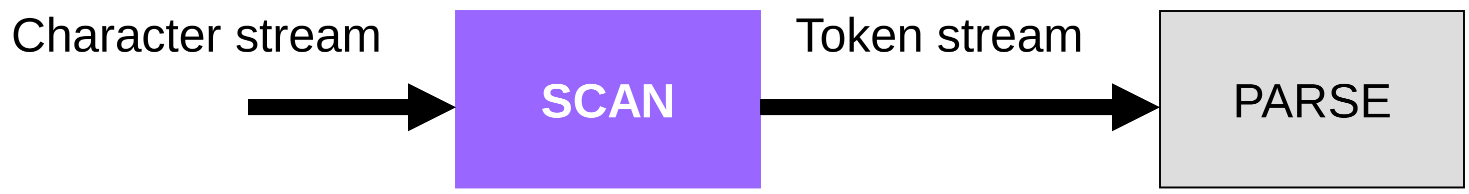
Compiler Architecture



Compiler Architecture

Source Code



Scanner: Overview

- A scanner transforms a string of characters into a string of *symbols/tokens*:
  - it corresponds to a *finite-state machine* (FSM);
  - plus some code to make it work;
  - FSM can be generated from specification.
- Symbols (*a.k.a.* tokens, lexemes) are the indivisible units of a languages syntax
  - key words, punctuation symbols, identifiers …
- A FSM recognizes the structure of a symbol
  - that structure is specified as a regular expression

Token Definitions

Described in language specification, e.g.:

“An *identifier* is an unlimited-length sequence of *Java letters* and *Java digits*, the first of which must be a Java letter.
An identifier cannot have the same spelling (Unicode character sequence) as a keyword (§3.9), Boolean literal (§3.10.3), or the null literal (§3.10.7).”

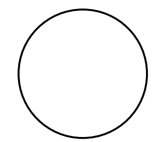
http://docs.oracle.com/javase/specs/

Finite State Machine (FSM) or Finite State Automaton (FSA)

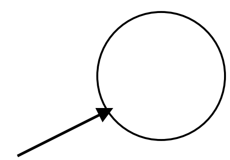
- a quintuple $(\boldsymbol{\Sigma}, \boldsymbol{S}, \boldsymbol{s_0}, \boldsymbol{\delta}, \boldsymbol{F})$, where
  - Σ, is a finite non-empty set of symbols (input alphabets)
  - S, is a finite non-empty set of states
  - $s_0 \in S$, is the initial state
  - $\delta: S \times \Sigma \to S$, is the state transition function
  - $F \subseteq S$, is the (possibly empty) set of accepting (~~final~~) states

FSM Graphs

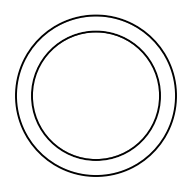
- A state



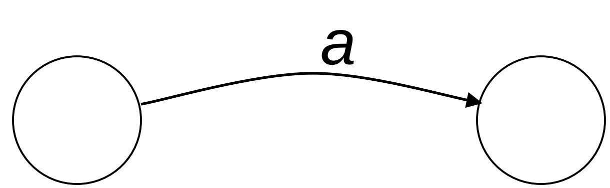
- The start state



- An accepting state



- A transition *a*

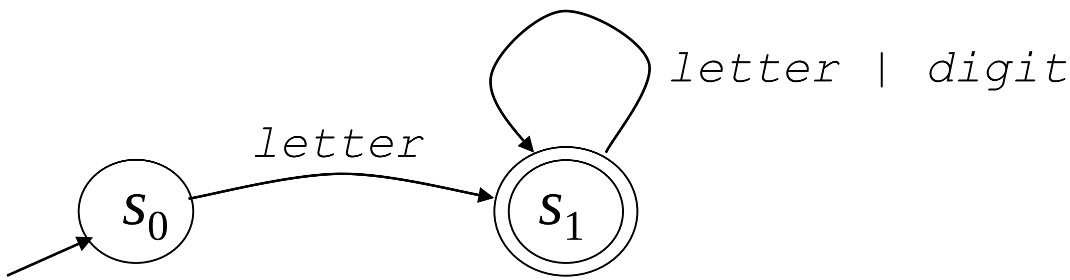


FSM Interpretation

- Transition: $s_1 \xrightarrow{a} s_2$
- Is read: in state s_1 on input a go to state s_2
- At end of input
  - if in accepting state => *accept*
  - otherwise => *reject*
- If no transition possible => reject

