Compilation

0368-3133

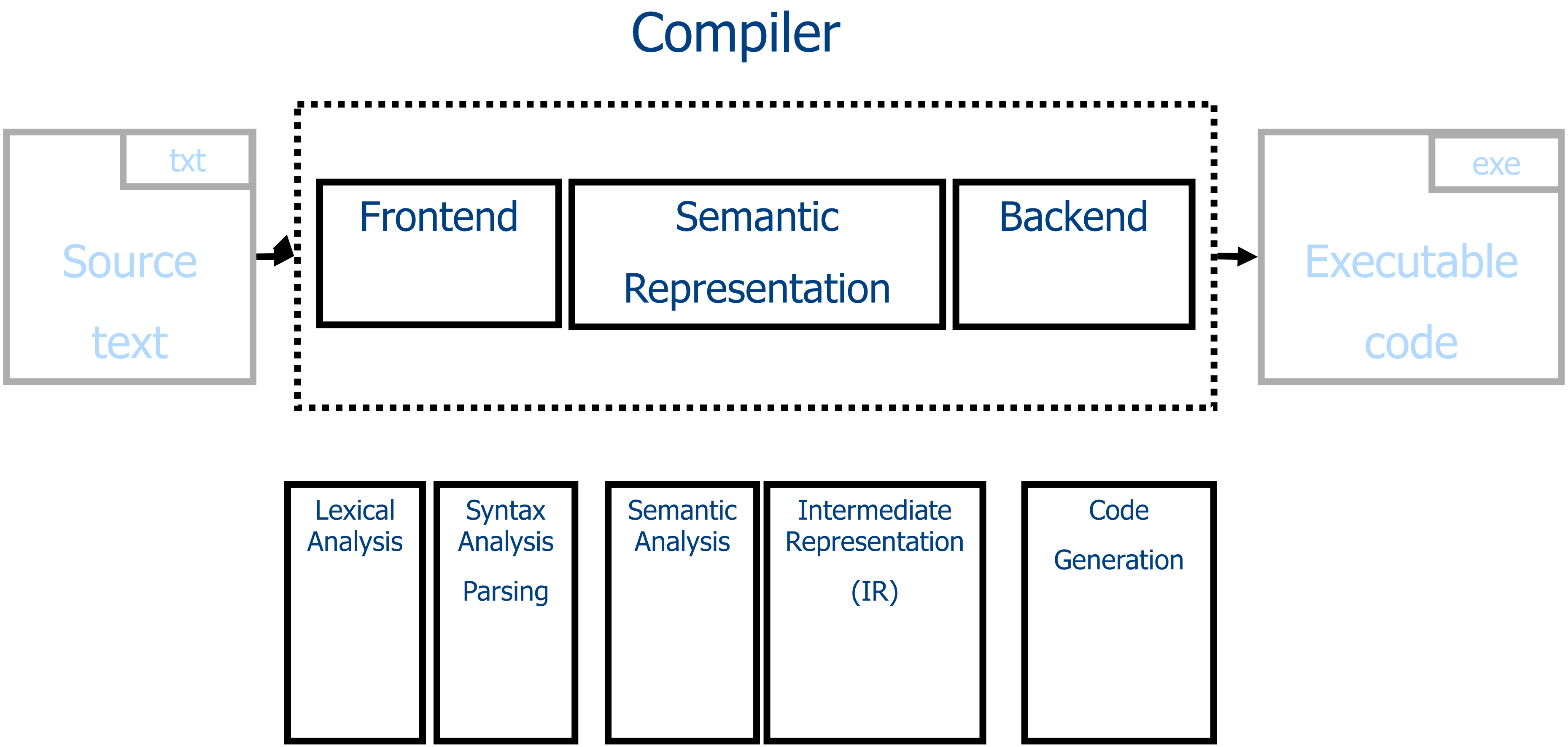
Lecture 2a:

Lexical Analysis

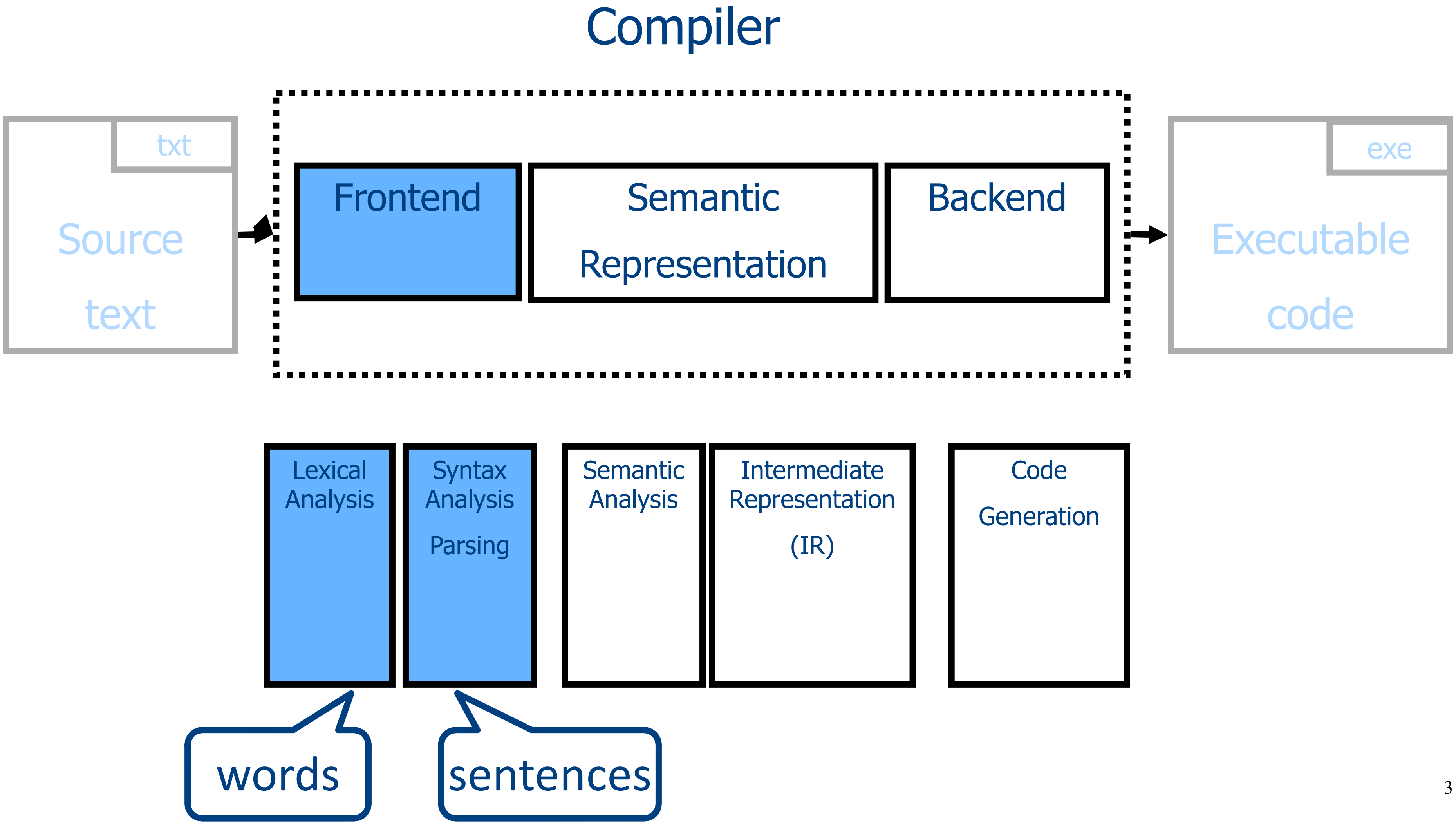
Modern Compiler Design: Chapter 2.1

Noam Rinetzky

Conceptual Structure of a Compiler



Conceptual Structure of a Compiler



What does Lexical Analysis do?

- Language: fully parenthesized expressions

  Expr → Num | LP Expr Op Expr RP

  Num → Dig | Dig Num

  Dig → '0' | '1' | '2' | '3' | '4' | '5' | '6' | '7' | '8' | '9'

  LP → '('

  RP → ')'

  Op → '+' | '*'

(	(	23	+	7	)	*	19	)

What does Lexical Analysis do?

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```
(   (   23   +   7   )   *   19   )
```

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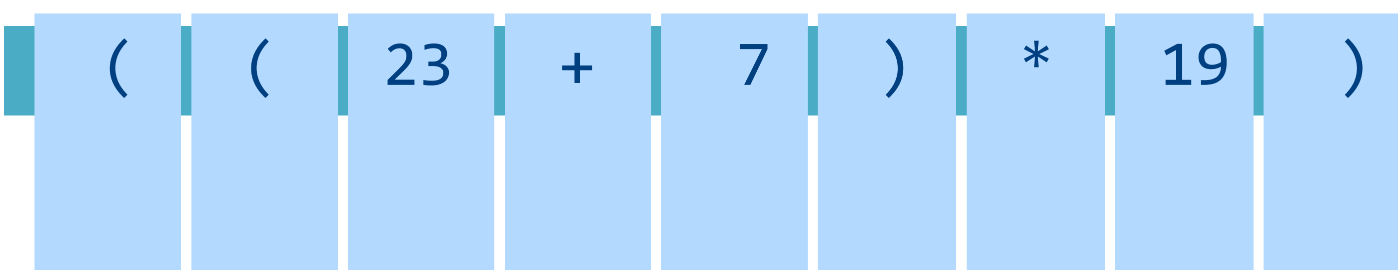

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(	(	23	+	7	)	*	19	)
LP	LP	Num	Op	Num	RP	Op	Num	RP

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Value	(	(	23	+	7	)	*	19	)
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What does Lexical Analysis do?

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LP → '('

RP → ')'

Op → '+' | '*'

Token Token …

Value	(	(	23	+	7	)	*	19	)
Kind	LP	LP	Num	Op	Num	RP	Op	Num	RP

What does Lexical Analysis do?

- Partitions the input into stream of tokens
  - Numbers
  - Identifiers
  - Keywords
  - Punctuation

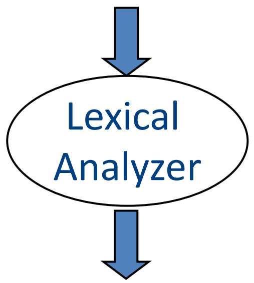
> - "word" in the source language
> - "meaningful" to the syntactical analysis

- Usually represented as (kind, value) pairs
  - (Num, 23)
  - (Op, '*')

From scanning to parsing

program text

((23 + 7) * x)



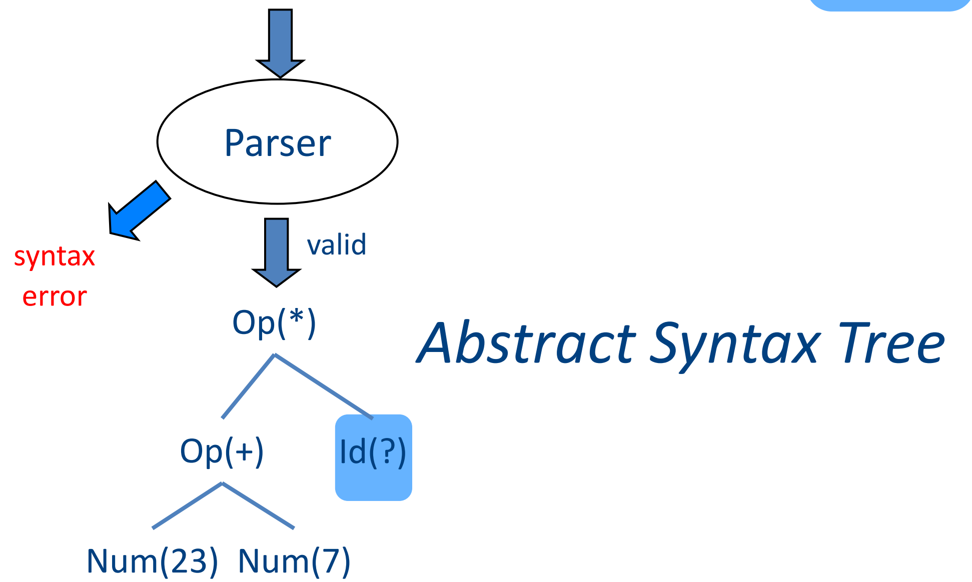
token stream

(	(	23	+	7	)	*	?	)
LP	LP	Num	OP	Num	RP	OP	Id	RP

Grammar:

Expr → ... | Id

Id → 'a' | ... | 'z'



Why Lexical Analysis?

- Well, not strictly necessary, but …
  - Regular languages $\subseteq$ Context-Free languages
- Simplifies the syntax analysis (parsing)
  - And language definition
- Modularity
- Reusability
- Efficiency

Lecture goals

- Understand role & place of lexical analysis
- Lexical analysis theory
- Using program generating tools

Lecture Outline

- ✓ Role & place of lexical analysis
- What is a token?
- Regular languages
- Lexical analysis
- Error handling
- Automatic creation of lexical analyzers

What is a token? (Intuitively)

- A "word" in the source language
  - Anything that should appear in the input to syntax analysis
    - Identifiers
    - Values
    - Language keywords
- Usually, represented as a pair of (kind, value)

Example Tokens

Type	**Examples**
ID	foo, n_14, last
NUM	73, 00, 517, 082
REAL	66.1, .5, 5.5e-10
IF	if
COMMA	,
NOTEQ	!=
LPAREN	(
RPAREN	)

Example Non Tokens

Type	**Examples**
comment	/* ignored */
preprocessor directive	#include <foo.h>
	#define NUMS 5.6
macro	NUMS
whitespace	\t, \n, \b, ‘ ‘

Some basic terminology

- Lexeme (aka symbol) - a series of letters separated from the rest of the program according to a convention (space, semi-column, comma, etc.)

- Pattern - a rule specifying a set of strings. Example: “an identifier is a string that starts with a letter and continues with letters and digits”
  – (Usually) a regular expression

- Token - a pair of (pattern, attributes)

Example

```
void match0(char *s) /* find a zero */
{
  if (!strncmp(s, “0.0”, 3))
    return 0.0 ;
}
```

```
VOID ID(match0) LPAREN CHAR DEREF ID(s) RPAREN

LBRACE

IF LPAREN NOT ID(strncmp) LPAREN ID(s) COMMA STRING(0.0)
COMMA NUM(3) RPAREN RPAREN

RETURN REAL(0.0) SEMI

RBRACE

EOF
```

Example Non Tokens

Type	Examples
comment	/* ignored */
preprocessor directive	#include <foo.h>
	#define NUMS 5.6
macro	NUMS
whitespace	\t, \n, \b, ‘ ‘

- Lexemes that are recognized but get consumed rather than transmitted to parser
  - if
  - i/*comment*/f

Lecture Outline

- ✓ Role & place of lexical analysis
- ✓ What is a token?
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- Automatic creation of lexical analyzers

How can we define tokens?

- Keywords – easy!
  - if, then, else, for, while, …

- Identifiers?
- Numerical Values?
- Strings?

- Characterize unbounded sets of values using a bounded description?

Regular languages

- Formal languages
  - Σ = finite set of letters
  - Word = sequence of letter
  - Language = set of words
- Regular languages defined equivalently by
  - Regular expressions
  - Finite-state automata

Common format for reg-exps

Basic Patterns	**Matching**
x	The character x
.	Any character, usually except a new line
[xyz]	Any of the characters x,y,z
^x	Any character except x
Repetition Operators	
R?	An R or nothing (=optionally an R)
R*	Zero or more occurrences of R
R+	One or more occurrences of R
Composition Operators	
R1R2	An R1 followed by R2
R1|R2	Either an R1 or R2
Grouping	
(R)	R itself

Examples

- ab*|cd? =
- (a|b)* =
- (0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9)* =

Escape characters

- What is the expression for one or more + symbols?
  - `(+)+` won't work
  - `(\+)+` will
- backslash \ before an operator turns it to `standard character`
  - `\*, \?, \+, a\(b\+\*, (a\(b\+\*)+,` …
- backslash double quotes surrounds text
  - `“a(b+*”, “a(b+*”+`

Shorthands

- Use names for expressions
  - letter = a | b | … | z | A | B | … | Z
  - letter_ = letter | _
  - digit = 0 | 1 | 2 | … | 9
  - id = letter_ (letter_ | digit)*
- Use hyphen to denote a range
  - letter = a-z | A-Z
  - digit = 0-9

Examples

- if = if
- then = then
- relop = < | > | <= | >= | = | <>

- digit = 0-9
- digits = digit+

Example

- A number is

```
number = ( 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 )+
     ( ε | \. ( 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 )+
          ( ε | E ( 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 )+
          )
)
```

- Using shorthands it can be written as

