Regular Expressions
and
Finite State Automata

With thanks to Steve Rowe at CNLP

Introduction

- Regular expressions are equivalent to Finite State Automata in recognizing regular languages, the first step in the Chomsky hierarchy of formal languages
- The term regular expressions is also used to mean the extended set of string matching expressions used in many modern languages
  - Some people use the term regexp to distinguish this use
- Some parts of regexps are just syntactic extensions of regular expressions and can be implemented as a regular expression – other parts are significant extensions of the power of the language and are not equivalent to finite automata

Concepts and Notations

- Set: An unordered collection of unique elements

  $S_1 = \{ a, b, c \}$ $S_2 = \{ 0, 1, \ldots, 19 \}$ *empty set*: $\varnothing$

  membership: $x \in S$ *union*: $S_1 \cup S_2 = \{ a, b, c, 0, 1, \ldots, 19 \}$

  universe of discourse: U *subset*: $S_1 \subset U$

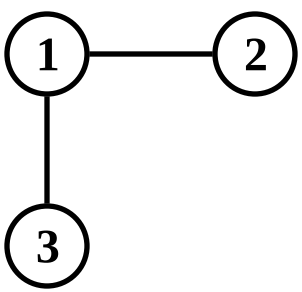
  complement: if $U = \{ a, b, \ldots, z \}$, then $S_1' = \{ d, e, \ldots, z \} = U - S_1$

- Alphabet: A finite set of symbols
  - Examples:
    - Character sets: ASCII, ISO-8859-1, Unicode
    - $\Sigma_1 = \{ a, b \}$ $\Sigma_2 = \{$ Spring, Summer, Autumn, Winter $\}$

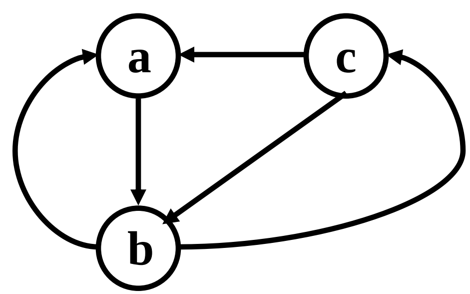
- String: A sequence of zero or more symbols from an alphabet
  - The empty string: ε

Concepts and Notations

- Language: A set of strings over an alphabet
  - Also known as a formal language; may not bear any resemblance to a natural language, but could model a subset of one.
  - The language comprising **all** strings over an alphabet Σ is written as: Σ^*
- Graph: A set of nodes (or vertices), some or all of which may be connected by edges.
  - An example:



  - A directed graph example:



Regular Expressions

- A regular expression defines a regular language over an alphabet Σ:
  - $\emptyset$ is a regular language: `//`
  - Any symbol from Σ is a regular language:

    $\Sigma = \{ a, b, c \}$ `/a/` `/b/` `/c/`
  - Two concatenated regular languages is a regular language:

    $\Sigma = \{ a, b, c \}$ `/ab/` `/bc/` `/ca/`

Regular Expressions

- Regular language (continued):
  - The union (or disjunction) of two regular languages is a regular language:

    $\Sigma = \{ a, b, c \}$ `/ab|bc/` `/ca|bb/`
  - The Kleene closure (denoted by the Kleene star: *) of a regular language is a regular language:

    $\Sigma = \{ a, b, c \}$ `/a*/` `/(ab|ca)*/`
  - Parentheses group a sub-language to override operator precedence (and, we'll see later, for "memory").