Language defined by FSM

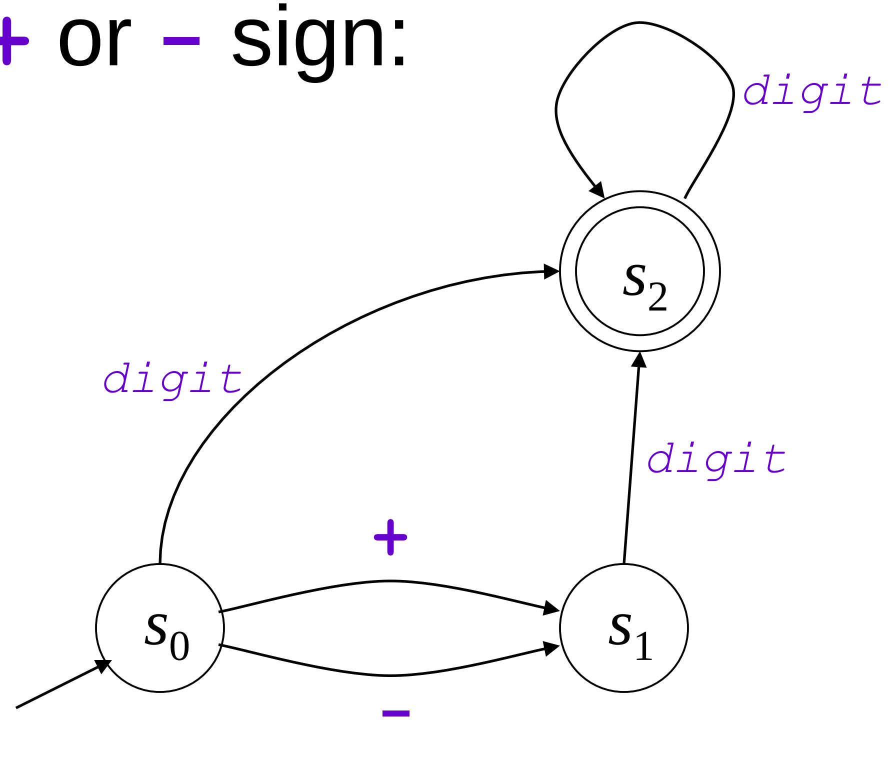
- The *language defined by an FSM* is the set of strings accepted by the FSM.



  - in the language of the FSM shown above:
    - **`x`**, **`tmp2`**, **`XyZzy`**, **`position27`**.
  - *not* in the language of the FSM shown above:
    - **`123`**, **`a?`**, **`13apples`**.

Example: Integer Literals

- FSM that accepts integer literals with an optional **+** or **–** sign:



Two kinds of FSM

Deterministic (DFA):

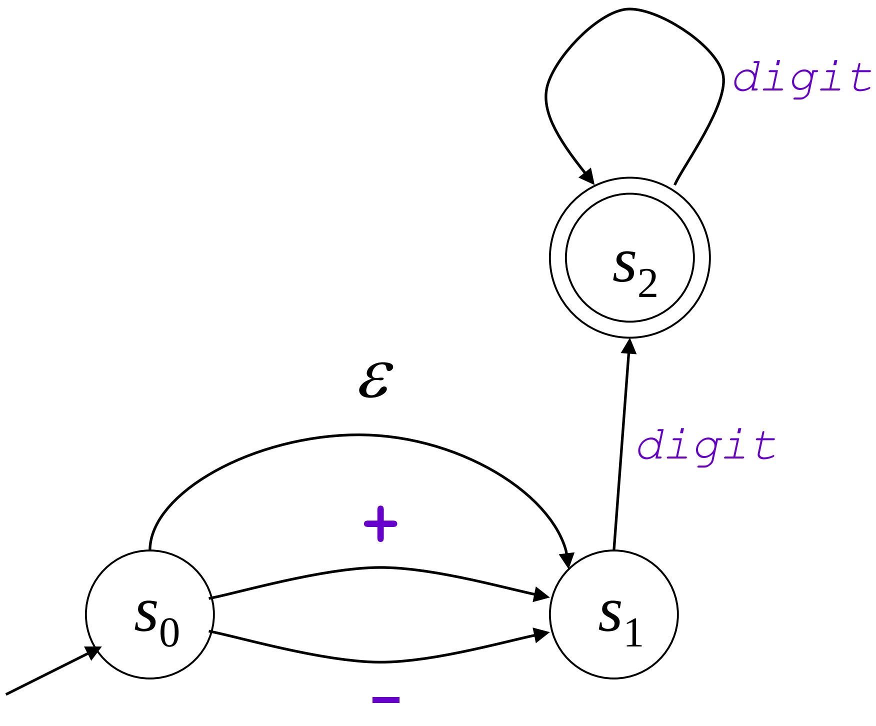
- No state has more than one outgoing edge with the same label.