```
number = digits (ε | \.digits (ε | E (ε|+|-) digits ) )
```

Exercise 1 - Question

- Language of rational numbers in decimal representation (no leading, ending zeros)
  - 0
  - 123.757
  - .933333
  - Not 007
  - Not 0.30

Exercise 1 - Answer

- Language of rational numbers in decimal representation (no leading, ending zeros)
  - Digit = 1|2|…|9
  - Digit0 = 0|Digit
  - Num = Digit Digit0*
  - Frac = Digit0* Digit
  - Pos = Num | \.Frac | 0\.Frac| Num\.Frac
  - PosNeg = (Є|-)Pos
  - R = 0 | PosNeg

Exercise 2 - Question

- Equal number of opening and closing parenthesis: $[^n]^n$ = [], [[]], [[[]]], …

Exercise 2 - Answer

- Equal number of opening and closing parenthesis: $[^n]^n$ = [], [[]], [[[]]], …
- Not regular
- Context-free
- Grammar: S ::= [] | [S]

Challenge: Ambiguity

- If = `if`
- Id = Letter (Letter | Digit)*

- “`if`” is a valid identifiers… what should it be?
- ”`iffy`” is also a valid identifier

- Solution
  – Longest matching token
  – Break ties using order of definitions…
    - Keywords should appear before identifiers

Creating a lexical analyzer

- Given a list of token definitions (pattern name, regex), write a program such that
  - Input: String to be analyzed
  - Output: List of tokens

- How do we build an analyzer?

Building a Scanner – Take I

- Input: String
- Output: Sequence of tokens

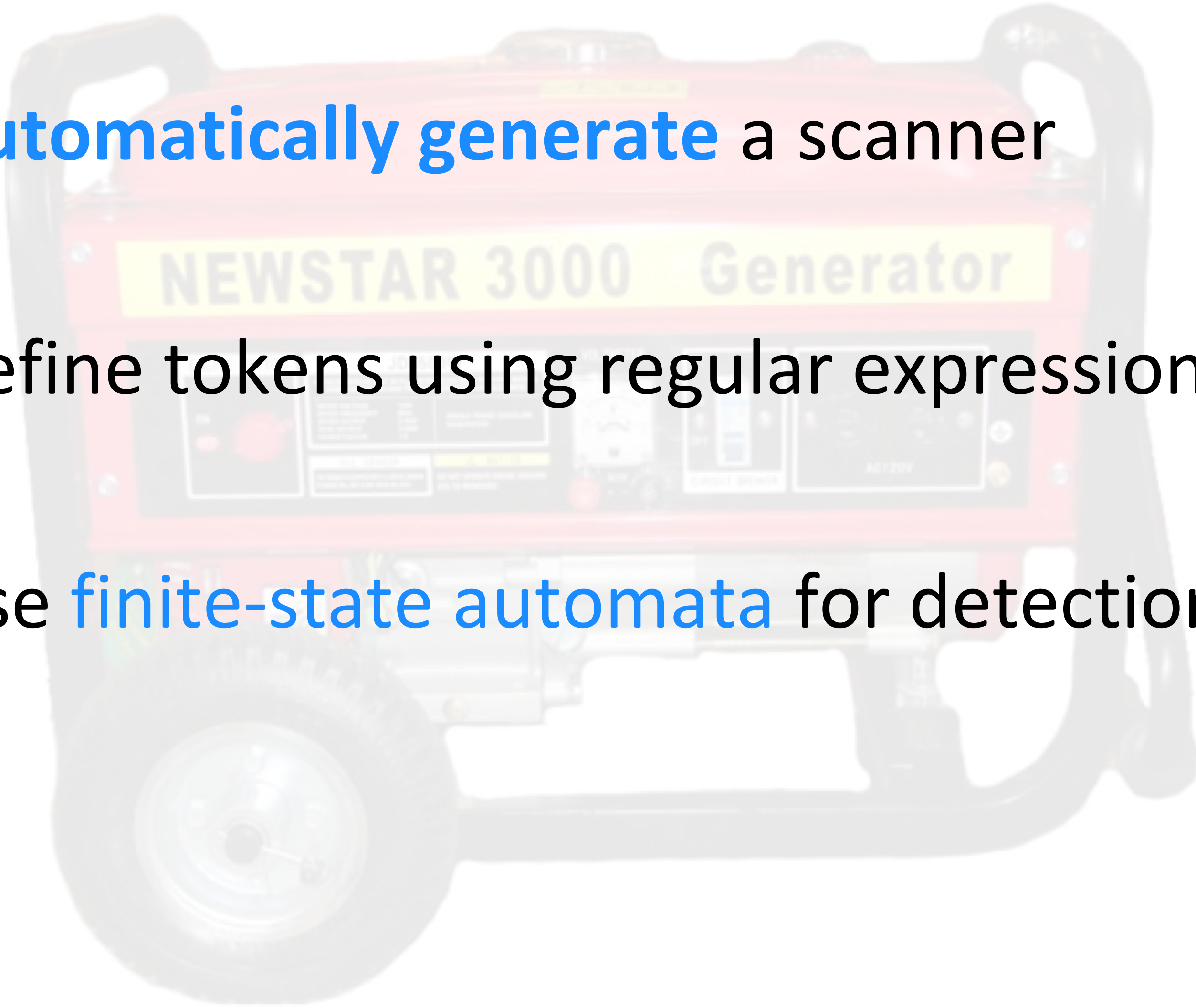
Building a Scanner – Take I

