Finite state automata

Data Structures and Algorithms for Computational Linguistics III (ISCL-BA-07)

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Why study finite-state automata?

- Unlike some of the abstract machines we discussed, finite-state automata are efficient models of computation
- There are many applications
  - Electronic circuit design
  - Workflow management
  - Games
  - Pattern matching
  - ...

  But more importantly ;-)
  - Tokenization, stemming
  - Morphological analysis
  - Shallow parsing/chunking
  - ...

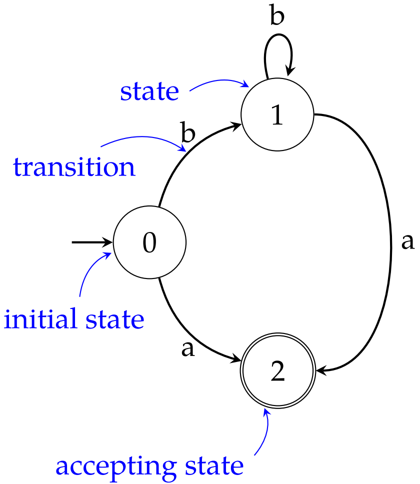
Finite-state automata (FSA)

- A finite-state machine is in one of a finite-number of states in a given time
- The machine changes its state based on its input
- Every regular language is generated/recognized by an FSA
- Every FSA generates/recognizes a regular language
- Two flavors:
  - *Deterministic finite automata* (DFA)
  - *Non-deterministic finite automata* (NFA)

Note: the NFA is a superset of DFA.

DFA as a graph

- States are represented as nodes
- Transitions are shown by the edges, labeled with symbols from an alphabet
- One of the states is marked as the *initial state*
- Some states are accepting states



DFA: formal definition

Formally, a finite state automaton, M, is a tuple $(\Sigma, Q, q_0, F, \Delta)$ with

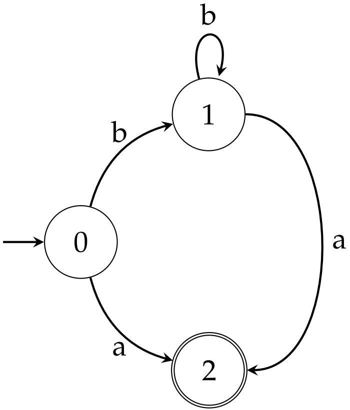
- Σ is the alphabet, a finite set of symbols
- Q a finite set of states
- q_0 is the start state, $q_0 \in Q$
- F is the set of final states, $F \subseteq Q$
- Δ is a function that takes a state and a symbol in the alphabet, and returns another state ($\Delta : Q \times \Sigma \to Q$)

At any given time, for any input,
a DFA has a single well-defined action to take.

DFA: formal definition

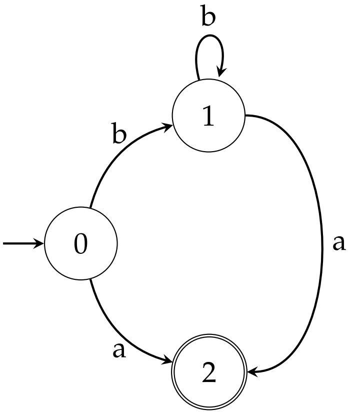
an example

$$
\begin{aligned}
\Sigma &= \{a, b\} \\
Q &= \{q_0, q_1, q_2\} \\
q_0 &= q_0 \\
F &= \{q_2\} \\
\Delta &= \{(q_0, a) \rightarrow q_2, \quad (q_0, b) \rightarrow q_1, \\
& \quad\; (q_1, a) \rightarrow q_2, \quad (q_1, b) \rightarrow q_1\}
\end{aligned}
$$



Another note on DFA

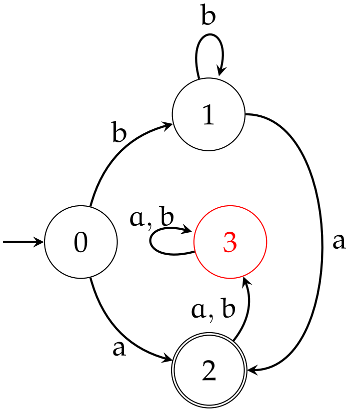
- Is this FSA deterministic?