Non-Deterministic (NFA):

- States *may* have more than one outgoing edge with the same label.
- Edges may be labeled with ε (epsilon), the empty string.
- The automaton can take an ε transition *without* looking at the current input character.

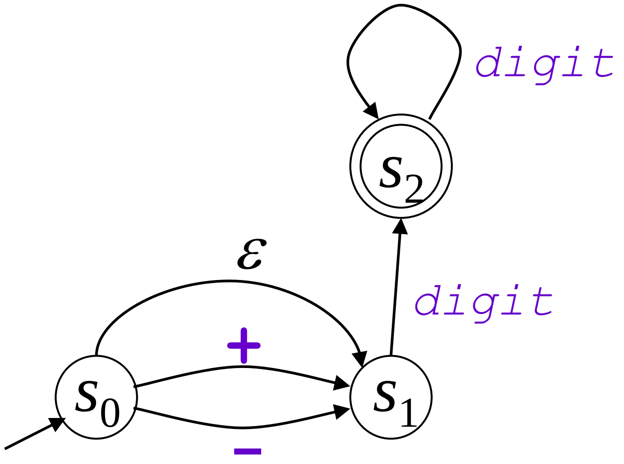
Example of NFA

- integer-literal example:



NFA

- sometimes simpler than DFA
- can be in multiple states at the same time
- NFA accepts a string if
  - there exists a sequence of moves
  - starting in the start state,
  - ending in an accepting state,
  - that consumes the <u>entire</u> string.



- Example:
  - the integer-literal NFA on input "**+75**"

Equivalence of DFA and NFA

- Theorem:
  - For every non-deterministic finite-state machine *M*, there exists a *deterministic* machine *M'* such that *M* and *M'* accept the *same* language.

- DFA are easy to implement
- NFA are easy to generate from specifications
- Algorithms exist to convert NFA to DFA (*see assignments*)

Regular Expressions (RE)

- Automaton is a good “visual” aid
  - but is not suitable as a specification
- Regular expressions are a suitable *specification*
  - a <u>compact</u> way to define a language that can be accepted by an automaton.
- used as the input to a scanner generator
  - define each token, and also
  - define white-space, comments, etc.
    - these do not correspond to tokens, but must be recognized and ignored.

Example: Pascal Identifier

- Lexical specification (in English):
  - a letter, followed by zero or more letters or digits.
- Lexical specification (as a regular expression):
  - *letter (letter | digit)**

|	means "or"
	means "followed by"
*	means zero or more instances of
( )	are used for grouping

Operands of RE Operators

- Operands are same as labels on the edges of an FSM
  - single characters or ε
- *`letter`* is a shorthand for
  - **`a | b | c | ... | z | A | ... | Z`**
- *`digit`* is a shorthand for
  - **`0 | 1 | … | 9`**
- sometimes we put the characters in quotes
  - necessary when denoting `| *`

Operator Precedence

Regular Expression Operator	Analogous Arithmetic Operator	Precedence
|	plus	lowest
	times	middle
*	exponentiation	highest

Consider regular expressions:

```
letter letter | digit*
letter (letter | digit)*
```

For You To Do

- Describe (in English) the language defined by each of the following regular expressions:

letter (*letter* | *digit**)

*digit digit** "." *digit digit**

Example: Integer Literals

- An integer literal with an optional sign can be defined in English as:

  "(nothing or + or -) followed by one or more digits"

- The corresponding regular expression is:

$$(+ \mid - \mid \varepsilon)\ (\mathit{digit}\ \mathit{digit}^*)$$

- Convenience operators

$a+$	is the same as	$a\ (a)^*$
$a?$	is the same as	$(a \mid \varepsilon)$

$$(\text{"+"} \mid -)?\ \mathit{digit}+$$

Language Defined by RE

- Recall: language = set of strings
- Language defined by an automaton
  - the set of strings accepted by the automaton
- Language defined by a regular expression
  - the set of strings that match the expression.