```
Token nextToken()
{
char c ;
loop: c = getchar();
switch (c){
  case ` `: goto loop ;
  case `;`: return SemiColumn;
  case `+`:
    c = getchar() ;
    switch (c) {
      case `+': return PlusPlus ;
      case '='  return PlusEqual;
      default:  ungetc(c); return Plus;
    };
  case `<`: …
  case `w`: …
 }
```

There must be a better way!

A better way

- **Automatically generate** a scanner
- Define tokens using regular expressions
- Use finite-state automata for detection



A better way

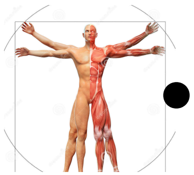

NEWSTAR 3000 Generator
ENGINE SWITCH
JD3500W
VOLTMETER
CIRCUIT BREAKER
AC120V

Reg-exp vs. automata

- Regular expressions are declarative
  - Good for humans
  - Not “executable”

- Automata are operative
  - Define an *algorithm* for deciding whether a given word is in a regular language
  - Not a natural notation for humans

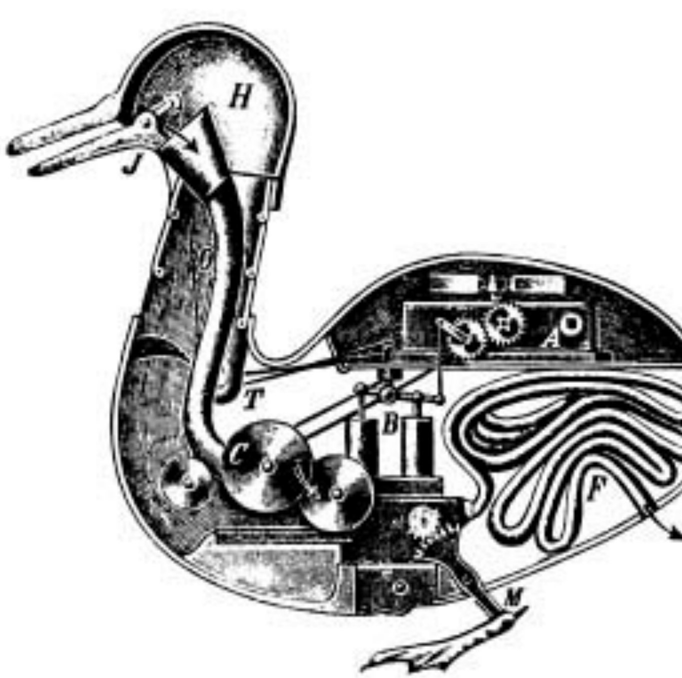
Overview



- Define tokens using regular expressions

- Construct a nondeterministic finite-state automaton (NFA) from regular expression
- Determinize the NFA into a deterministic finite-state automaton (DFA)
- DFA can be directly used to identify tokens

Automata theory: a bird's-eye view



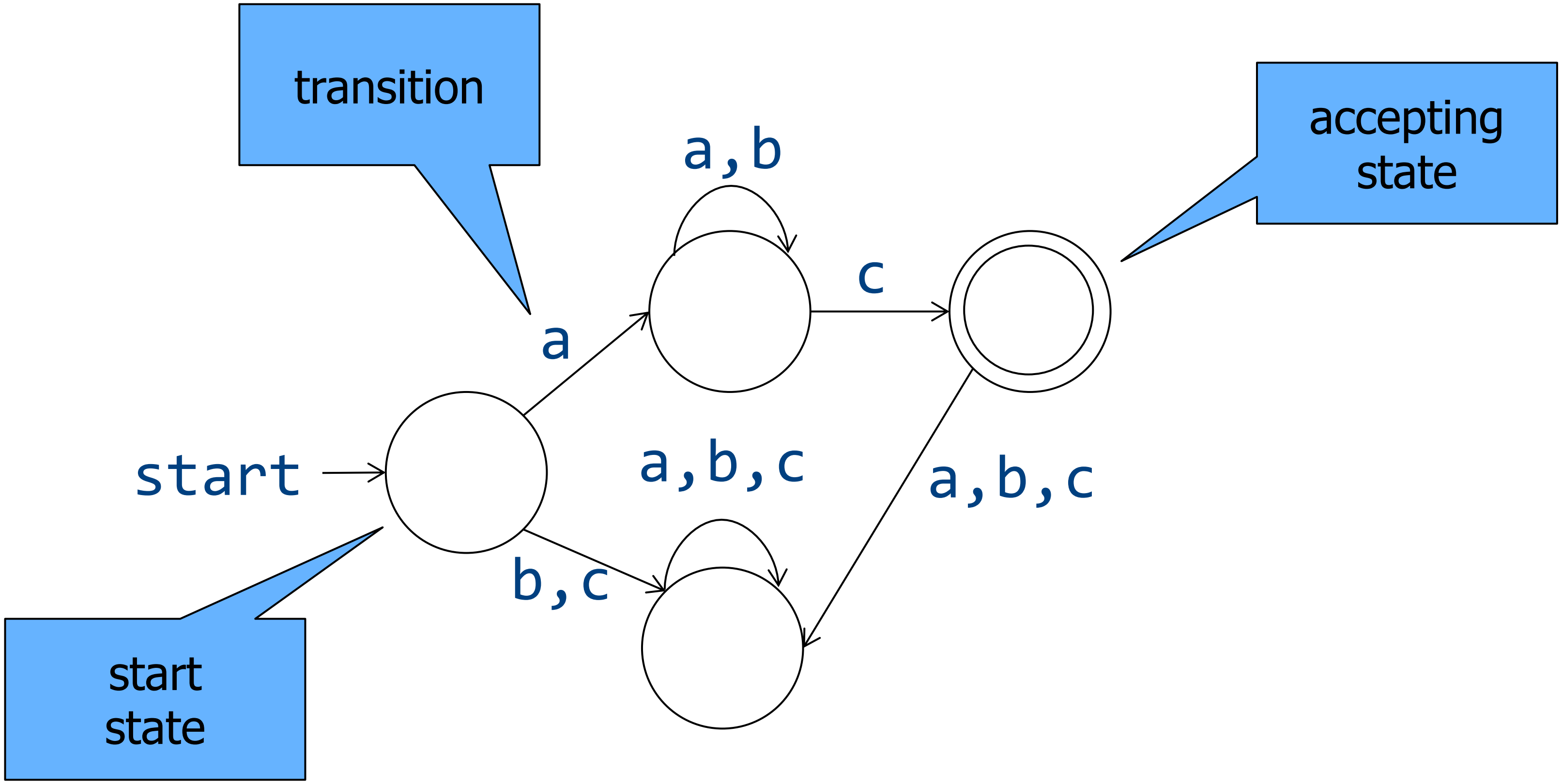
Deterministic Automata (DFA)

- $M = (\Sigma, Q, \delta, q_0, F)$
  - Σ - alphabet
  - Q – finite set of state
  - $q_0 \in Q$ – initial state
  - $F \subseteq Q$ – final states
  - $\delta : Q \times \Sigma \rightarrow Q$ - transition function

- For a word w, M reach some state x
  - M accepts w if $x \in F$

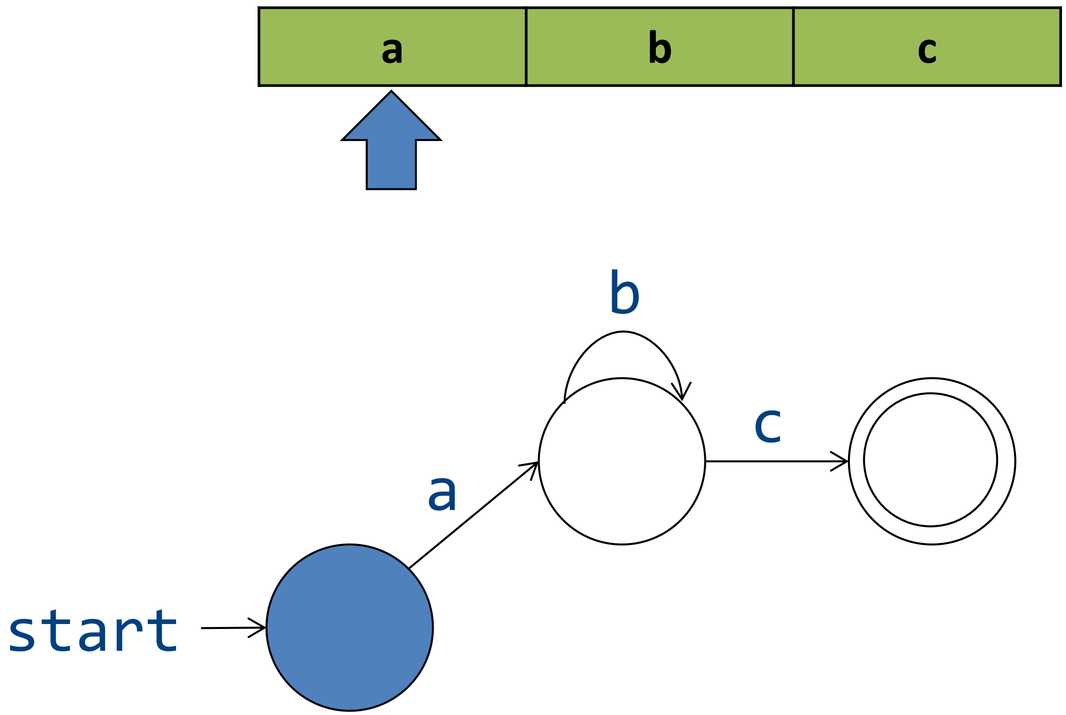
DFA in pictures

- An automaton is defined by states and transitions



Accepting Words

- Words are read left-to-right



- Missing transition = non-acceptance
  - "Stuck state"

Accepting Words

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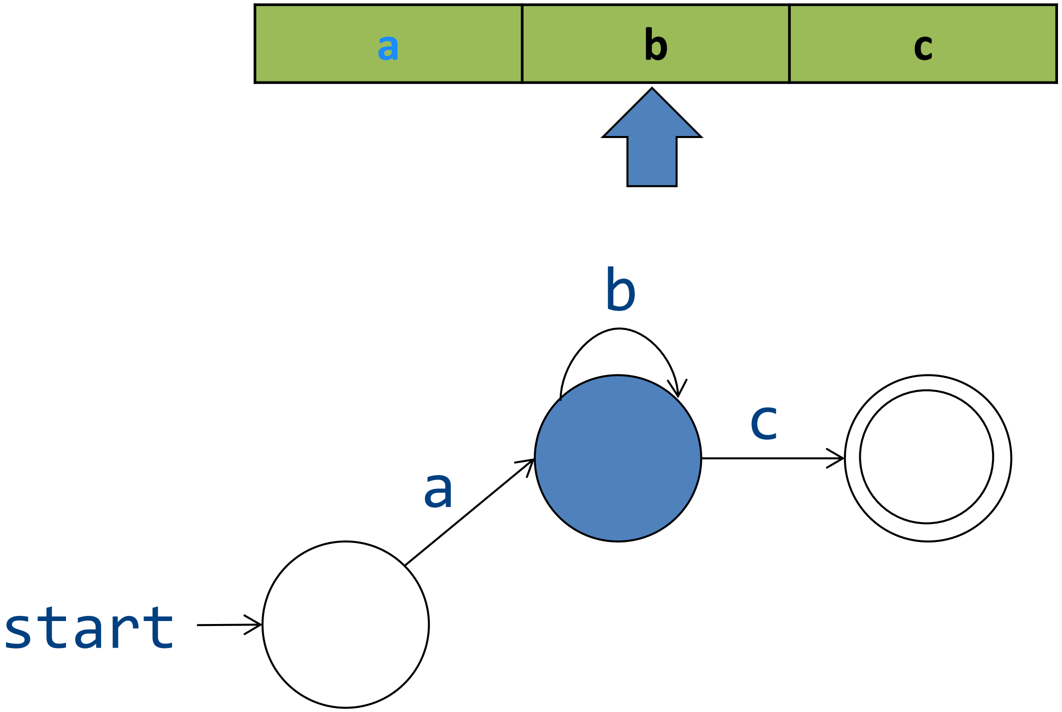

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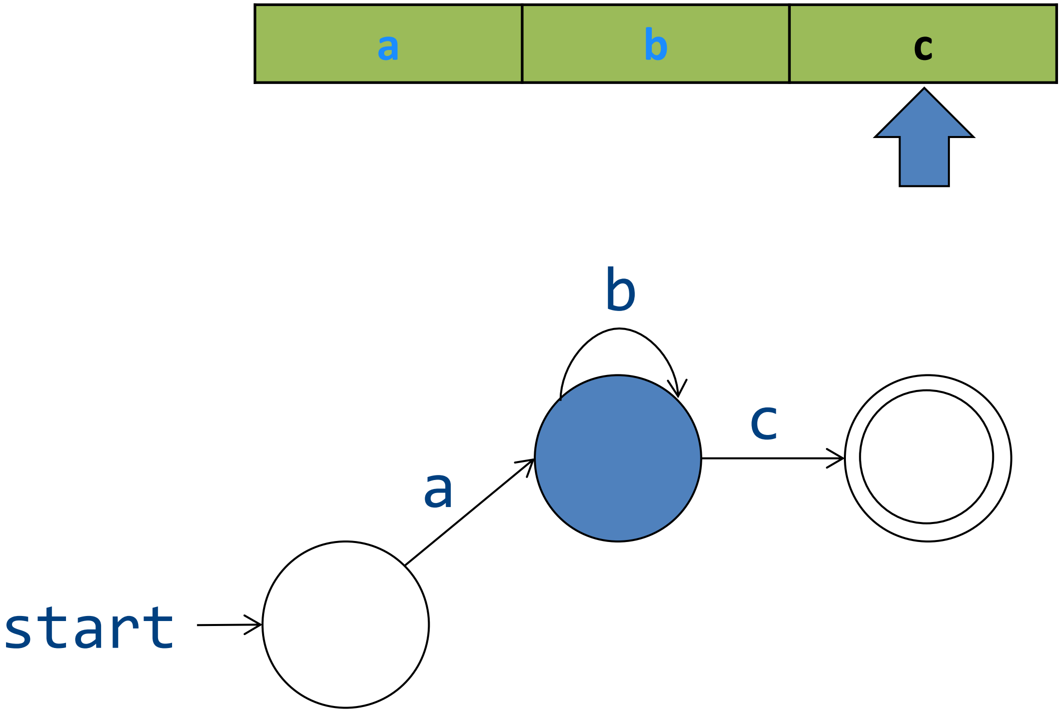

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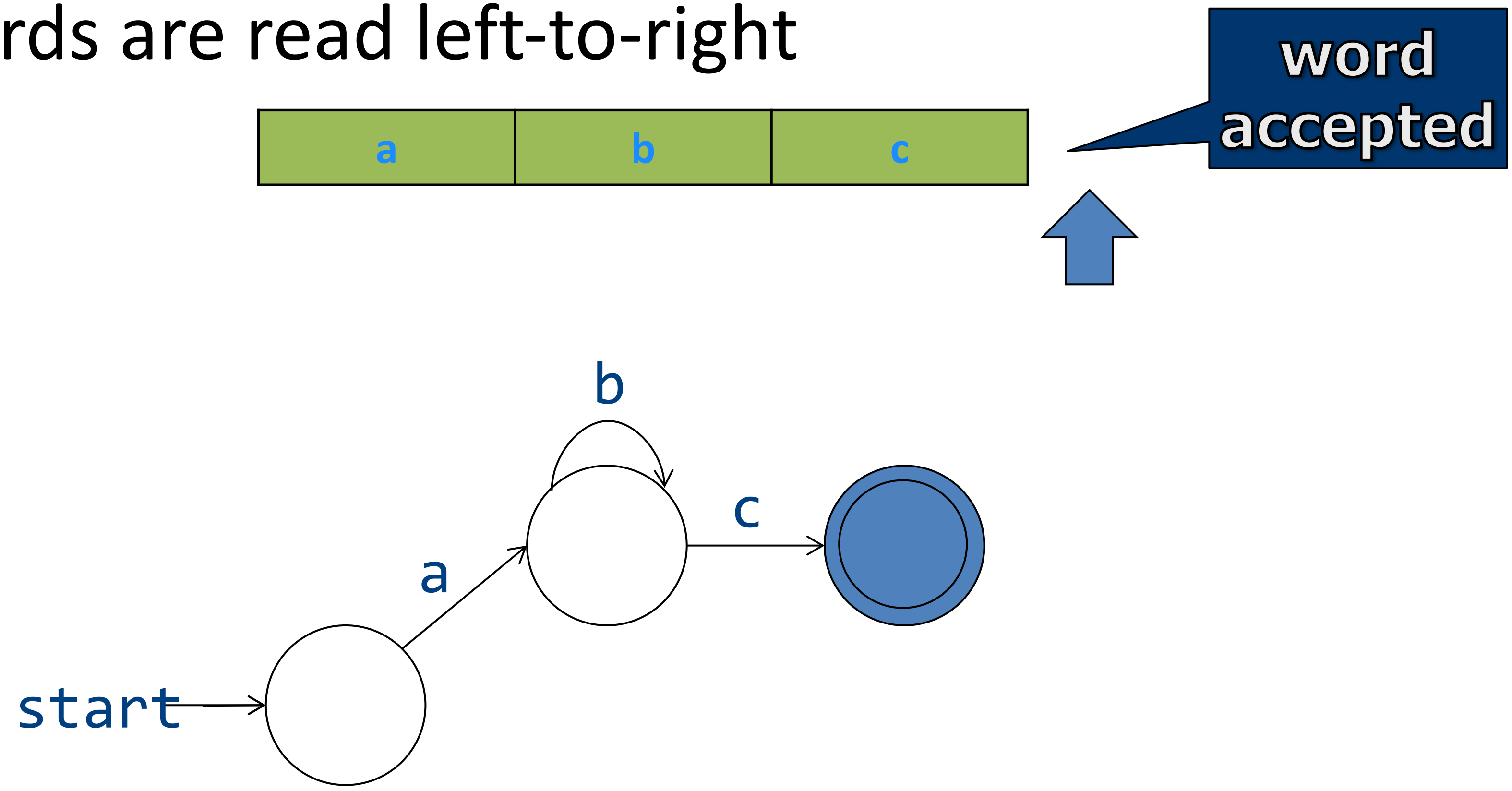

Rejecting Words

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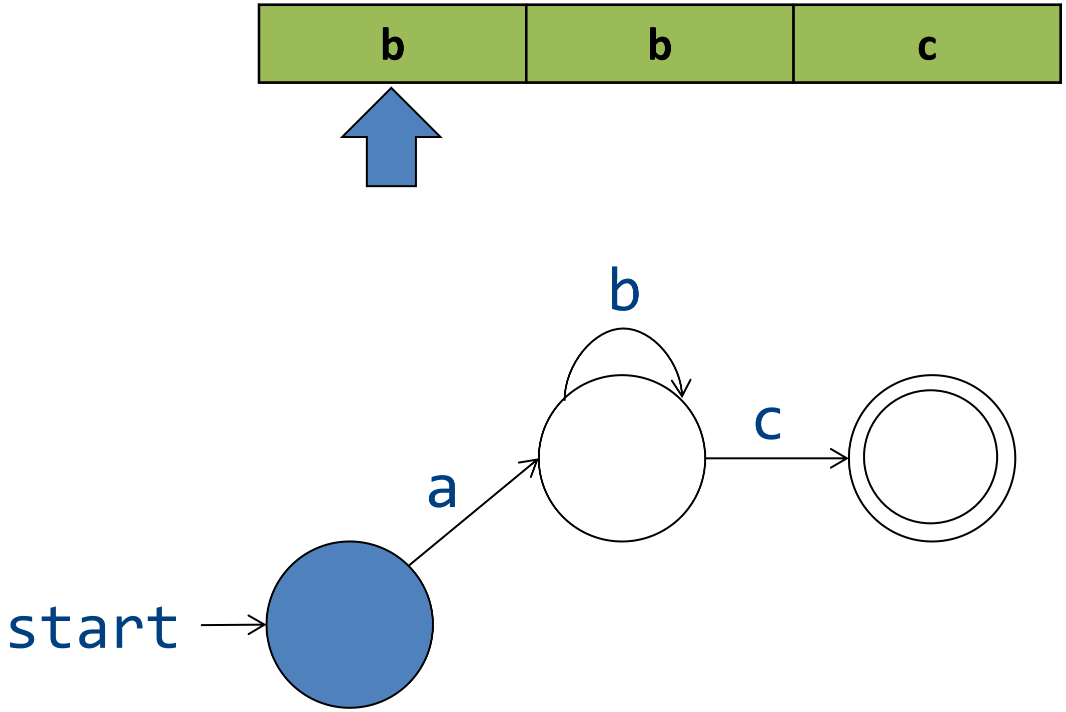

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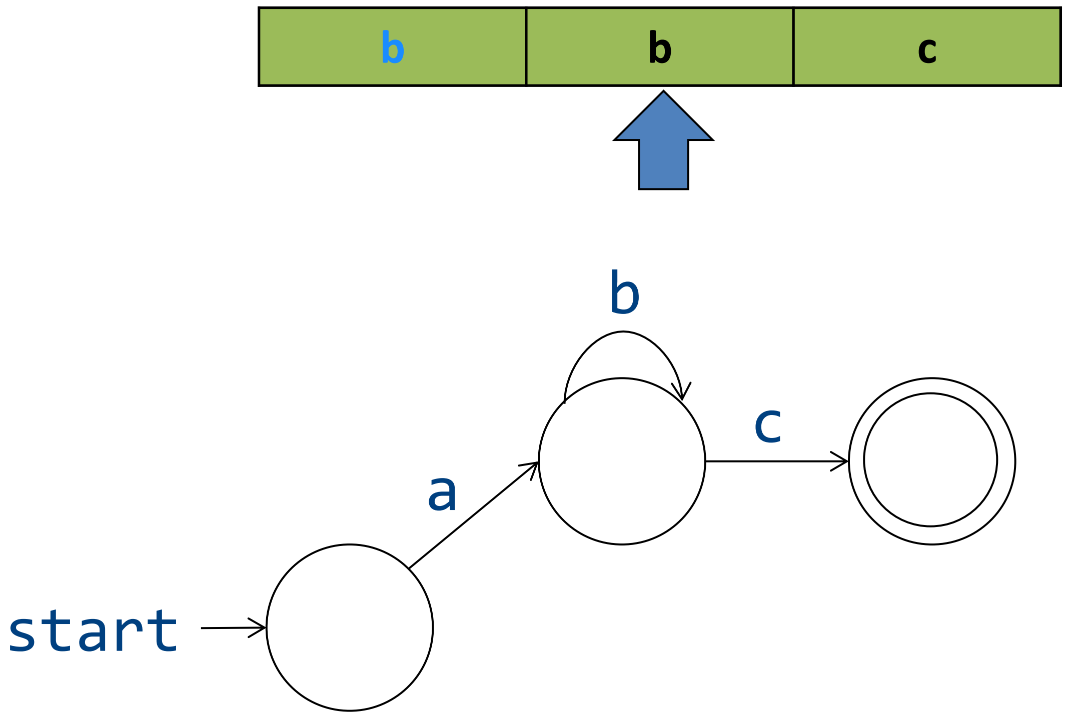


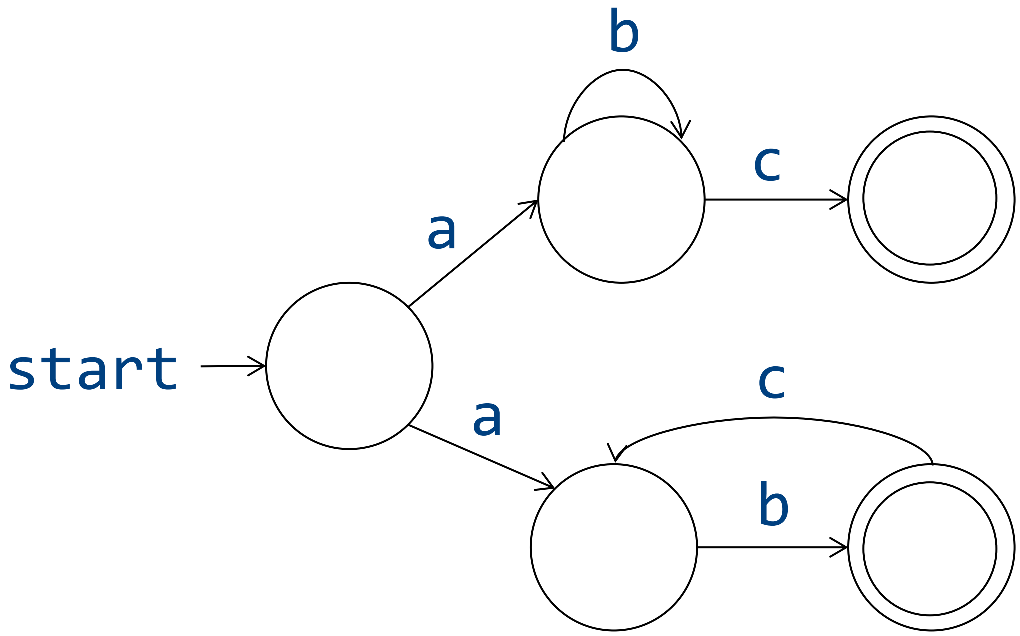
Non-deterministic Automata (NFA)

- $M = (\Sigma, Q, \delta, q_0, F)$
  - Σ - alphabet
  - Q – finite set of state
  - $q_0 \in Q$ – initial state
  - $F \subseteq Q$ – final states
  - $\delta : Q \times (\Sigma \cup \{\varepsilon\}) \rightarrow 2^Q$ - transition function
    - DFA: $\delta : Q \times \Sigma \rightarrow Q$

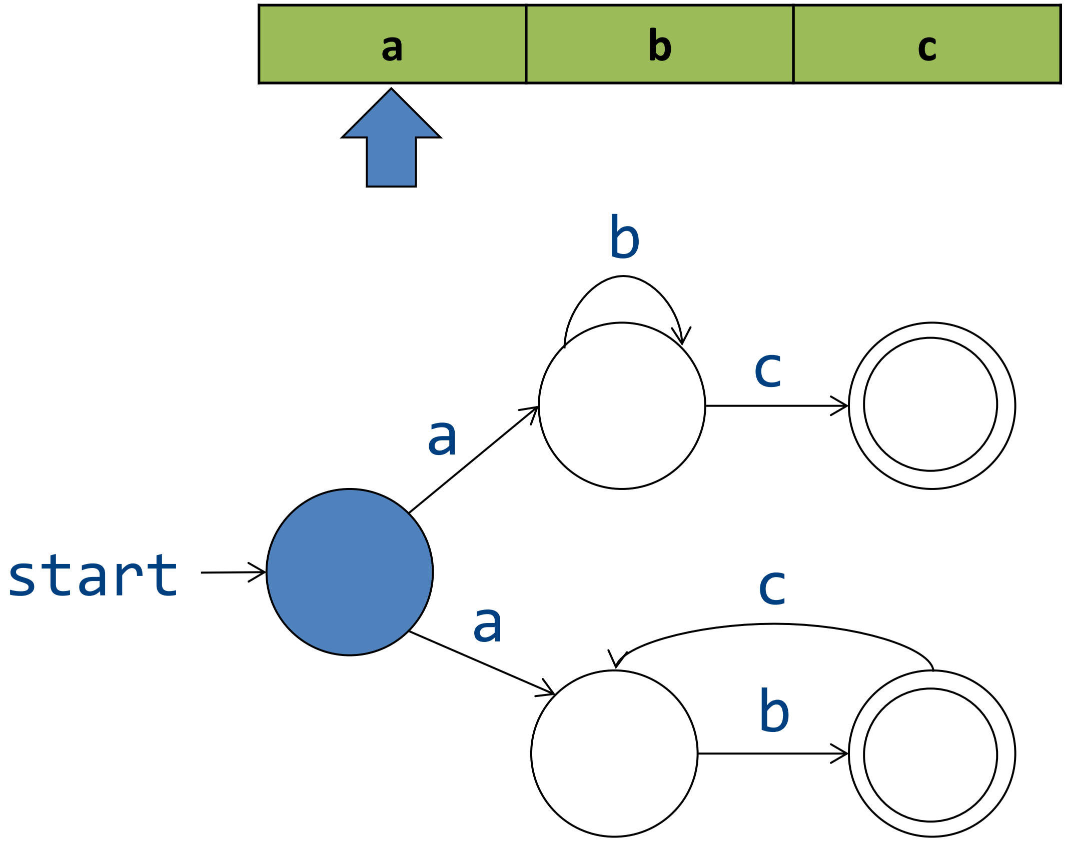
- For a word w, M can reach a number of states X
  - M accepts w if $X \cap M \neq \{\}$
    - Possible: $X = \{\}$
- Possible ε-transitions

NFA

- Allow multiple transitions from given state labeled by same letter

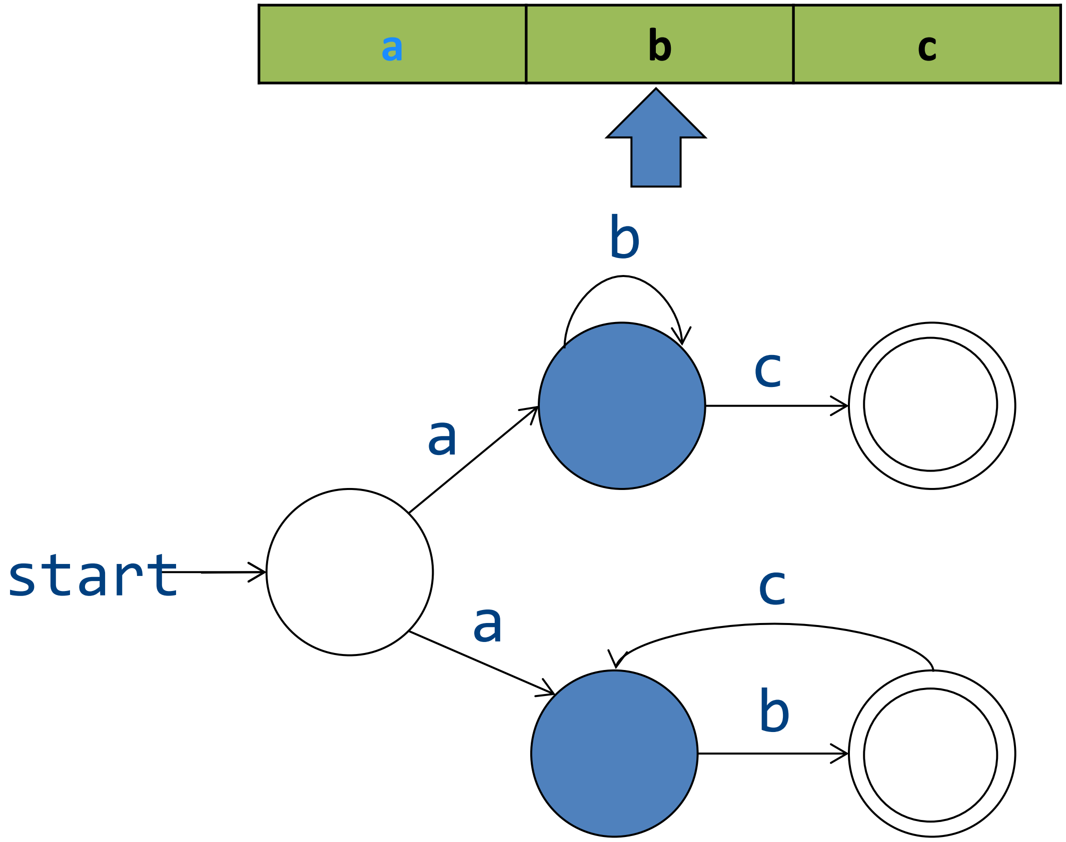


Accepting words

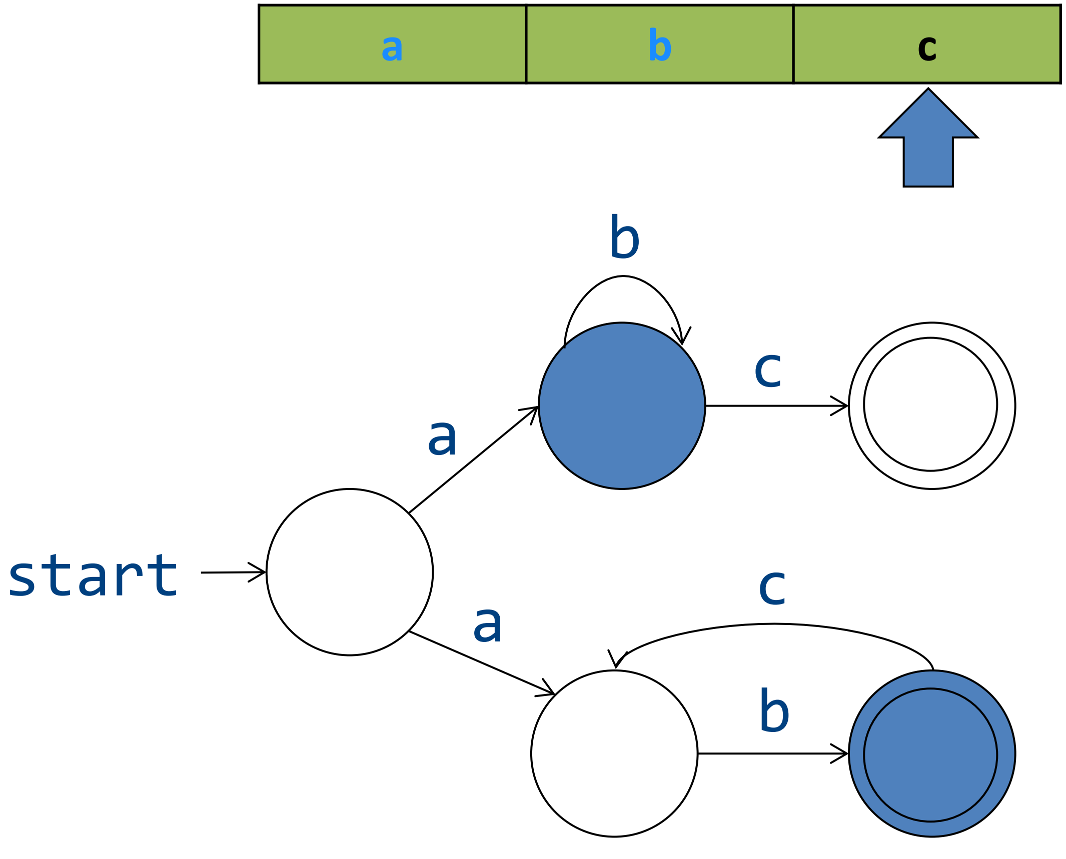


Accepting words

- Maintain set of states

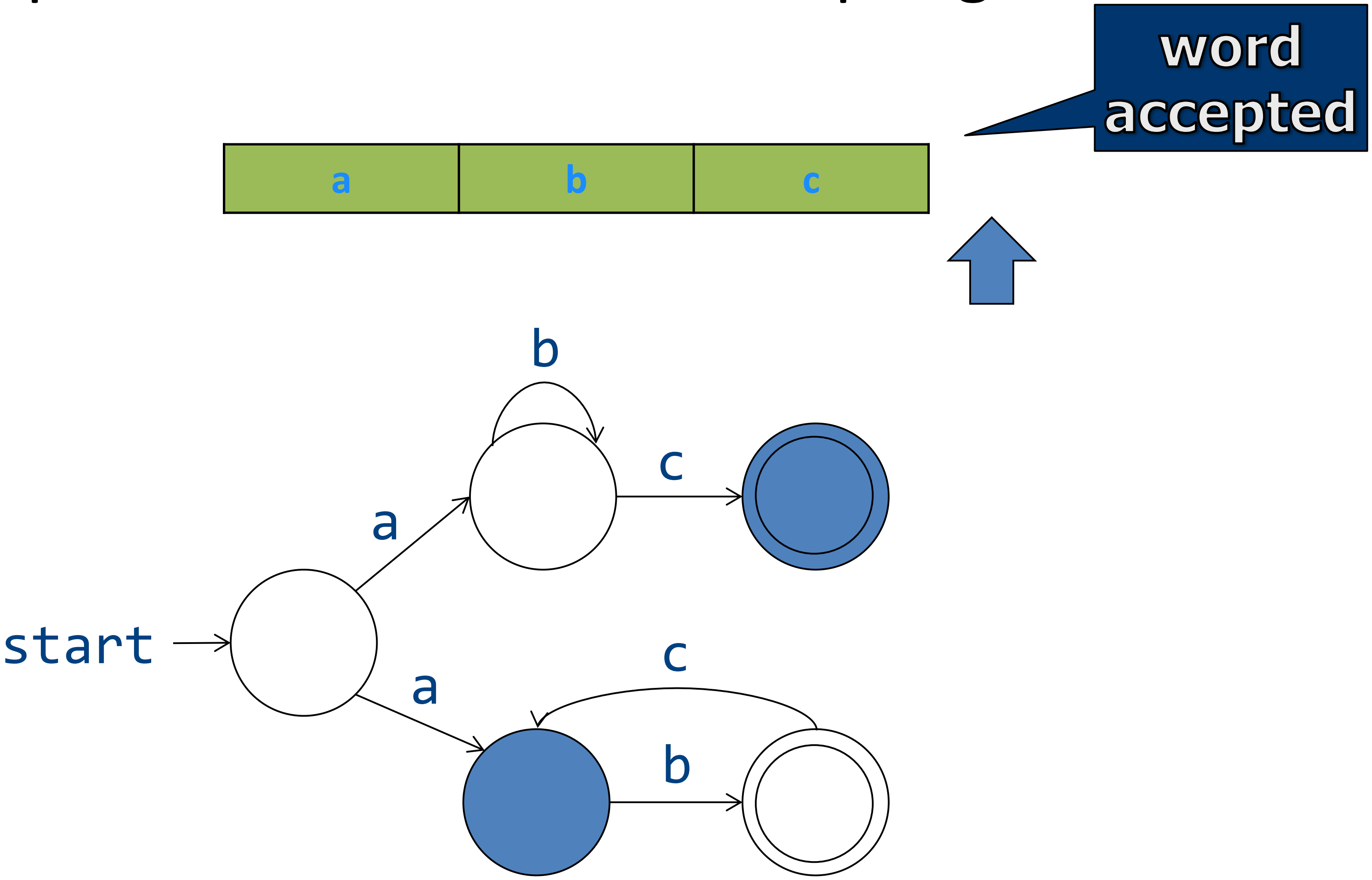


Accepting words



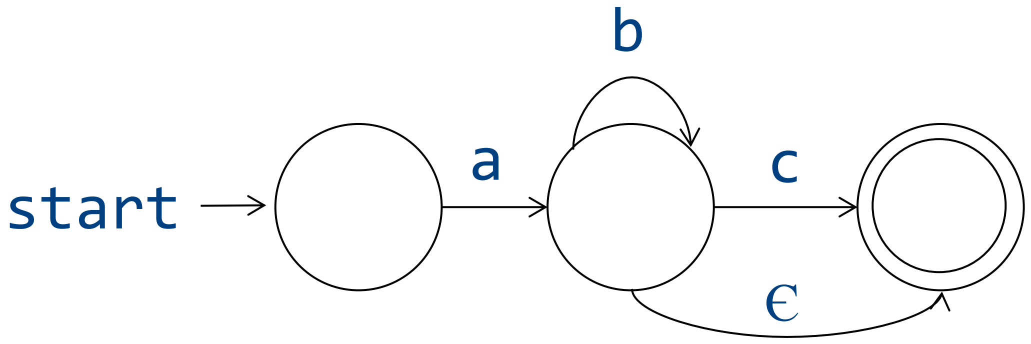
Accepting words

- Accept word if reached an accepting state

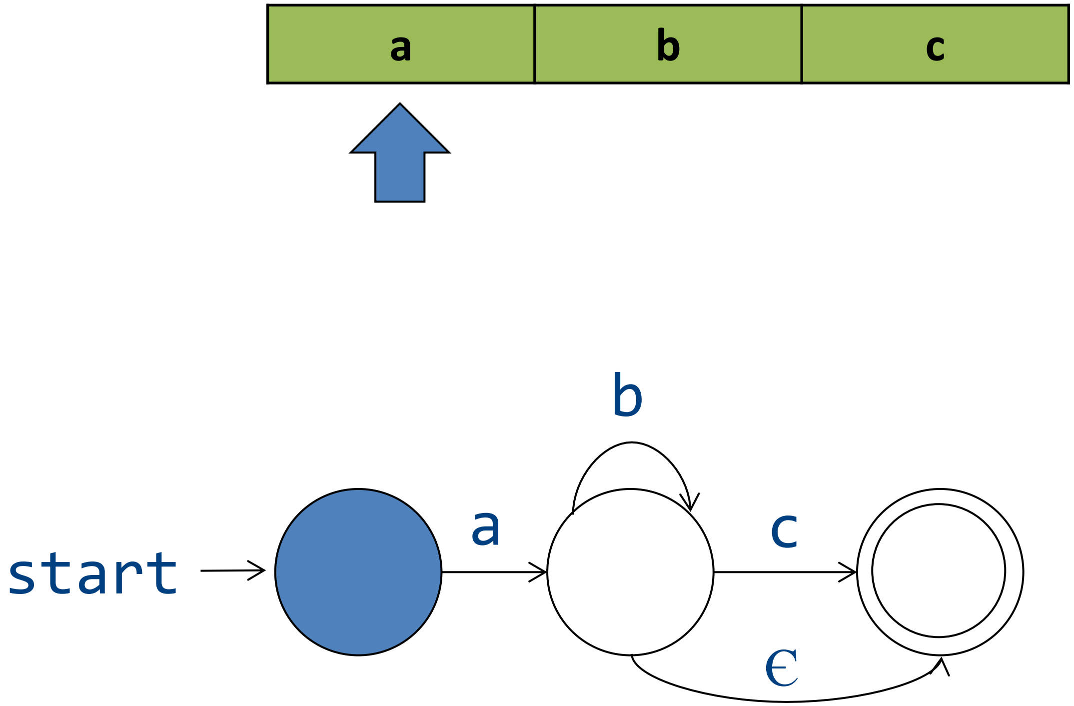