Finite Automata

- Finite State Automaton

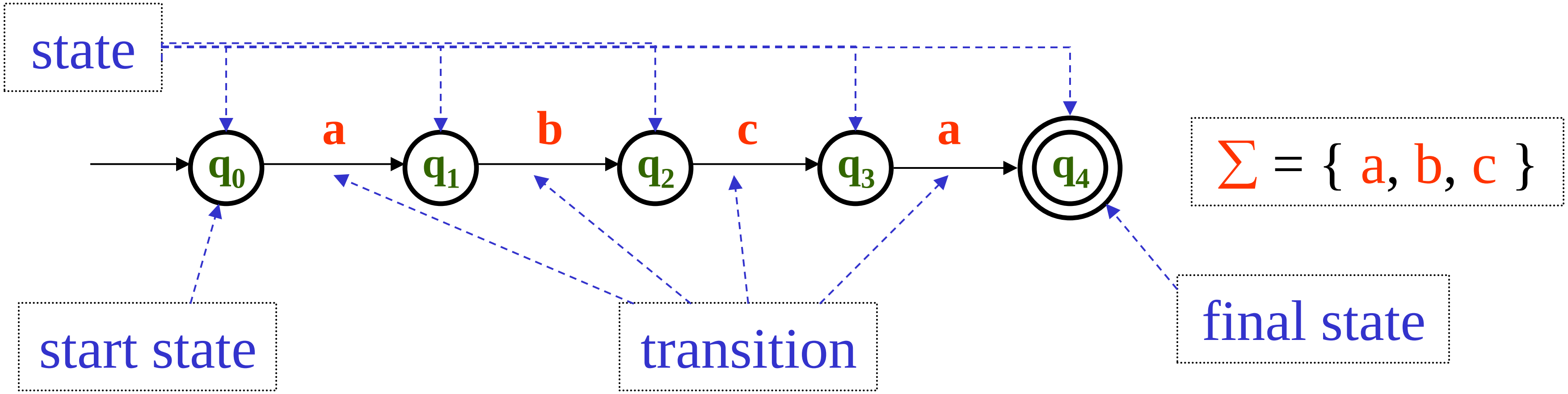
  a.k.a. Finite Automaton, Finite State Machine, FSA or FSM

  - An abstract machine which can be used to implement regular expressions (etc.).
  - Has a finite number of states, and a finite amount of memory (i.e., the current state).
  - Can be represented by directed graphs or transition tables

Finite-state Automata (1/23)

- Representation
  - An FSA may be represented as a directed graph; each node (or vertex) represents a state, and the edges (or arcs) connecting the nodes represent transitions.
  - Each state is labelled.
  - Each transition is labelled with a symbol from the alphabet over which the regular language represented by the FSA is defined, or with ε, the empty string.
  - Among the FSA's states, there is a start state and at least one final state (or accepting state).

Finite-state Automata (2/23)



- Representation (continued)
  - An FSA may also be represented with a state-transition table. The table for the above FSA:

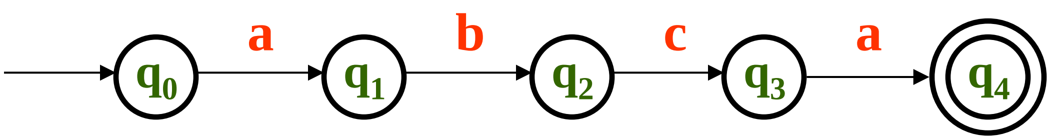
	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

Finite-state Automata (3/23)

- Given an input string, an FSA will either accept or reject the input.
  - If the FSA is in a final (or accepting) state after all input symbols have been consumed, then the string is accepted (or recognized).
  - Otherwise (including the case in which an input symbol cannot be consumed), the string is rejected.

Finite-state Automata (3/23)

$\Sigma = \{ a, b, c \}$



State	Input a	Input b	Input c
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	b	c	a

IS_2:

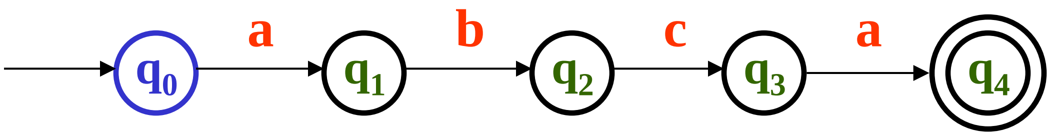
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (4/23)

$\Sigma = \{ a, b, c \}$



	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	b	c	a

IS_2:

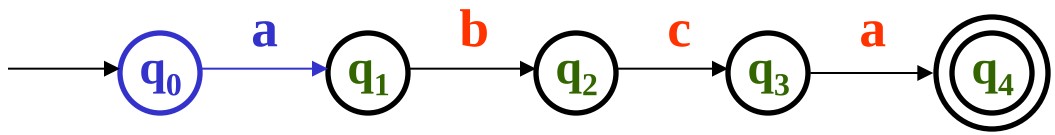
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (5/23)