Another note on DFA

error or sink state

- Is this FSA deterministic?
- To make all transitions well-defined, we can add a sink (or error) state



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- Is this FSA deterministic?
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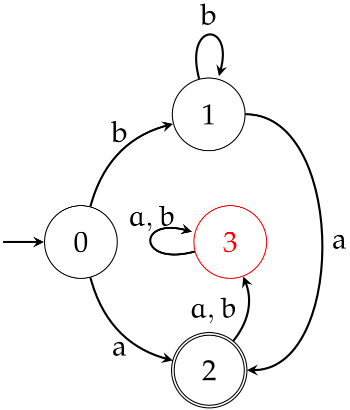
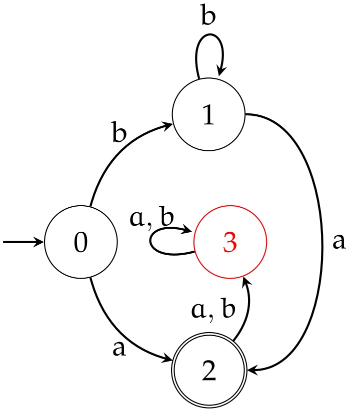
- For brevity, we skip the explicit error state



Another note on DFA

error or sink state

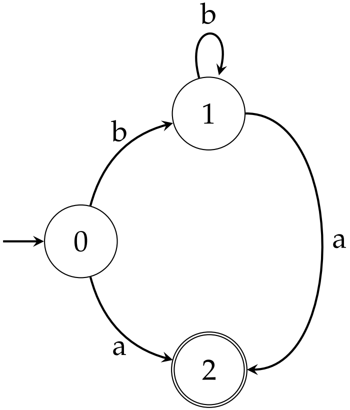
- Is this FSA deterministic?
- To make all transitions well-defined, we can add a sink (or error) state
- For brevity, we skip the explicit error state
  - In that case, when we reach a dead end, recognition fails



DFA: the transition table

transition table

		symbol	
		a	**b**
state	→**0**	2	1
	1	2	1
	***2**	∅	∅



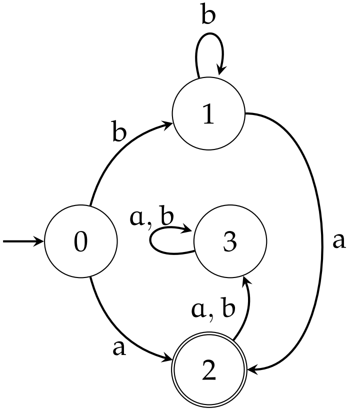
→ marks the start state

* marks the accepting state(s)

DFA: the transition table

transition table

state	*symbol* a	*symbol* b
→**0**	2	1
1	2	1
***2**	3	3
3	3	3

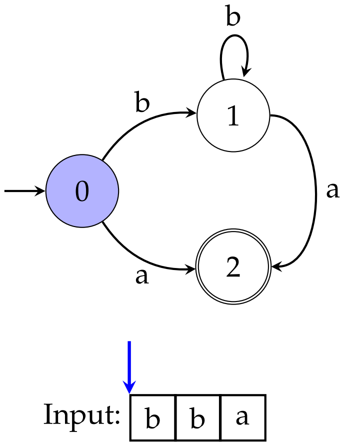


→ marks the start state

* marks the accepting state(s)

DFA recognition

1. Start at q_0
2. Process an input symbol, move accordingly
3. Accept if in a final state at the end of the input



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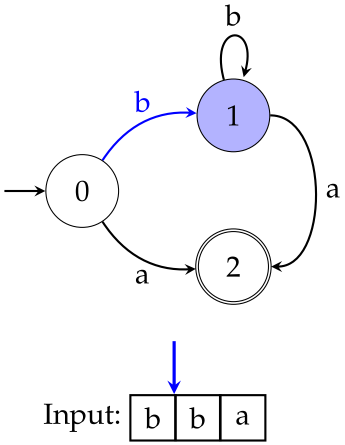

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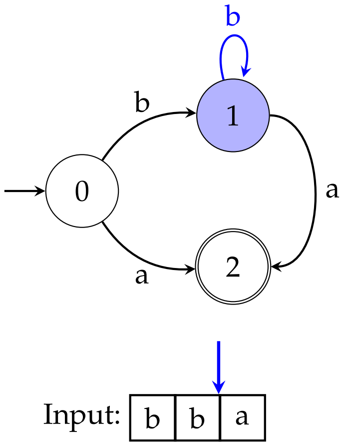

DFA recognition

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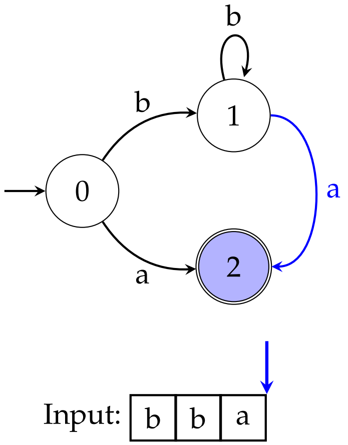