NFA+ϵ automata

- ϵ transitions can “fire” without reading the input

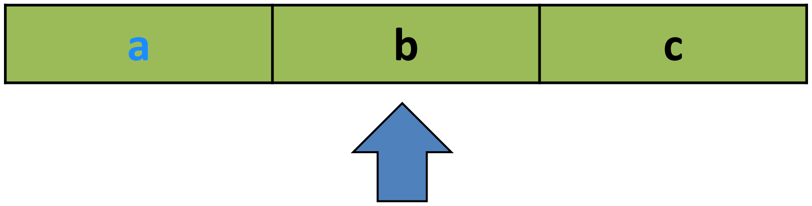


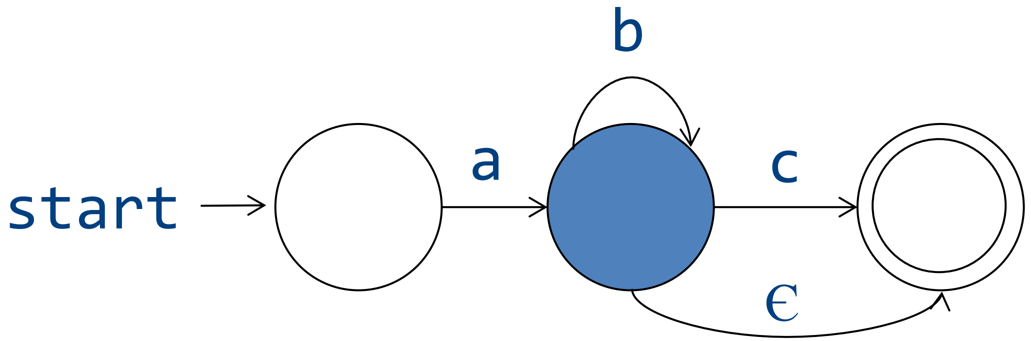
NFA+Є run example



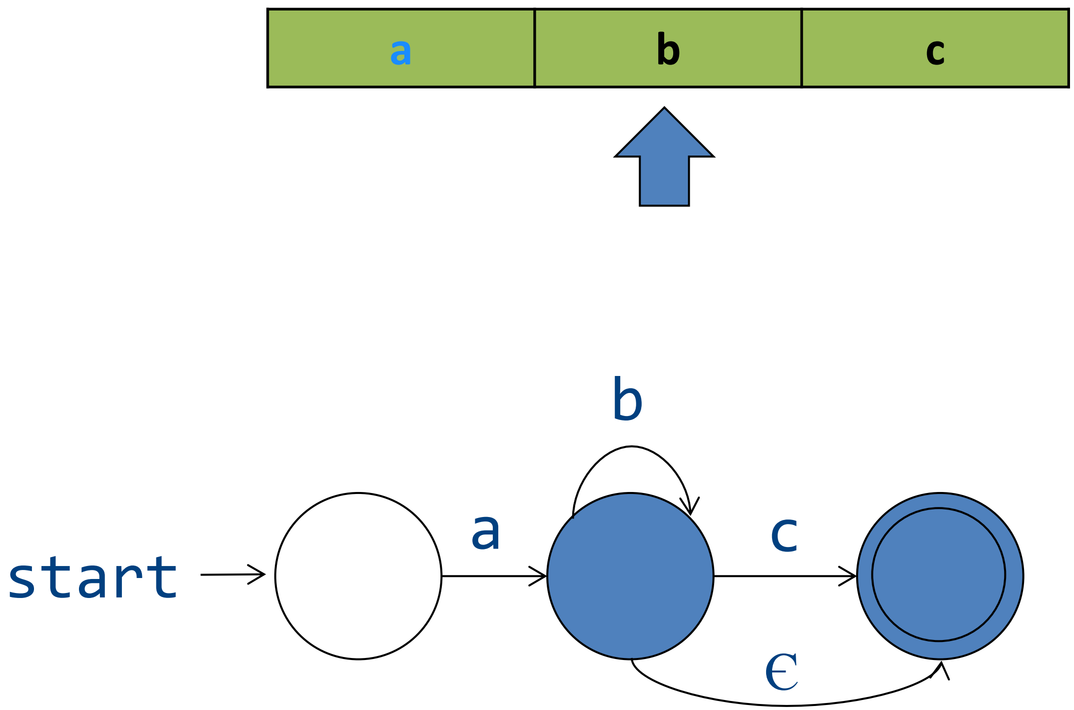
NFA+ϵ run example

- Now ϵ transition can non-deterministically take place





NFA+Є run example



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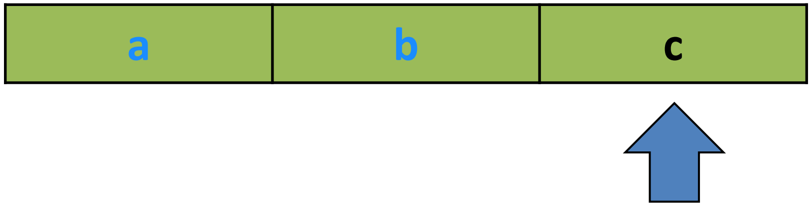
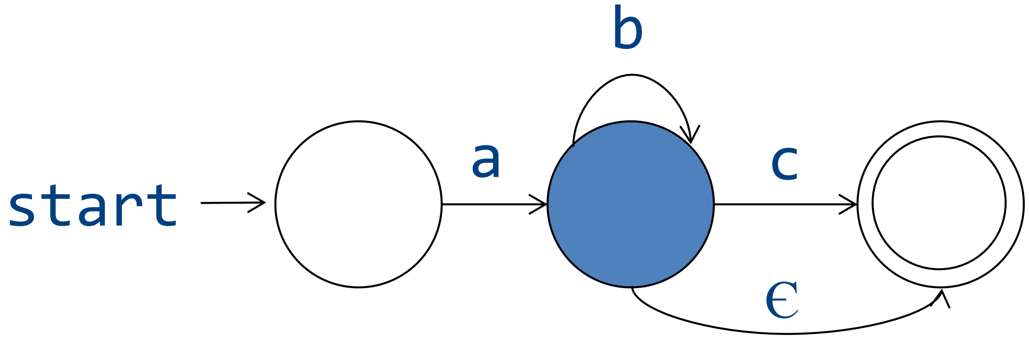
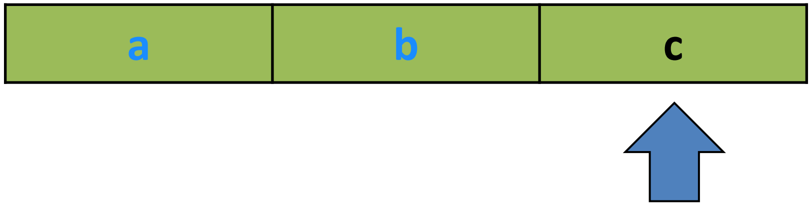
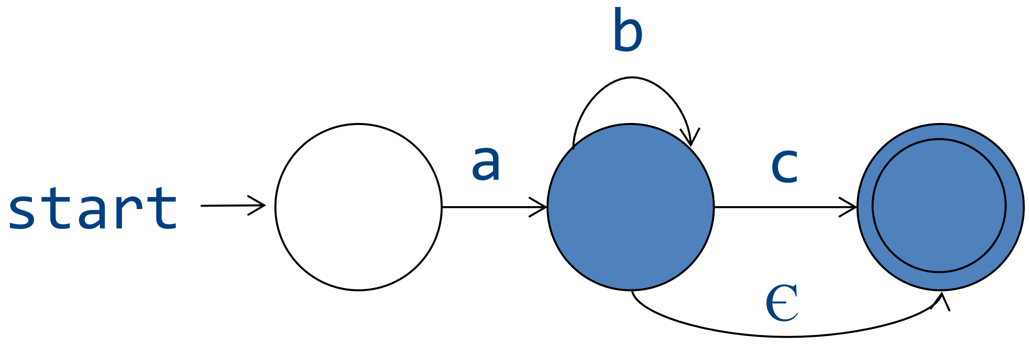




NFA+Є run example

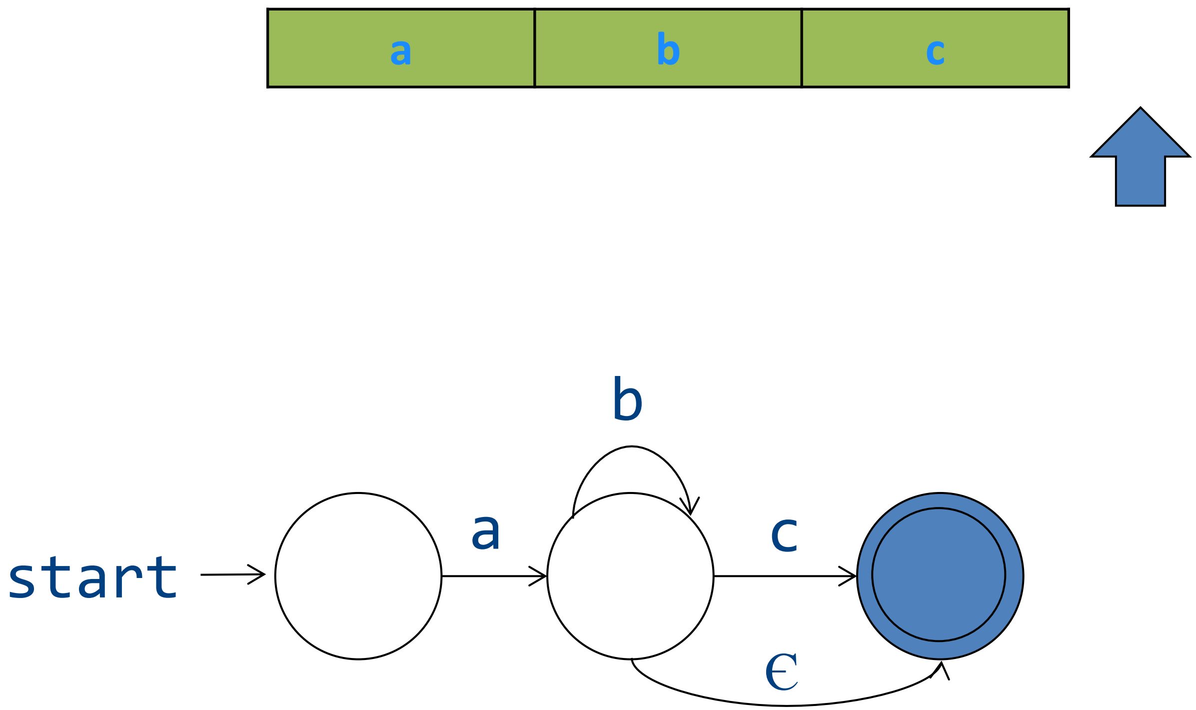
- Є transitions can "fire" without reading the input



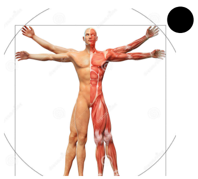


NFA+Є run example

- Word accepted



From regular expressions to NFA



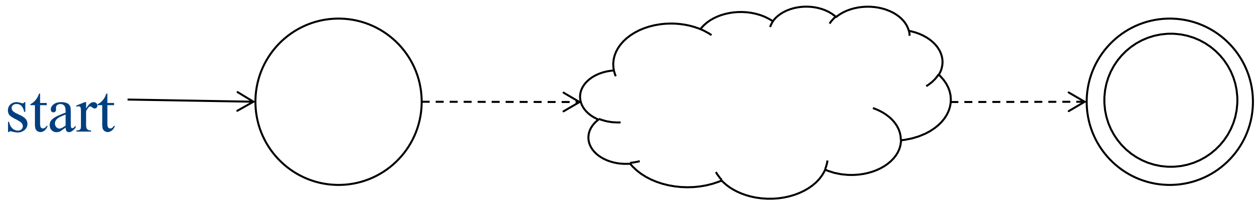
- Step 1: assign expression names and obtain pure regular expressions $R_1 \ldots R_m$

- Step 2: construct an NFA M_i for each regular expression R_i
- Step 3: combine all M_i into a single NFA

- *Ambiguity resolution: prefer longest accepting word*

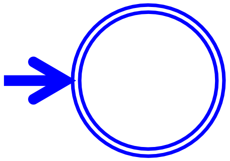
From reg. exp. to automata

- Theorem: *there is an algorithm to build an NFA+Є automaton for any regular expression*
- Proof: *by induction on the structure of the regular expression*

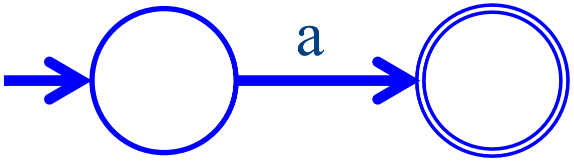


Basic constructs

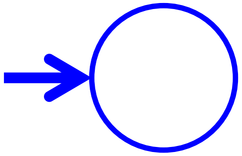
$R = \varepsilon$



$R = a$

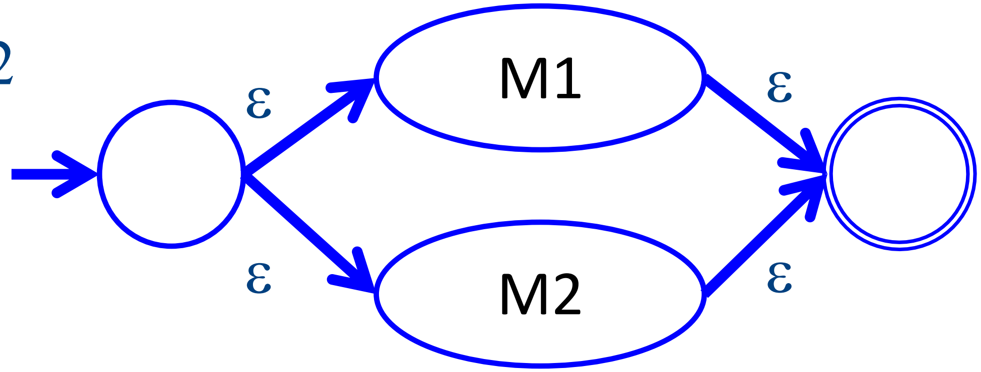


$R = \phi$

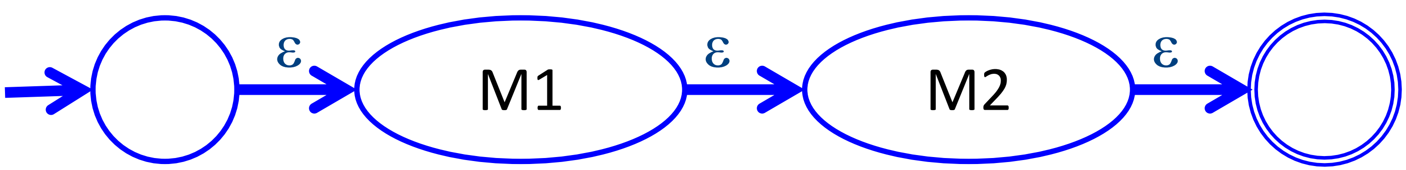


Composition

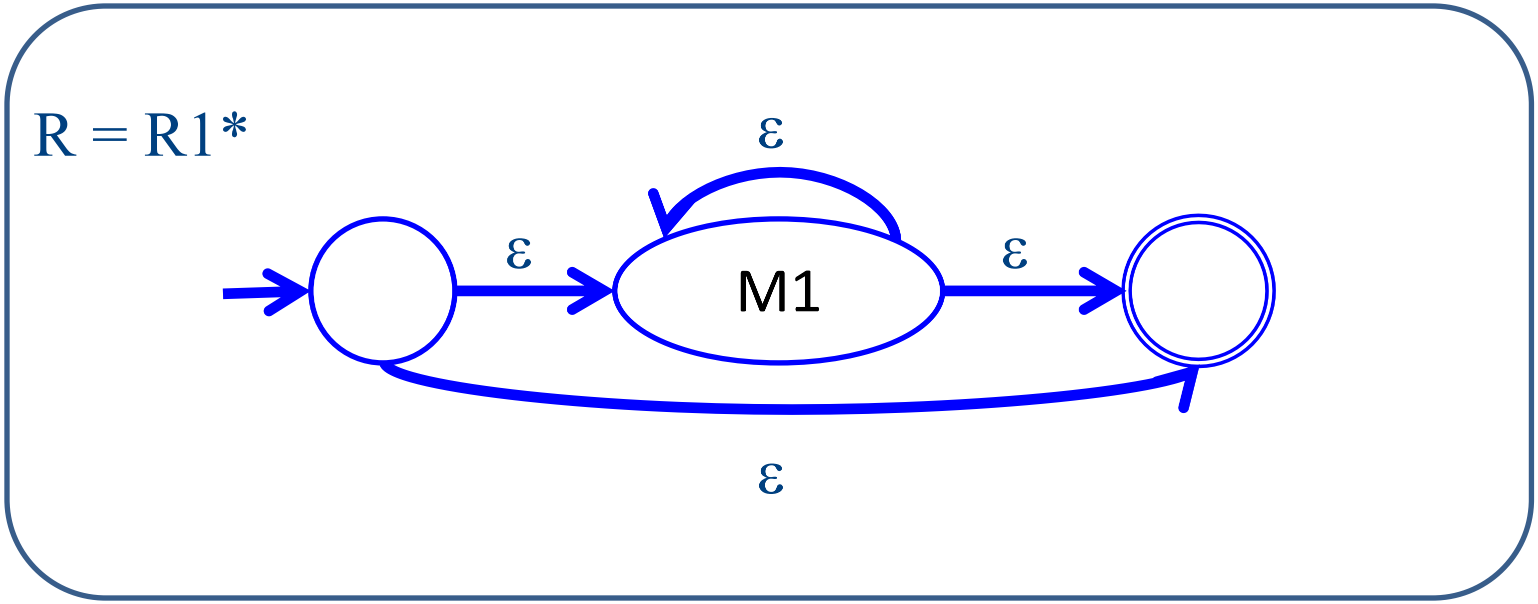
$R = R1 \mid R2$

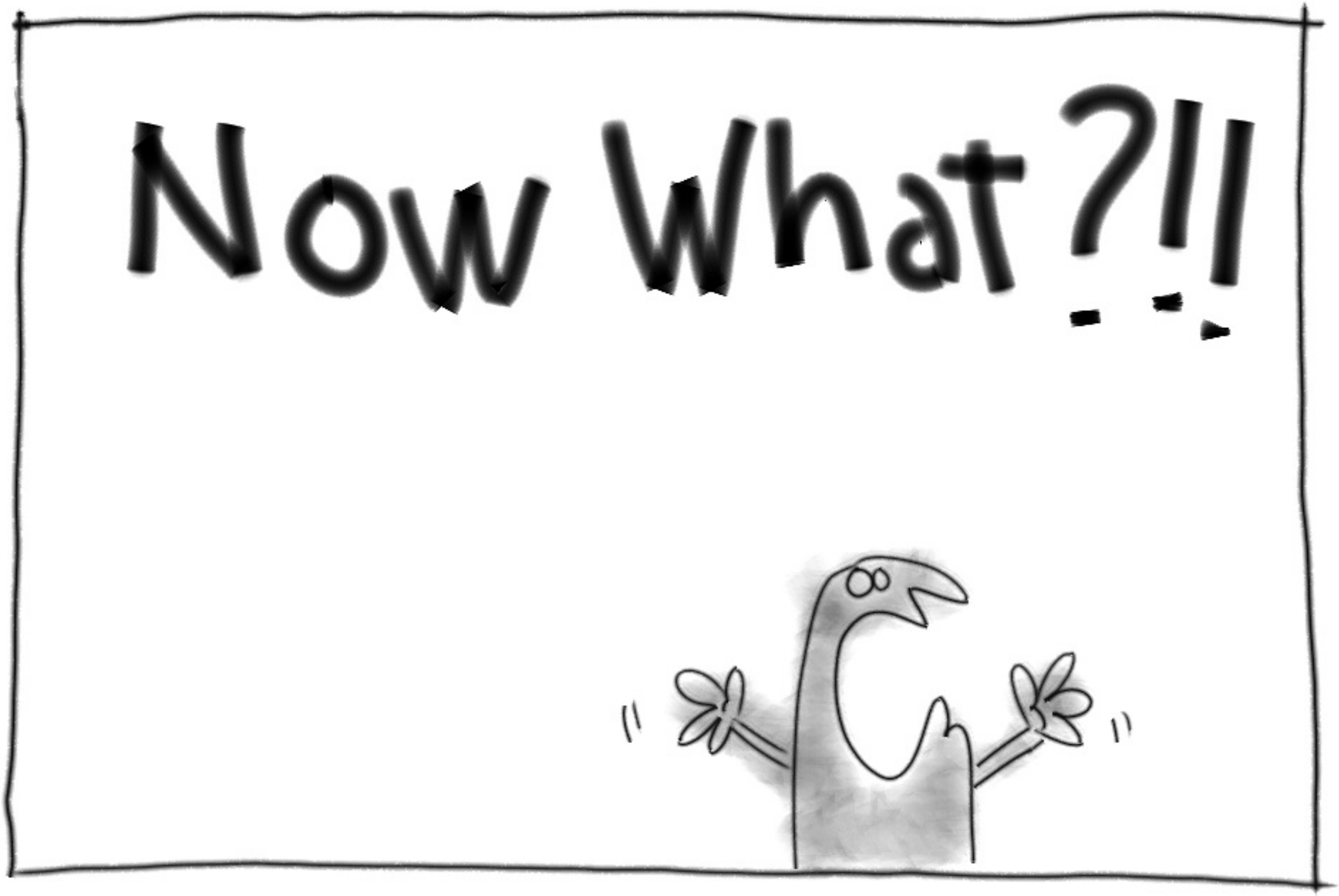


$R = R1R2$



Repetition




Now What?!!

Naïve approach

- Try each automaton separately
- Given a word w:
  - Try $M_1(w)$
  - Try $M_2(w)$
  - …
  - Try $M_n(w)$
- Requires resetting after every attempt

Actually, we combine automata

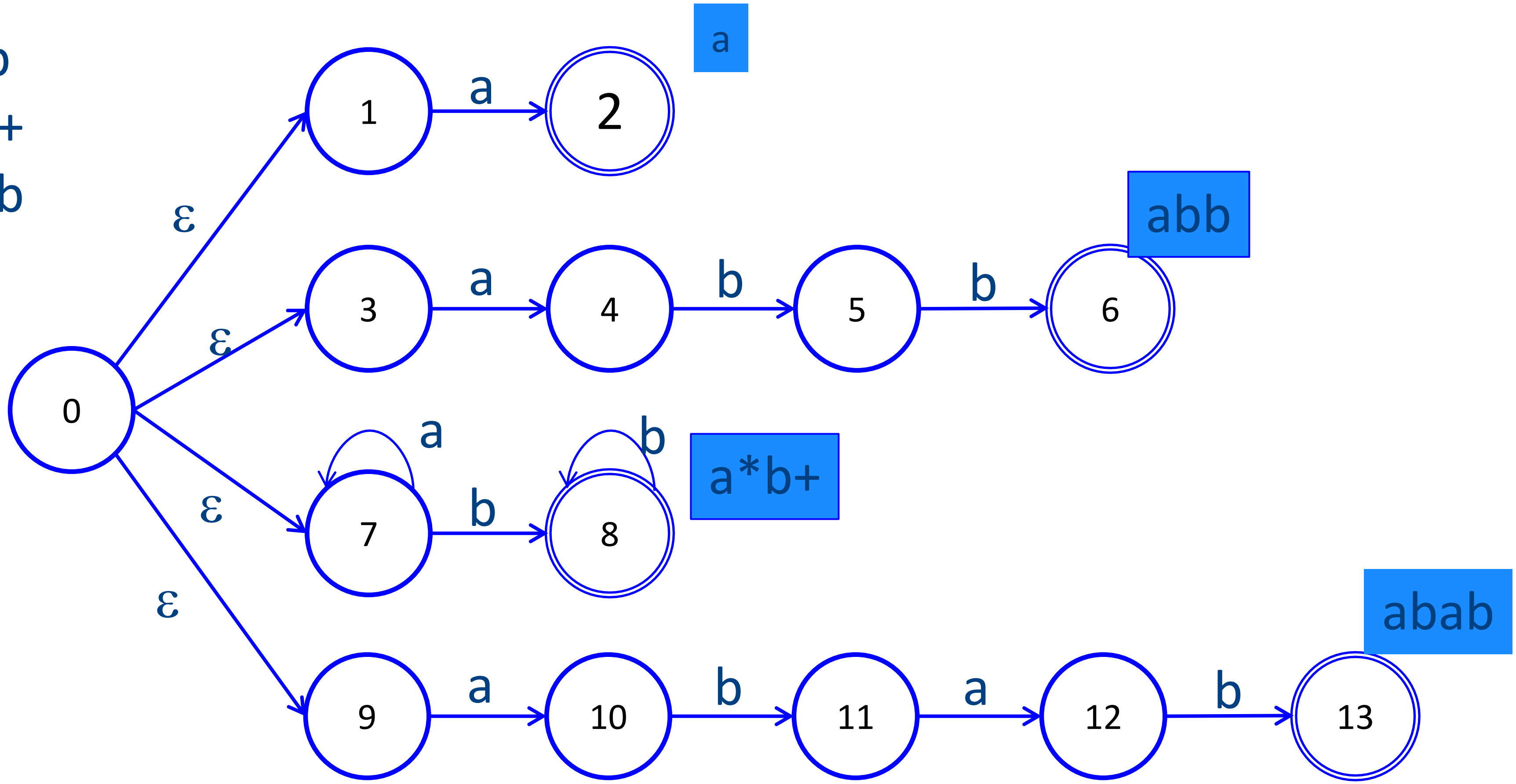
combines

a

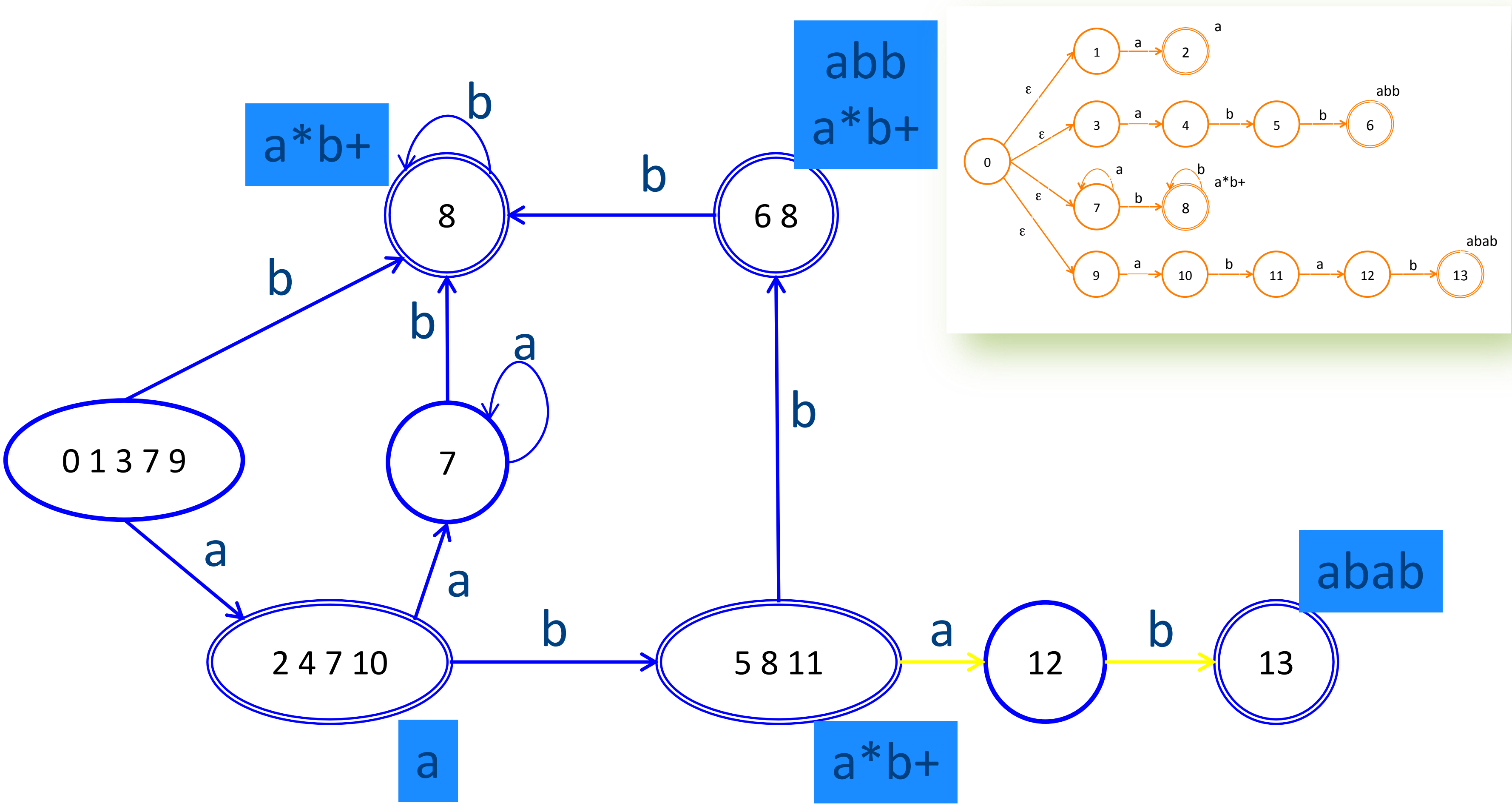
abb

a*b+

abab



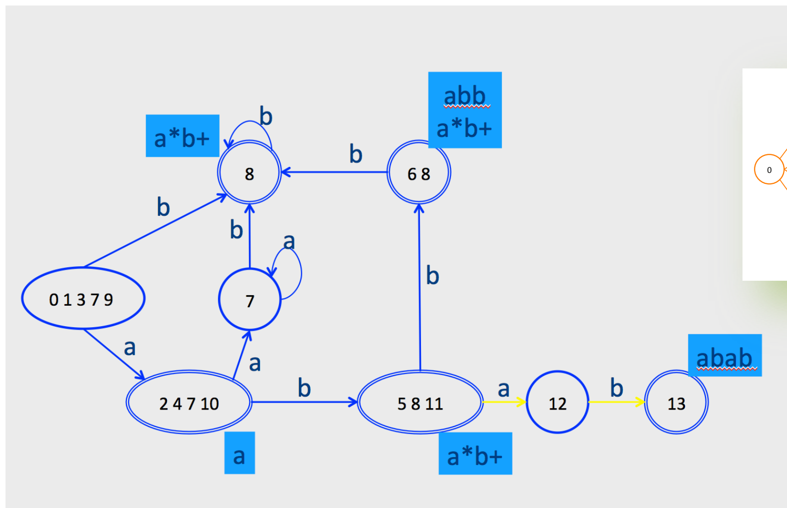
Corresponding DFA

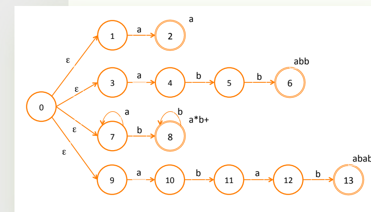


Scanning with DFA

- Run until stuck
  - **Remember last accepting state**
- Go back to accepting state
- Return token

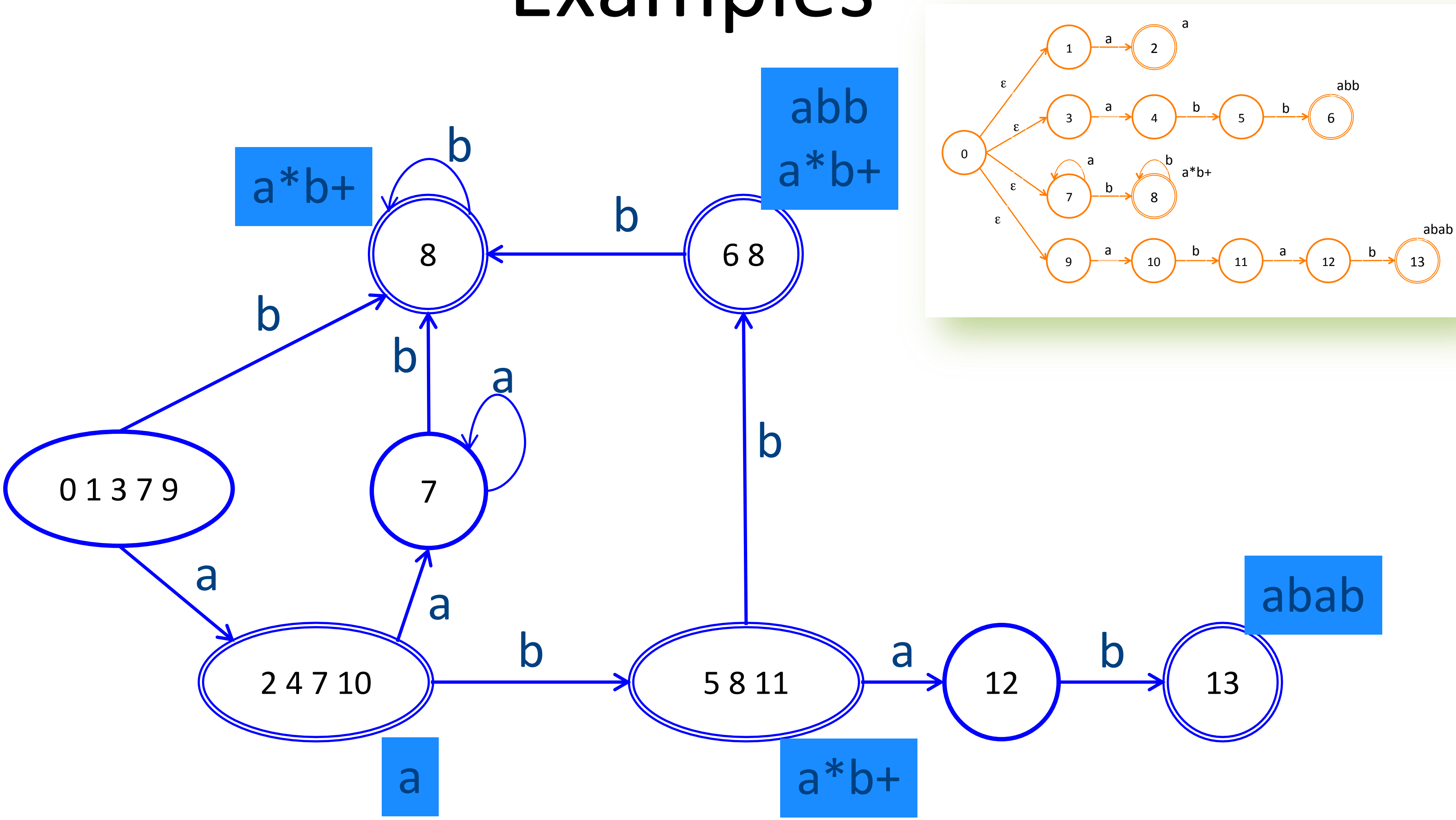
Ambiguity resolution





- Longest word
- Tie-breaker based on **order of rules** when words have same length

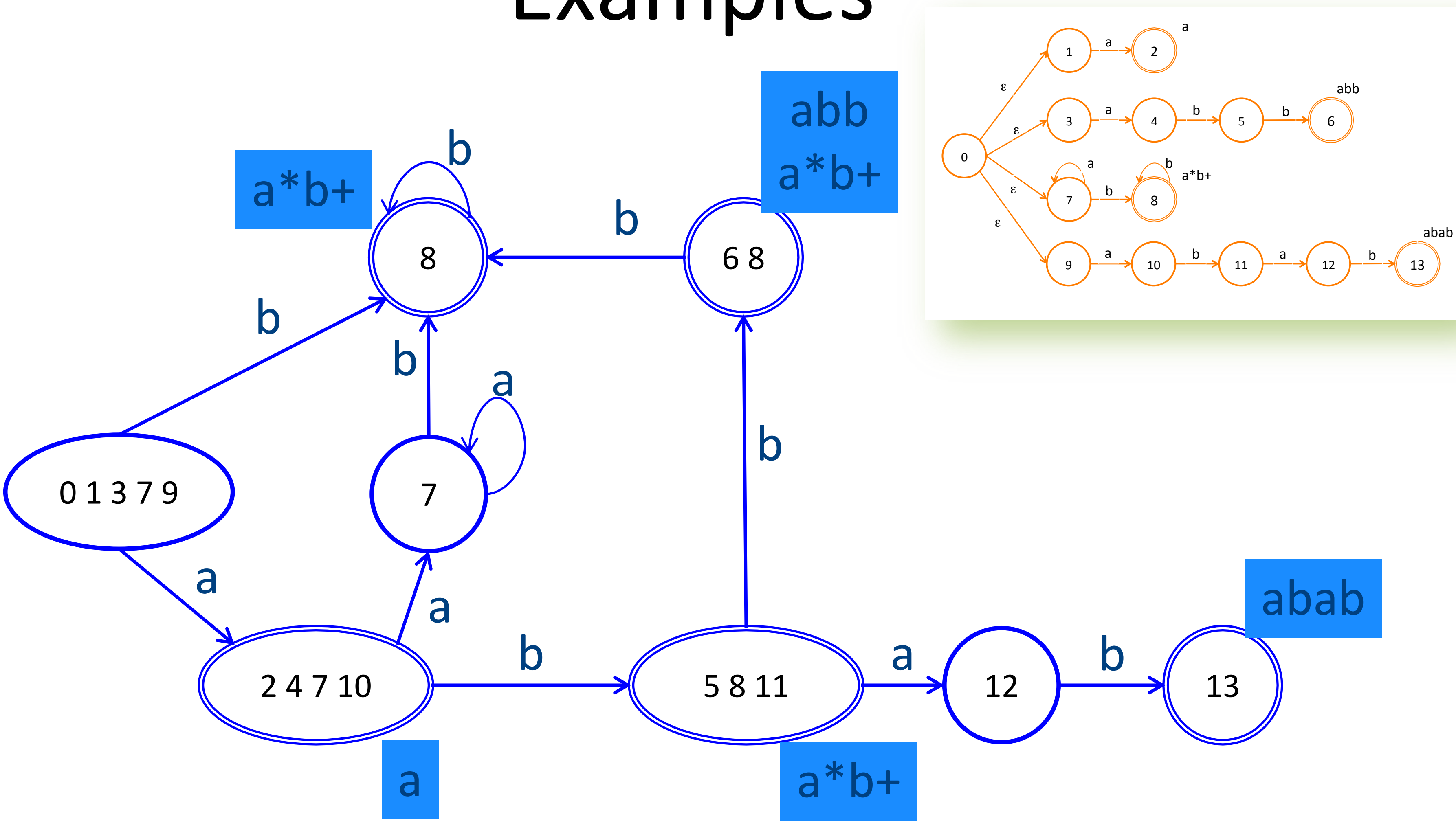
Examples



abaa: gets stuck after aba in state 12, backs up to state (5 8 11) pattern is a*b+, token is ab

Tokens: <a*b+, ab> <a,a><a,a>

Examples



abba: stops after second b in (6 8), token is abb because it comes first in spec

Tokens: <abb, abb> <a,a>

Summary of Construction

- Describe tokens as regular expressions
  - Decide attributes (values) to save for each token

- Regular expressions turned into a DFA
  - Also, records which attributes (values) to keep

- Lexical analyzer simulates the run of an automata with the given transition table on any input string

A Few Remarks

- Turning an NFA to a DFA is expensive, but
  - Exponential in the worst case
  - In practice, works fine

- The construction is done once per-language
  - At Compiler construction time
  - Not at compilation time

Implementation

Implementation by Example