$\sum = \{ a, b, c \}$

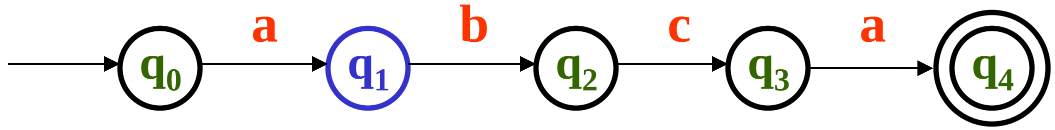


IS$_1$:	**a**	b	c	a	
IS$_2$:	c	c	b	a	
IS$_3$:	a	b	c	a	c

	Input		
State	**a**	**b**	**c**
0	**1**	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

Finite-state Automata (6/23)

$\Sigma = \{ a, b, c \}$



	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	b	c	a

IS_2:

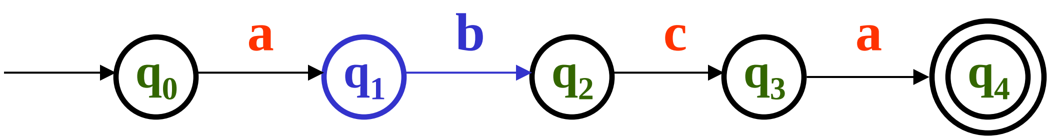
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (7/23)

$\Sigma = \{ a, b, c \}$



IS$_1$:

a	**b**	c	a

IS$_2$:

c	c	b	a

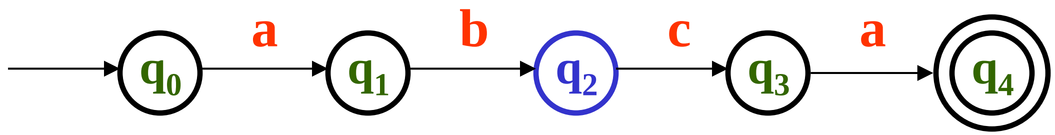
IS$_3$:

a	b	c	a	c

	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

Finite-state Automata (8/23)

$\Sigma = \{ a, b, c \}$



	Input		
State	a	b	c
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	**b**	c	a

IS_2:

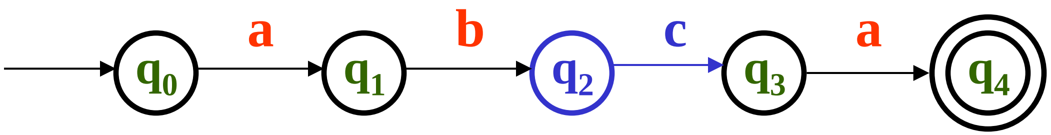
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (9/23)

$\Sigma = \{ a, b, c \}$



IS1:

a	**b**	**c**	a

IS2:

c	c	b	a

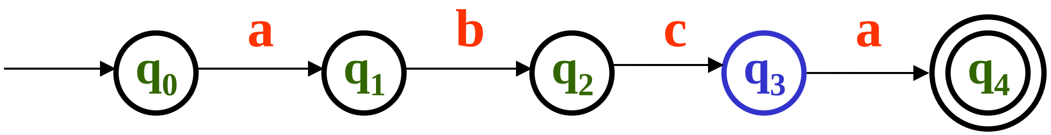
IS3:

a	b	c	a	c

	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	**3**
3	4	∅	∅
4	∅	∅	∅

Finite-state Automata (10/23)

$\sum = \{ a, b, c \}$



State	Input a	Input b	Input c
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	**b**	**c**	a

IS_2:

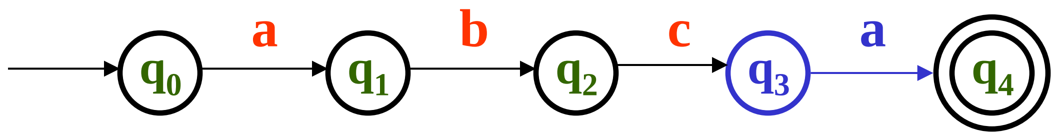
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (11/23)