Regular Exp. r		Corresponding Set of Strings $L(r)$	
ε		{""}	
`a`		{"`a`"}	
`r s`	`a b c`	$L(r)\,L(s)$	{"`abc`"}
`r | s`	`a|b|c`	$L(r) \cup L(s)$	{"`a`", "`b`", "`c`"}
`r*`	`(a|b)*`	$L(r)^*$	{"", "`a`", "`b`", "`aa`", "`ab`", ..., "`bbab`“, ...}

The Role of Regular Expressions

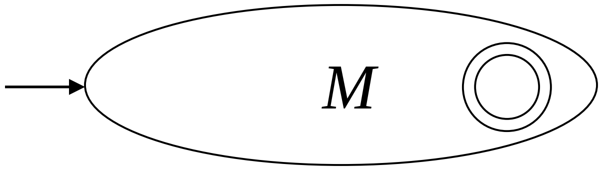
- Theorem:
  - For every regular expression, there exists a nondeterministic finite-state machine that defines the same language, and vice versa.

- Q: Why is the theorem important for *scanner generation*?

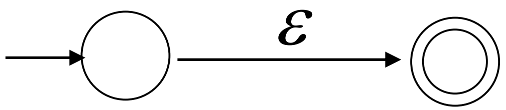
- Q: Theorem is not enough: what do we need for *automatic* scanner generation?

Regular Expressions to NFA (1)

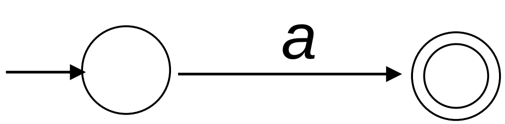
- For each kind of RE, define an NFA
  - Notation: NFA for RE *M*



ε

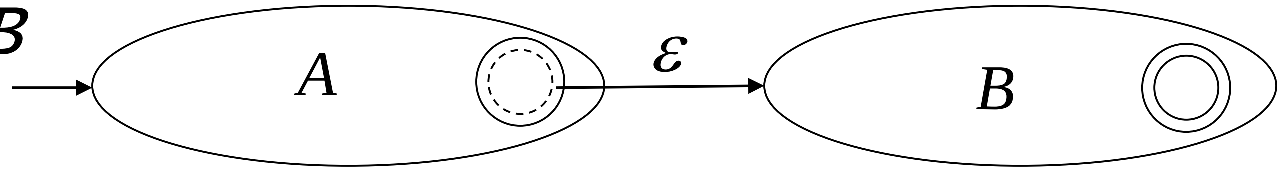


a

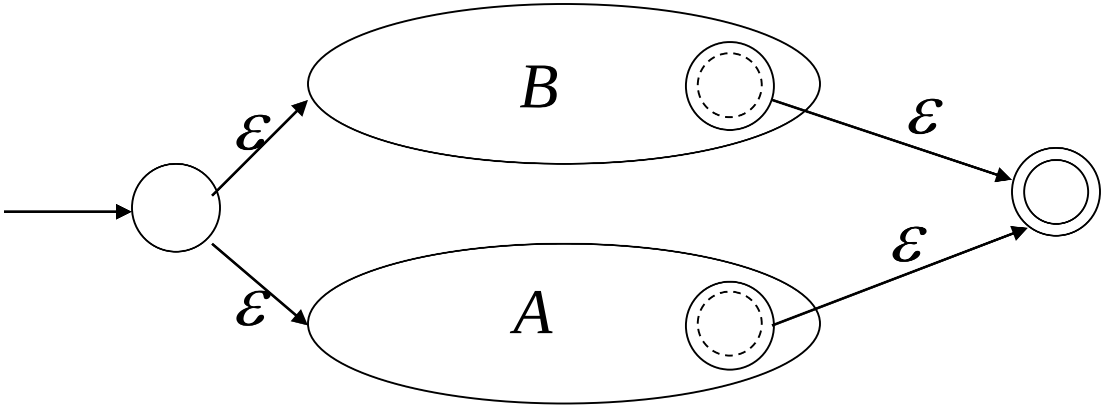


Regular Expressions to NFA (2)