```
if                                    { return IF; }
[a-z][a-z0-9]*                        { return ID; }
[0-9]+                                { return NUM; }
[0-9]”.”[0-9]+|[0-9]*”.”[0-9]+        { return REAL; }
(\-\-[a-z]*\n)|(“  “|\n|\t)           { ; }
.                                     { error(); }
```

- if
- xy, i, zs98
- 3,32, 032
- 0.55, 33.1
- --comm\n
  \n, \t, “ “

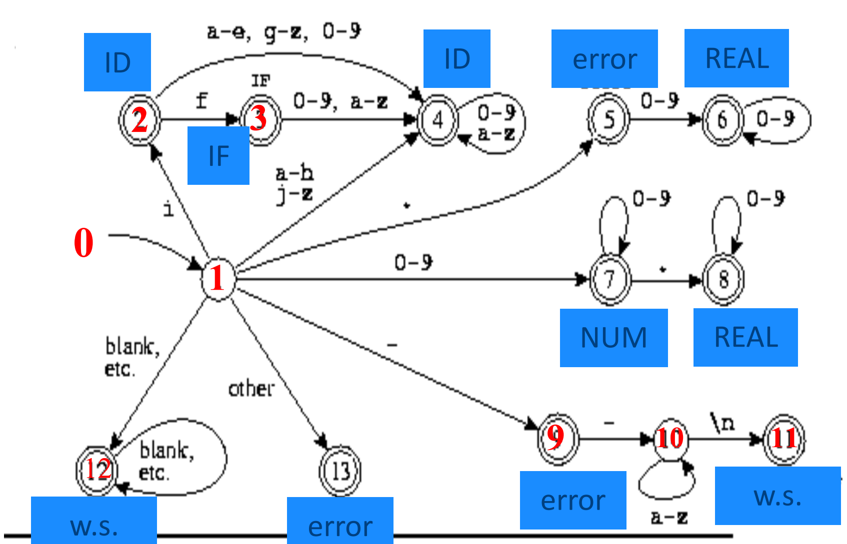


FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
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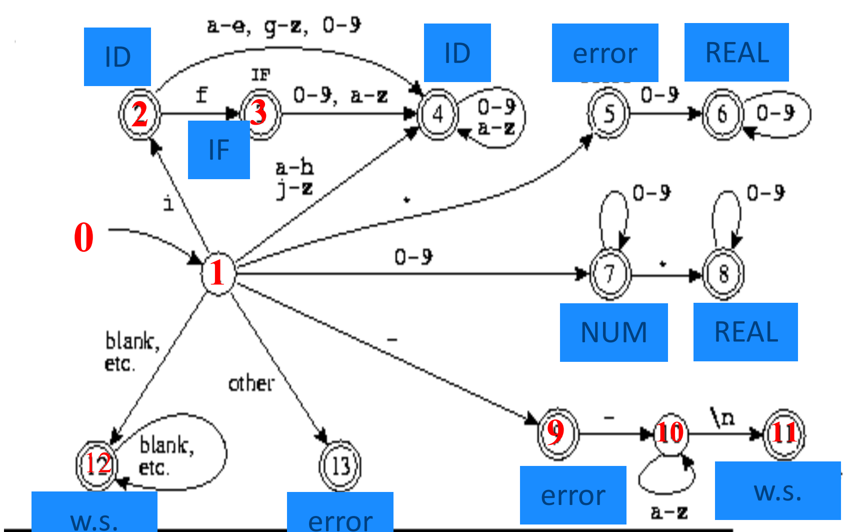

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
Cambridge University Press, ©1998 Andrew W. Appel