$\Sigma = \{ a, b, c \}$



State	Input: a	b	c
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	**4**	∅	∅
4	∅	∅	∅

IS_1:

a	**b**	**c**	**a**

IS_2:

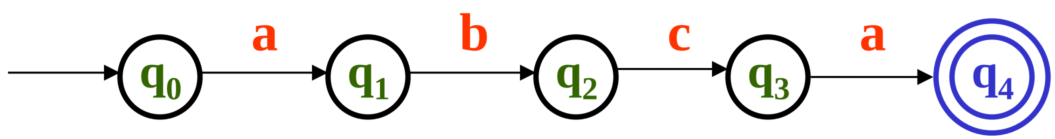
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (12/23)

Σ = { a, b, c }



IS_1:

a	**b**	**c**	**a**

IS_2:

c	c	b	a

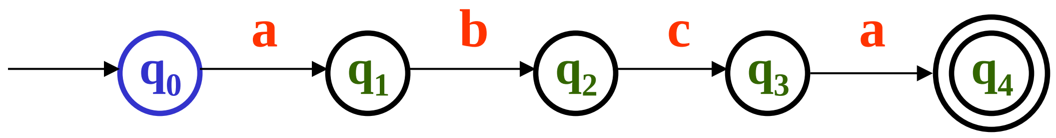
IS_3:

a	b	c	a	c

	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

Finite-state Automata (13/23)

$\Sigma = \{ a, b, c \}$



State	Input		
	a	b	c
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	b	c	a

IS_2:

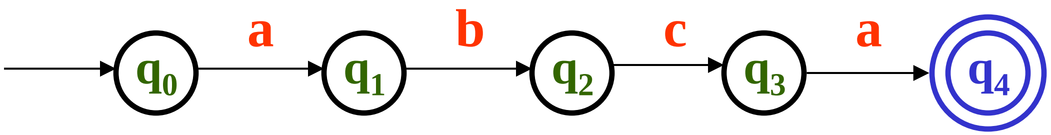
c	c	b	a

IS_3:

a	b	c	a	c

Finite-state Automata (14/23)

$\Sigma = \{ a, b, c \}$



	Input		
State	**a**	**b**	**c**
0	1	∅	∅
1	∅	2	∅
2	∅	∅	3
3	4	∅	∅
4	∅	∅	∅

IS_1:

a	b	c	a

IS_2:

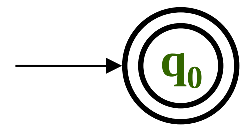
c	c	b	a

IS_3:

a	**b**	**c**	**a**	**c**

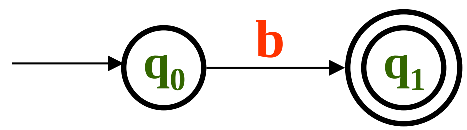
Finite-state Automata (22/23)

- An FSA defines a regular language over an alphabet Σ:
  - $\varnothing$ is a regular language:

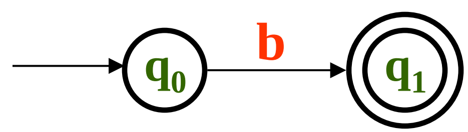


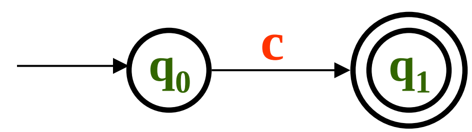
  - Any symbol from Σ is a regular language:

$\Sigma = \{ a, b, c\}$

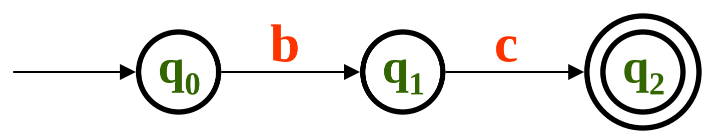


  - Two concatenated regular languages is a regular language:



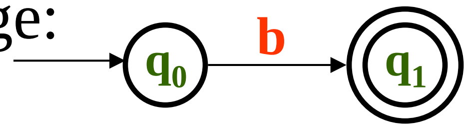


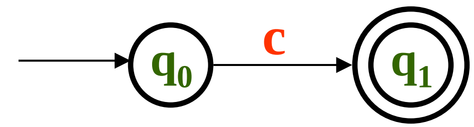
$\Sigma = \{ a, b, c\}$



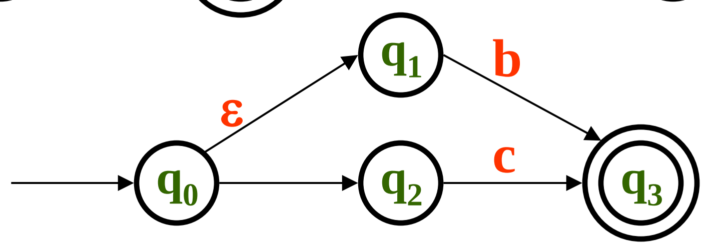
Finite-state Automata (23/23)

- regular language (continued):
  - The union (or disjunction) of two regular languages is a regular language:



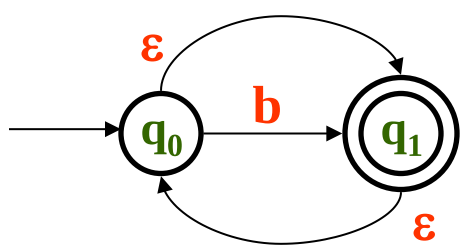


$\Sigma = \{ a, b, c \}$



  - The Kleene closure (denoted by the Kleene star: *) of a regular language is a regular language:

$\Sigma = \{ a, b, c \}$

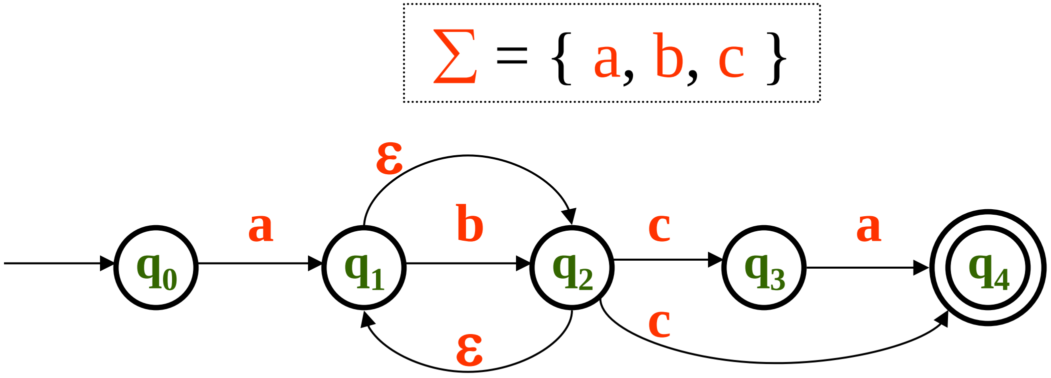


Finite-state Automata (15/23)

- Determinism
  - An FSA may be either deterministic (DFSA or DFA) or non-deterministic (NFSA or NFA).
    - An FSA is deterministic if its behavior during recognition is fully determined by the state it is in and the symbol to be consumed.
      - I.e., given an input string, only one path may be taken through the FSA.
    - Conversely, an FSA is non-deterministic if, given an input string, more than one path may be taken through the FSA.
      - One type of non-determinism is ε-transitions, i.e. transitions which consume the empty string (no symbols).

Finite-state Automata (16/23)

- An example NFA:



State	Input a	b	c	ε
0	1	∅	∅	∅
1	∅	2	∅	2
2	∅	∅	3,4	1
3	4	∅	∅	∅
4	∅	∅	∅	∅

– The above NFA is equivalent to the regular expression `/ab*ca?/`.