A B

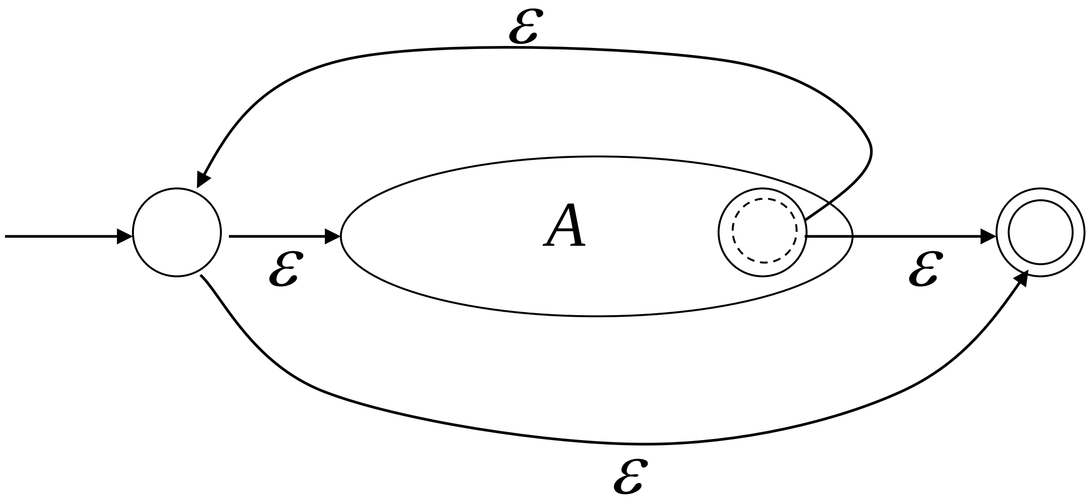


A | *B*



Regular Expressions to NFA (3)

A^*

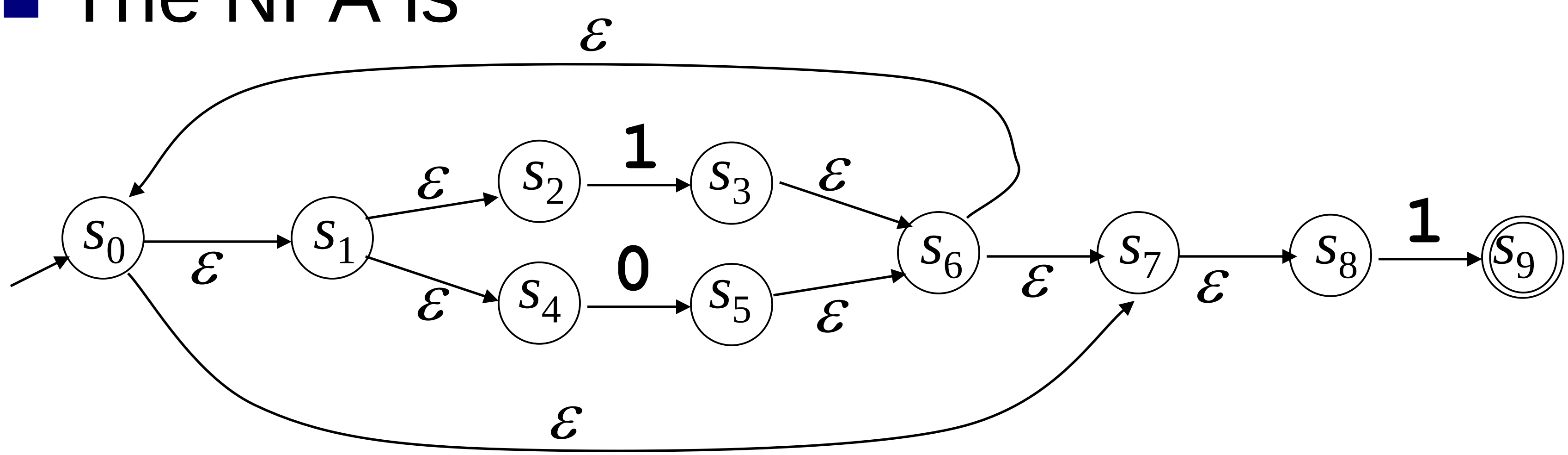


Example : RE to NFA

- Consider the regular expression

  (1|0)*1

- The NFA is



Putting It All Together

- Specify regular expression for each token
  - Generate NFA and convert to DFA
- Define appropriate action for each token
  - *ignore* comments and whitespace
  - *return string* for identifier or numeric constant
  - *indicate* keyword, operator, punctuations, …
- Associate patterns and actions
- Integrate matching of all possible patterns