```
int edges[][256]= {
                      /* …, 0, 1, 2, 3, ..., -, e, f, g, h, i, j,  ... */
/* state 0  */  {0, …, 0, 0, …,  0, 0, 0, 0, 0, ..., 0, 0, 0, 0, 0, 0},
/* state 1  */  {13, … , 7, 7, 7, 7,  …,  9,  4, 4, 4, 4, 2, 4, …, 13, 13},
/* state 2  */  {0,  …, 4, 4, 4, 4,  ..., 0,  4, 3, 4, 4, 4, 4, …, 0, 0},
/* state 3  */  {0, …,  4, 4, 4, 4,  …, 0,  4, 4, 4, 4, 4, 4, , 0, 0},
/* state 4  */  {0, …,  4, 4, 4, 4,   …, 0,  4, 4, 4, 4, 4, 4, …, 0, 0},
/* state 5  */  {0, …,  6, 6, 6, 6,   …, 0,  0, 0, 0, 0, 0, 0, …,  0, 0},
/* state 6  */  {0,  …,  6, 6, 6, 6,  …, 0,  0, 0, 0, 0, 0, 0, ..., 0, 0},
/* state 7  */
/* state …  */                          ...
/* state 13 */  {0,  …,  0, 0, 0, 0,  …, 0,  0, 0, 0, 0, 0, 0, …,  0, 0}
};
```

Pseudo Code for Scanner