Finite-state Automata (17/23)

- String recognition with an NFA:
  - Backup (or backtracking): remember choice points and revisit choices upon failure
  - Look-ahead: choose path based on foreknowlege about the input string and available paths
  - Parallelism: examine all choices simultaneously

Finite-state Automata (18/23)

- Recognition as search
  - Recognition can be viewed as selection of the correct path from all possible paths through an NFA (this set of paths is called the state-space)
  - Search strategy can affect efficiency: in what order should the paths be searched?
    - Depth-first (LIFO [last in, first out]; stack)
    - Breadth-first (FIFO [first in, first out]; queue)
    - Depth-first uses memory more efficiently, but may enter into an infinite loop under some circumstances

RegExps

- The extended use of regular expressions is in many modern languages:
  - Perl, php, Java, python, …
- Can use regexps to specify the rules for any set of possible strings you want to match
  - Sentences, e-mail addresses, ads, dialogs, etc
- “Does this string match the pattern?”, or “Is there a match for the pattern anywhere in this string?”
- Can also define operations to do something with the matched string, such as extract the text or substitute for it
- Regular expression patterns are compiled into a executable code within the language

Regular Expressions

- Regexp syntax is a superset of the notation required to express a regular language.
  - Some examples and shortcuts:
    1. `/[abc]/ = /a|b|c/` Character class; disjunction
    2. `/[b-e]/ = /b|c|d|e/` Range in a character class
    3. `/[\012\015]/ = /\n|\r/` Octal characters; special escapes
    4. `/./ = /[\x00-\xFF]/` Wildcard; hexadecimal characters
    5. `/[^b-e]/ = /[\x00-af-\xFF]/` Complement of character class
    6. `/a*/  /[af]*/  /(abc)*/` Kleene star: zero or more
    7. `/a?/ = /a|/  /(ab|ca)?/` Zero or one
    8. `/a+/  /([a-zA-Z]1|ca)+/` Kleene plus: one or more
    9. `/a{8}/  /b{1,2}/  /c{3,}/` Counters: exact repeat quantification

Regular Expressions

- Anchors
  - Constrain the position(s) at which a pattern may match
  - Think of them as "extra" alphabet symbols, though they actually consume ε (the zero-length string):
  - `/^a/` Pattern must match at beginning of string
  - `/a$/` Pattern must match at end of string
  - `/\bword23\b/` "Word" boundary: `/[a-zA-Z0-9_][^a-zA-Z0-9_]/`
    or `/[^a-zA-Z0-9_][a-zA-Z0-9_]/`
  - `/\B23\B/` "Word" **non**-boundary

Regular Expressions

- Escapes
  - A backslash "\" placed before a character is said to "escape" (or "quote") the character. There are six classes of escapes:
    1. **Numeric character representation**: the octal or hexadecimal position in a character set: "`\012`" = "`\xA`"
    2. **Meta-characters**: The characters which are syntactically meaningful to regular expressions, and therefore must be escaped in order to represent themselves in the alphabet of the regular expression: "`[](){}|^$.?+*\`" (note the inclusion of the backslash).
    3. **"Special" escapes** (from the "C" language):

newline:	"`\n`" = "`\xA`"	carriage return:	"`\r`" = "`\xD`"
tab:	"`\t`" = "`\x9`"	formfeed:	"`\f`" = "`\xC`"

Regular Expressions

- Escapes (continued)
  - Classes of escapes (continued):

4. **Aliases**: shortcuts for commonly used character classes. (Note that the capitalized version of these aliases refer to the complement of the alias's character class):
   - whitespace: "`\s`" = "`[ \t\r\n\f\v]`"
   - digit: "`\d`" = "`[0-9]`"
   - word: "`\w`" = "`[a-zA-Z0-9_]`"
   - non-whitespace: "`\S`" = "`[^ \t\r\n\f]`"
   - non-digit: "`\D`" = "`[^0-9]`"
   - non-word: "`\W`" = "`[^a-zA-Z0-9_]`"
5. **Memory/registers/back-references**: "`\1`", "`\2`", etc.
6. **Self-escapes**: any character other than those which have special meaning can be escaped, but the escaping has no effect: the character still represents the regular language of the character itself.