Example : Expressions

operators: `"*"`, `"/"`, `"+"`, `"-"`

parentheses: `"("`, `")"`

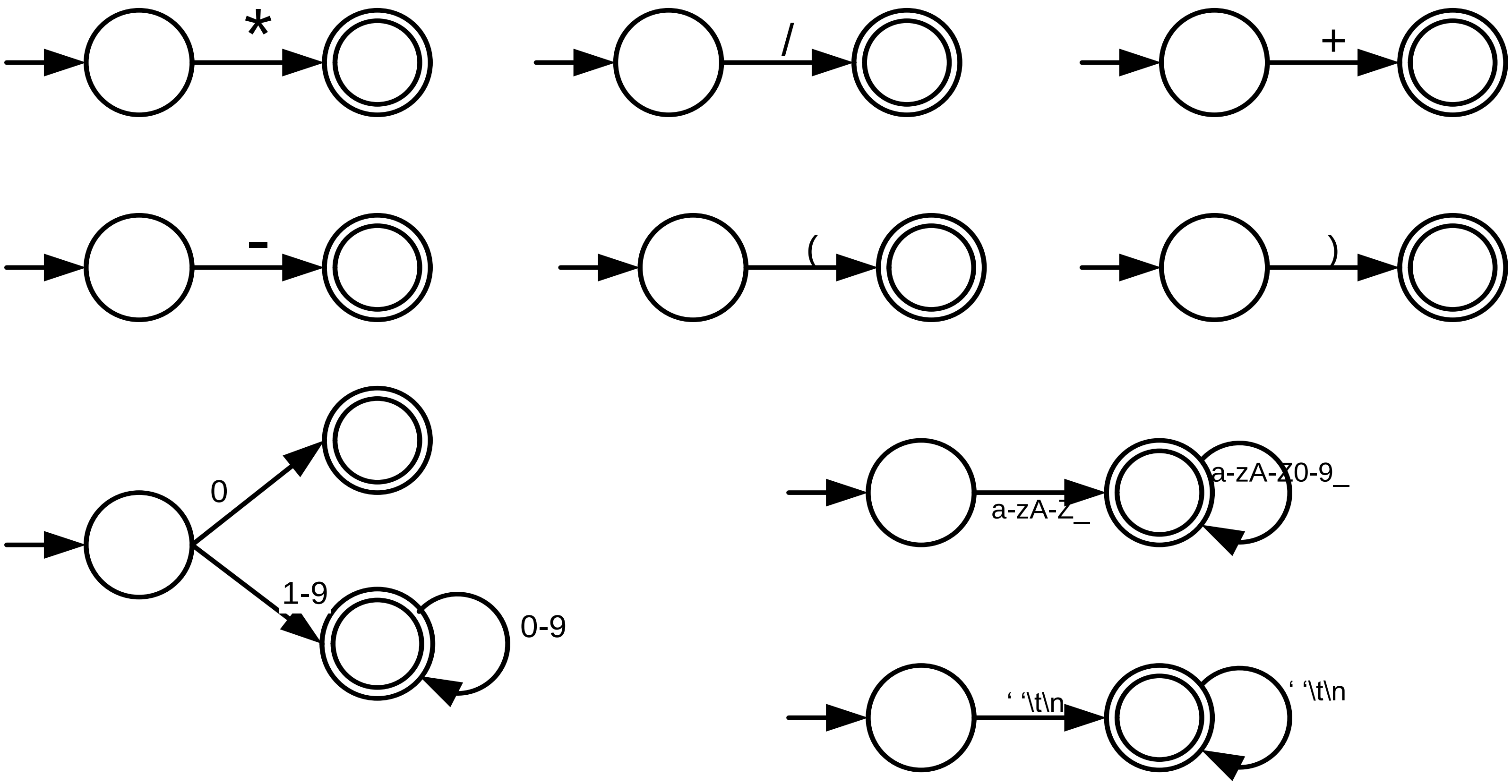
integer constants: `0|([1-9] [0-9]*)`

identifiers: `[a-zA-Z_][a-zA-Z0-9_]*`

white space: `[ \t\n]+`

where: `[abc] = (a|b|c)`

Symbol DFAs



Scanner Algorithm

Given DFA $D_1, \ldots, D_n$

```
while input is not empty do
      foreach i ∈ {1,..,n} do
            s_i := the longest prefix that D_i accepts;
      k := max{|s_i|  |  i ∈ {1,..,n} };
      if k > 0 then
            remove k characters from input;
            j := min{i | |s_i| = k };
            perform the j^th action
      else
            move one character from input to output
            // alternatively produce scan error
```

For You To Do

- What if more than one prefix matches a pattern?
  - Which prefix is used?
- What if a prefix matches more than one pattern?
  - Which pattern is used?
- What happens if a string matches no patterns?