```
char* input = … ;

Token nextToken() {
    lastFinal = 0;
    currentState = 1 ;
    inputPositionAtLastFinal = input;
    currentPosition = input;
    while (not(isDead(currentState)))  {
        nextState = edges[currentState][*currentPosition];
        if  (isFinal(nextState)) {
                lastFinal = nextState ;
                inputPositionAtLastFinal = currentPosition;
        }
        currentState = nextState;
        advance currentPosition;
    }
    input = inputPositionAtLastFinal + 1;
    return action[lastFinal];
}
```

Example

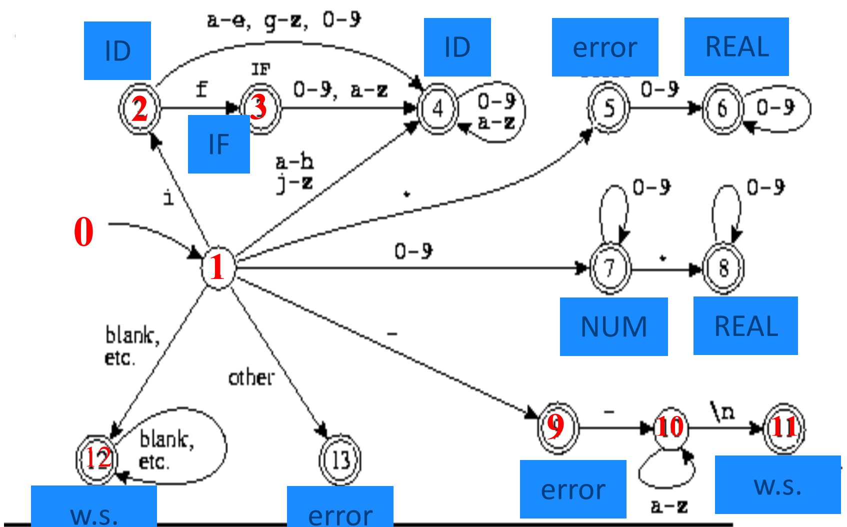

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
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Input: “if --not-a-com”

2 blanks

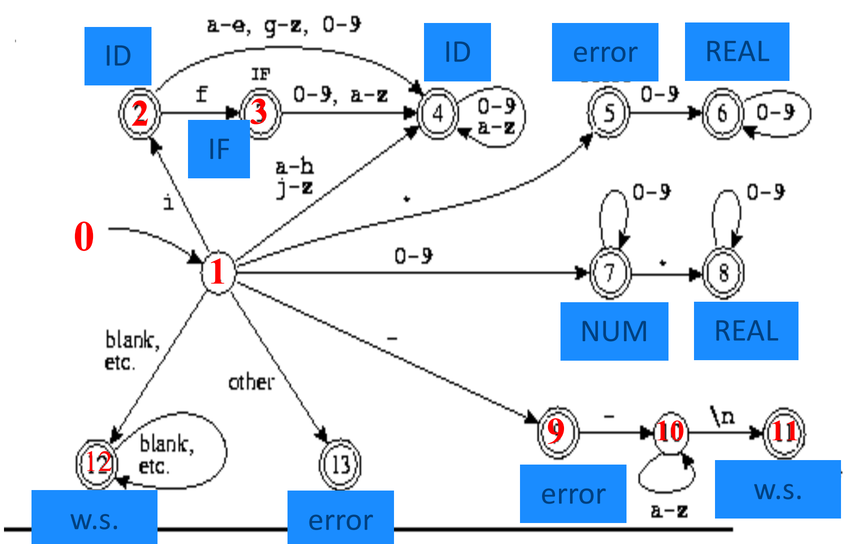

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
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final	state	input
0	1	if --not-a-com
2	2	if --not-a-com
3	3	if --not-a-com
3	0	if --not-a-com

return IF

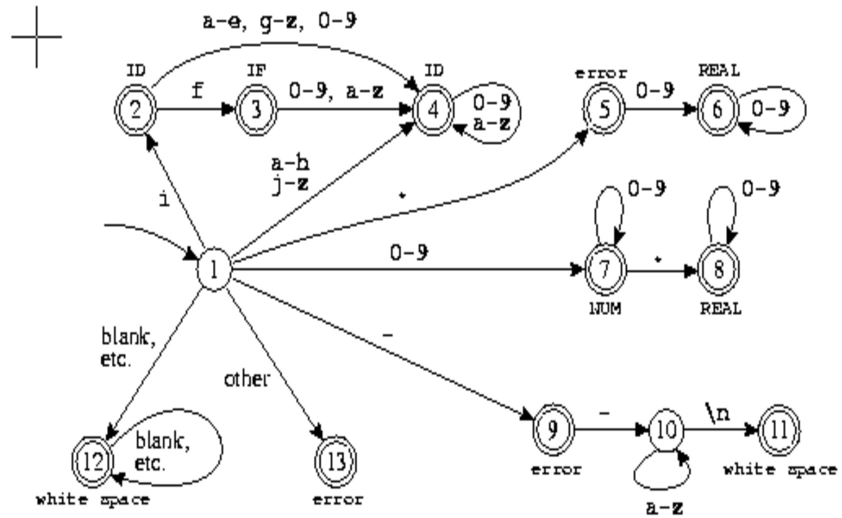

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
Cambridge University Press, ©1998 Andrew W. Appel

found whitespace

final	state	input
0	1	--not-a-com
12	12	--not-a-com
12	12	--not-a-com
12	0	--not-a-com

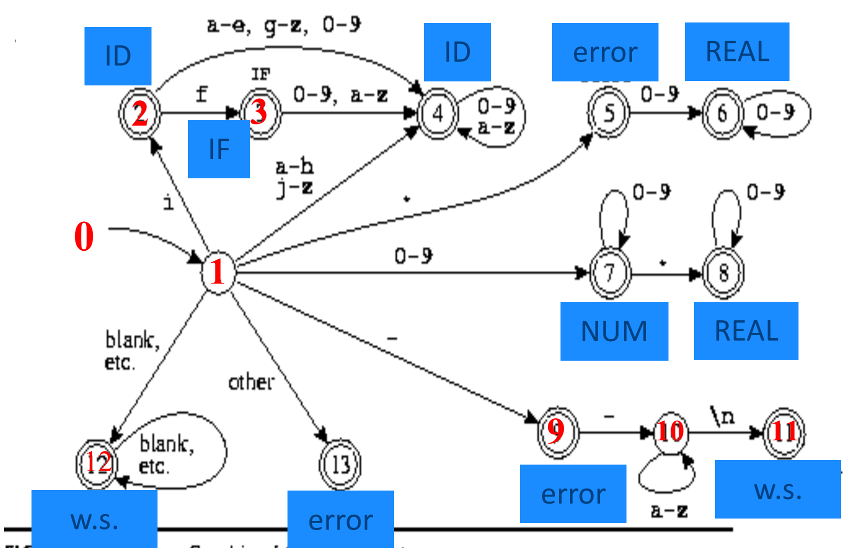

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
Cambridge University Press, ©1998 Andrew W. Appel

error

final	state	input
0	1	--not-a-com
9	9	--not-a-com
9	10	--not-a-com
10	10	--not-a-com
10	10	--not-a-com
10	0	--not-a-com

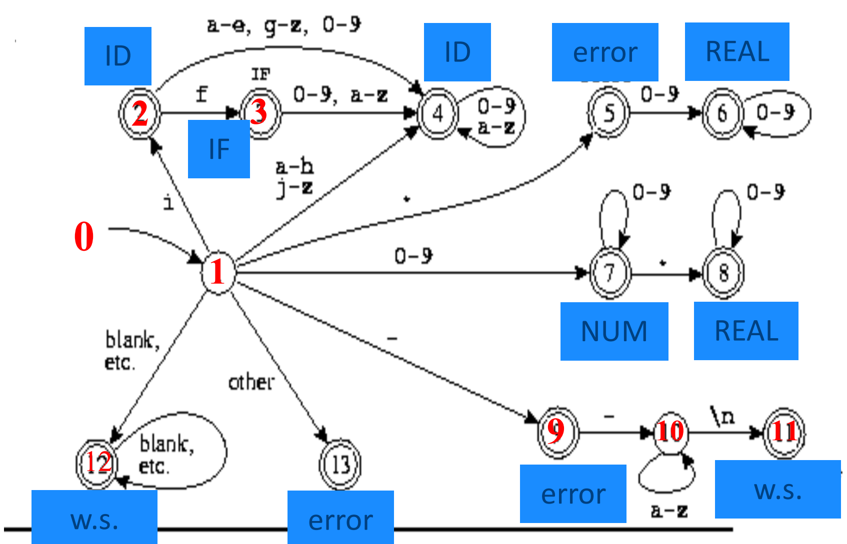

FIGURE 2.4. Combined finite automaton.
From *Modern Compiler Implementation in ML*,
Cambridge University Press, ©1998 Andrew W. Appel

error

final	state	input
0	1	-not-a-com
9	9	-not-a-com
9	0	-not-a-com
9	0	-not-a-com
9	0	-not-a-com

Concluding remarks

- Efficient scanner
- Minimization
- Error handling
- Automatic creation of lexical analyzers

Efficient Scanners

- Efficient state representation
- Input buffering
- Using switch and gotos instead of tables

Minimization

- Create a non-deterministic automaton (NDFA) from every regular expression
- Merge all the automata using epsilon moves (like the | construction)
- Construct a deterministic finite automaton (DFA)
  - State priority
- Minimize the automaton
  - separate accepting states by token kinds

Example

```
if                    { return IF; }
[a-z][a-z0-9]*        { return ID; }
[0-9]+                { return NUM; }
```

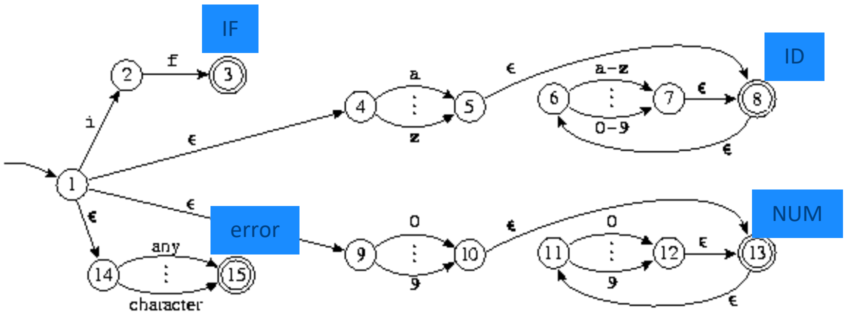

FIGURE 2.7. Four regular expressions translated to an NFA. From *Modern Compiler Implementation in ML*, Cambridge University Press, ©1998 Andrew W. Appel

Modern compiler implementation in ML, Andrew Appel, (c)1998, Figures 2.7,2.8

Example