Regular Expressions

- Memory/Registers/Back-references
  - Many regular expression languages include a memory/register/back-reference feature, in which sub-matches may be referred to later in the regular expression, and/or when performing replacement, in the replacement string:
    - Perl: `/(\w+)\s+\1\b/` matches a repeated word
    - Python: `re.sub(”(the\s+)the(\s+|\b)”,”\1”,string)` removes the second of a pair of ‘the’s
  - **Note: finite automata cannot be used to implement the memory feature.**

Regular Expression Examples

Character classes and Kleene symbols

[A-Z]   = one capital letter

[0-9]   = one numerical digit

[st@!9] = s, t, @, ! or 9

[A-Z]   = matches G or W or E

does not match GW or FA or h or fun

[A-Z]+   = one or more consecutive capital letters

matches GW or FA or CRASH

[A-Z]? = zero or one capital letter

[A-Z]*   = zero, one or more consecutive capital letters

matches on eat or EAT or I

so, [A-Z]ate

matches Gate, Late, Pate, Fate, but not GATE or gate

and   [A-Z]+ate

matches: Gate, GRate, HEate, but not Grate or grate or STATE

and   [A-Z]*ate

matches: Gate, GRate, and ate, but not STATE, grate or Plate

Regular Expression Examples (cont'd)

[A-Za-z] = any single letter

so   [A-Za-z]+

matches on any word composed of only letters,

but will not match on "words": bi-weekly , yes@SU or IBM325

they will match on bi, weekly, yes, SU and IBM

a shortcut for [A-Za-z] is \w, which in Perl also includes _

so (\w)+   will match on Information, ZANY, rattskellar and jeuvbaew

\s will match whitespace

so   (\w)+(\s)(\w+)   will match   real estate   or   Gen Xers

Regular Expression Examples (cont'd)

Some longer examples:

([A-Z][a-z]+)\s([a-z0-9]+)

matches: Intel c09yt745 but not IBM series5000

[A-Z]\w+\s\w+\s\w+[!]

matches: The dog died!

It also matches that portion of " he said, " The dog died! "

[A-Z]\w+\s\w+\s\w+[!]$

matches: The dog died!

But does not match "he said, " The dog died! " because the $ indicates end of Line, and there is a quotation mark before the end of the line

(\w+ats?\s)+

parentheses define a pattern as a unit, so the above expression will match:

Fat cats eat Bats that Splat

Regular Expression Examples (cont'd)

To match on part of speech tagged data:

(\w+[-]?\w+\|[A-Z]+)   will match on:

bi-weekly|RB

camera|NN

announced|VBD

(\w+\|V[A-Z]+)   will match on:

ruined|VBD

singing|VBG

Plant|VB

says|VBZ

(\w+\|VB[DN]) will match on:

coddled|VBN

Rained|VBD

But not changing|VBG

Regular Expression Examples (cont'd)

Phrase matching:

```
a\|DT ([a-z]+\|JJ[SR]?) (\w+\|N[NPS]+)
```

matches: a|DT loud|JJ noise|NN
a|DT better|JJR Cheerios|NNPS

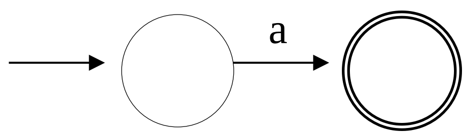
```
(\w+\|DT) (\w+\|VB[DNG])* (\w+\|N[NPS]+)+
```

matches: the|DT singing|VBG elephant|NN seals|NNS
an|DT apple|NN
an|DT IBM|NP computer|NN
the|DT outdated|VBD aging|VBG Commodore|NNNP computer|NN hardware|NN

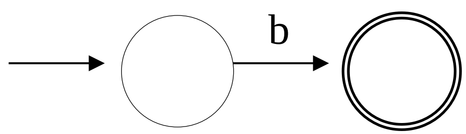
RE to ε-NFA Example

- Convert R= (ab+a)* to an NFA
  - We proceed in stages, starting from simple elements and working our way up

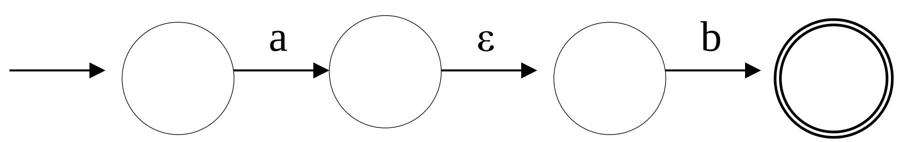
a



b

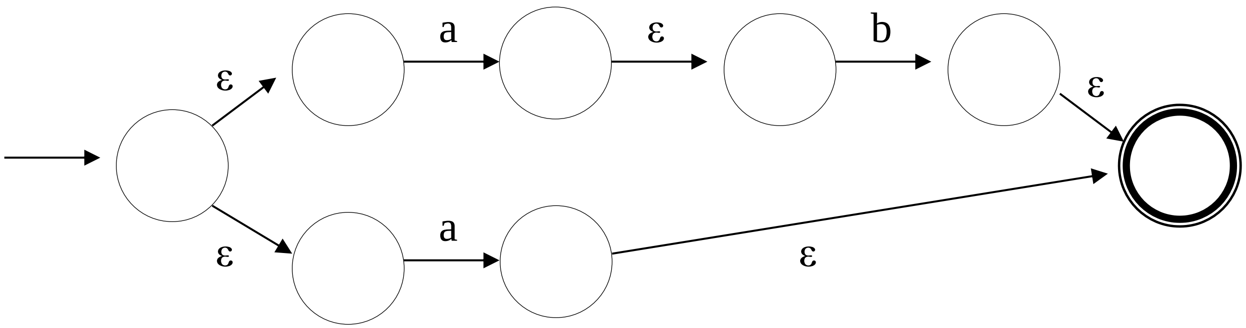


ab

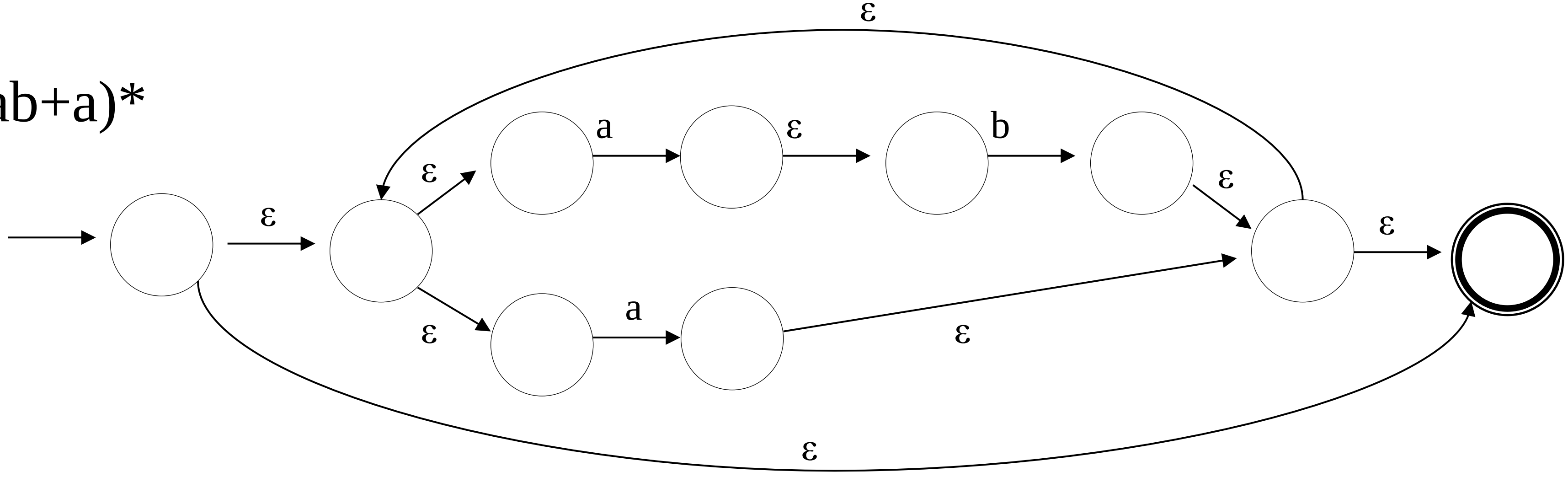


RE to ε-NFA Example (2)

ab+a



(ab+a)*



Conclusion

- Both regular expressions and finite-state automata represent regular languages.
- The basic regular expression operations are: concatenation, union/disjunction, and Kleene closure.
- The regular expression language is a powerful pattern-matching tool.
- Any regular expression can be automatically compiled into an NFA, to a DFA, and to a unique minimum-state DFA.
- An FSA can use any set of symbols for its alphabet, including letters and words.