```
if                      { return IF; }
[a-z][a-z0-9]*          { return ID; }
[0-9]+                  { return NUM; }
```

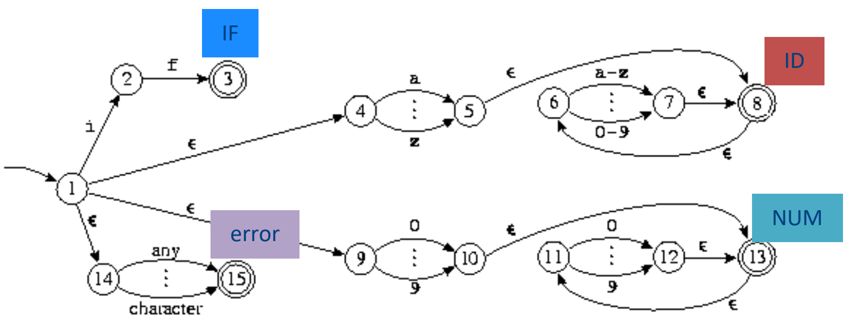

FIGURE 2.7. Four regular expressions translated to an NFA.
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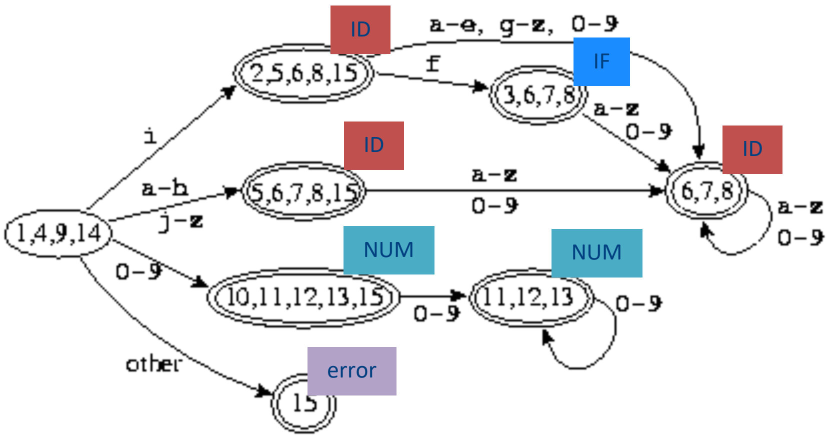
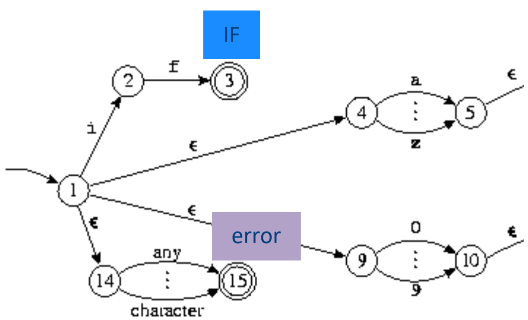
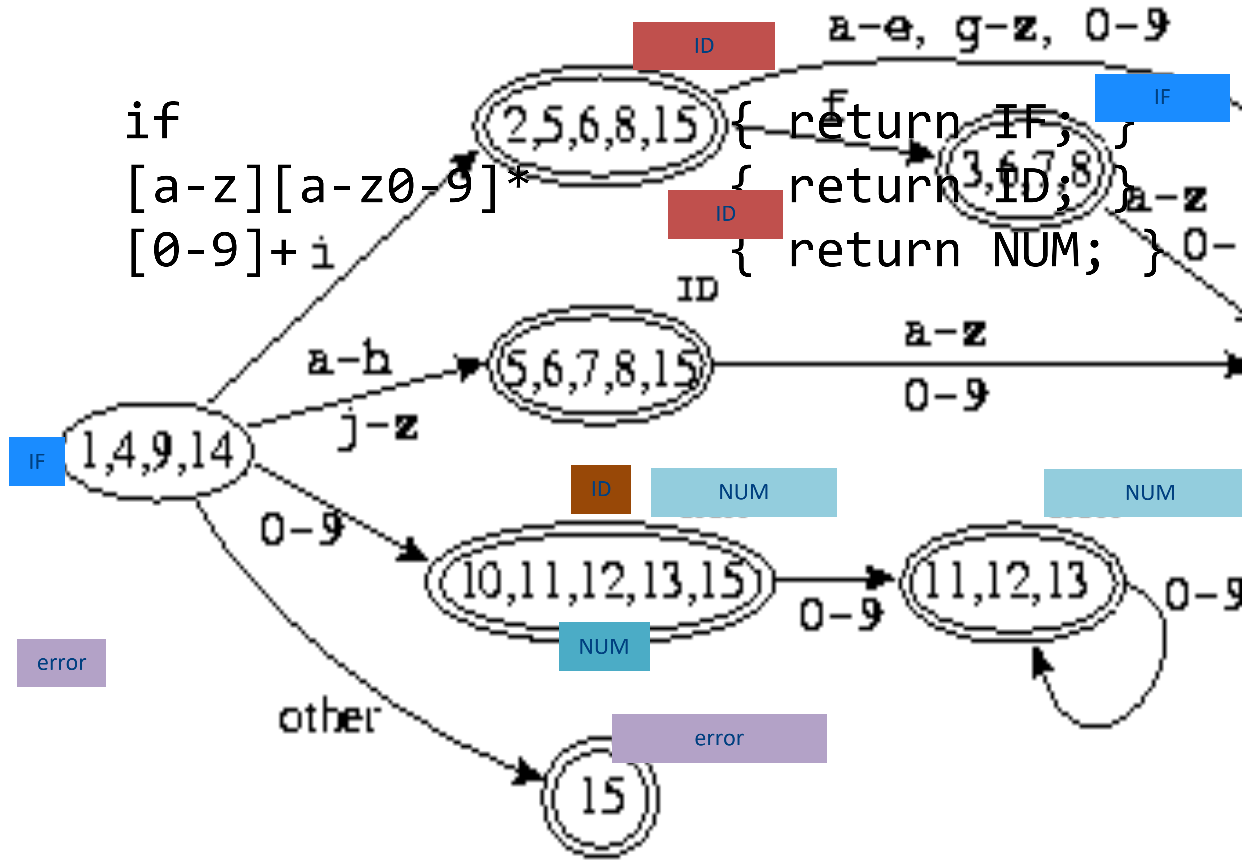


Modern compiler implementation in ML, Andrew Appel, (c)1998, Figures 2.7,2.8

Example

```
if                   { return IF; }
[a-z][a-z0-9]*       { return ID; }
[0-9]+               { return NUM; }
```

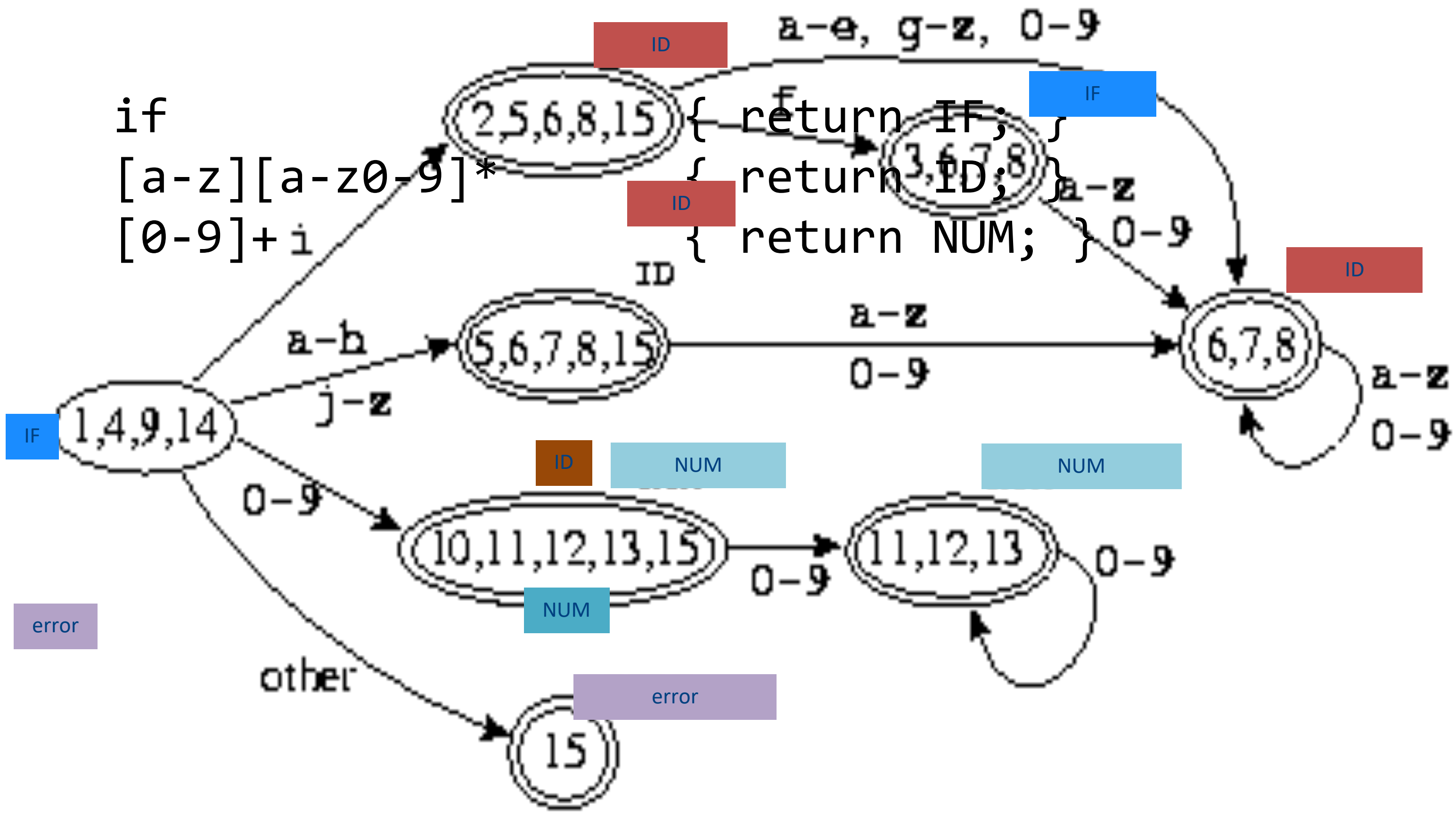




Modern compiler implementation in ML, Andrew Appel, (c)1998, Figures 2.7,2.8

Example

```
if             { return IF; }
[a-z][a-z0-9]* { return ID; }
[0-9]+         { return NUM; }
```



Modern compiler implementation in ML, Andrew Appel, (c)1998, Figures 2.7,2.8

Error Handling

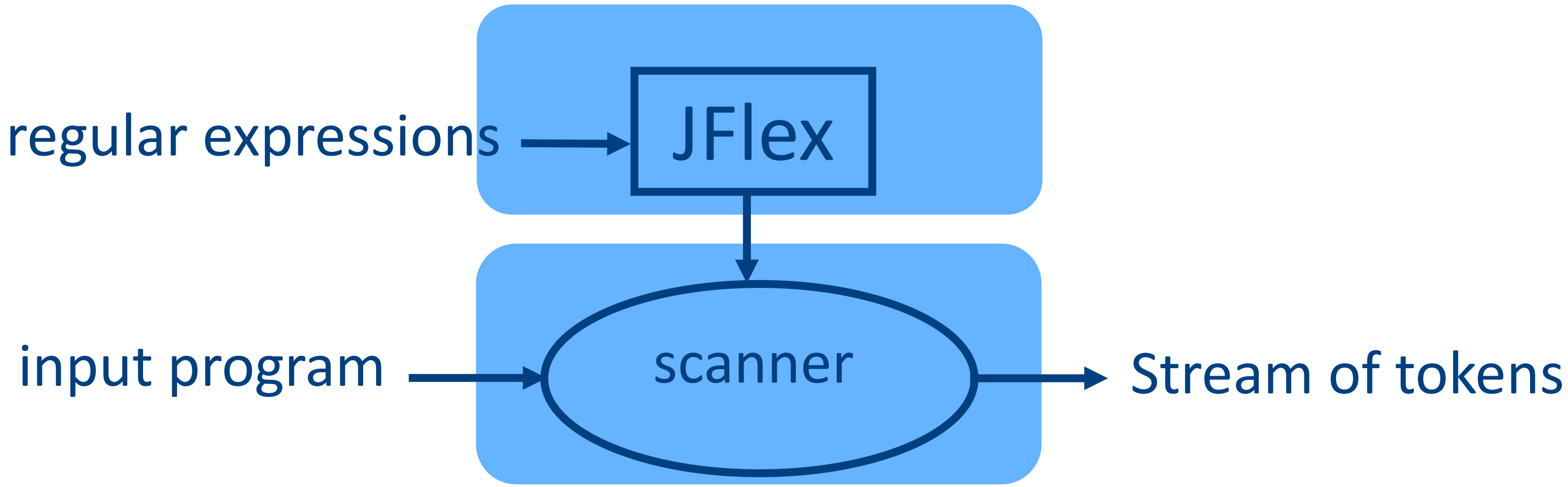
- Many errors cannot be identified at this stage
- Example: “fi (a==f(x))”. Should “fi” be “if”? Or is it a routine name?
  - We will discover this later in the analysis
  - At this point, we just create an identifier token

- Sometimes the lexeme does not match any pattern
  - Easiest: eliminate letters until the beginning of a legitimate lexeme
  - Alternatives: eliminate/add/replace one letter, replace order of two adjacent letters, etc.

- Goal: allow the compilation to continue
- Problem: errors that spread all over

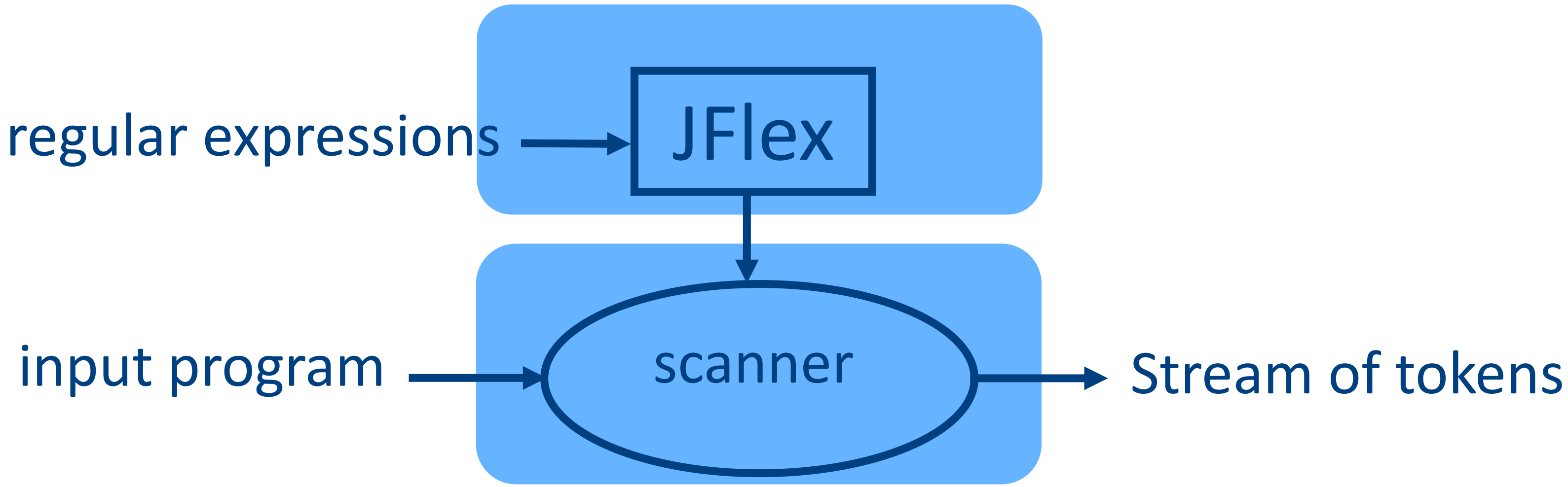
Automatically generated scanners

- Use of Program-Generating Tools
  - Specification ➔ Part of compiler
  - Compiler-Compiler



Use of Program-Generating Tools

- Input: regular expressions and actions
  - Action = Java code
- Output: a scanner program that
  - Produces a stream of tokens
  - Invoke actions when pattern is matched



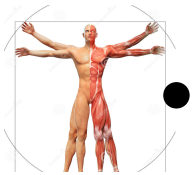
Missing

- Creating a lexical analysis by hand
- Table compression
- Symbol Tables
- Nested Comments
- Handling Macros

Lexical Analysis: What

- Input: program text (file)
- Output: sequence of tokens

Lexical Analysis: How



- Define tokens using regular expressions

- Construct a nondeterministic finite-state automaton (NFA) from regular expression
- Determinize the NFA into a deterministic finite-state automaton (DFA)
- DFA can be directly used to identify tokens

Lexical Analysis: Why

- Read input file
- Identify language keywords and standard identifiers
- Handle include files and macros
- Count line numbers
- Remove whitespaces
- Report illegal symbols

- [Produce symbol table]

The Real Anatomy of a Compiler