DFA recognition

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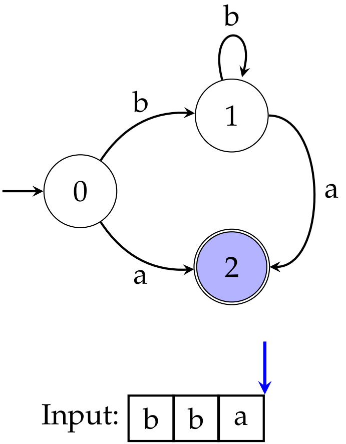
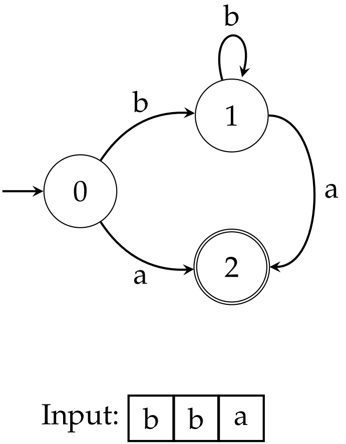


DFA recognition

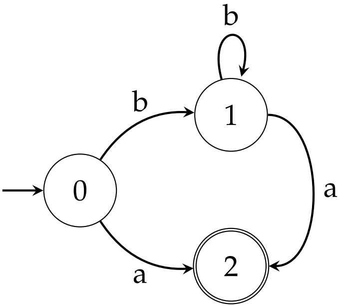
1. Start at q_0
2. Process an input symbol, move accordingly
3. Accept if in a final state at the end of the input

- What is the complexity of the algorithm?
- How about inputs:
  - bbbb
  - aa



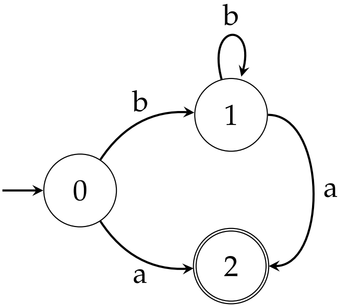
A few questions

- What is the language recognized by this FSA?



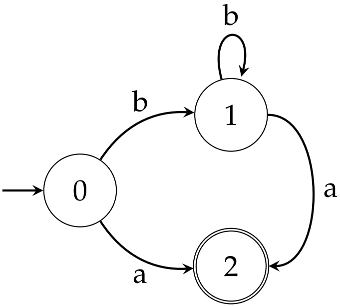
A few questions

- What is the language recognized by this FSA?
- Can you draw a simpler DFA for the same language?



A few questions

- What is the language recognized by this FSA?
- Can you draw a simpler DFA for the same language?
- Draw a DFA recognizing strings with even number of 'a's over $\Sigma = \{a, b\}$



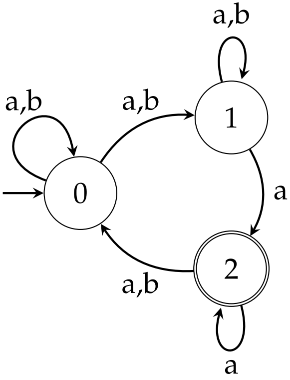
Non-deterministic finite automata

Formal definition

A non-deterministic finite state automaton, M, is a tuple $(\Sigma, Q, q_0, F, \Delta)$ with

- Σ is the alphabet, a finite set of symbols
- Q a finite set of states
- q_0 is the start state, $q_0 \in Q$
- F is the set of final states, $F \subseteq Q$
- Δ is a function from (Q, Σ) to $P(Q)$, power set of Q $(\Delta : Q \times \Sigma \to P(Q))$

An example NFA



transition table

state		*symbol* **a**	**b**
	→**0**	0,1	0,1
	1	1,2	1
	***2**	0,2	0

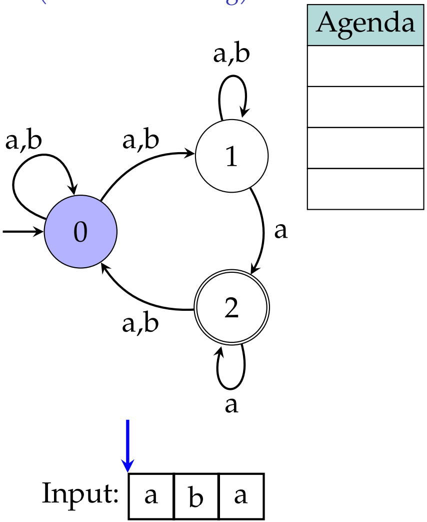
- We have nondeterminism, e.g., if the first input is a, we need to choose between states 0 or 1
- Transition table cells have *sets* of states

Dealing with non-determinism

- Follow one of the links, store alternatives, and *backtrack* on failure
- Follow all options in parallel

NFA recognition

as search (with backtracking)

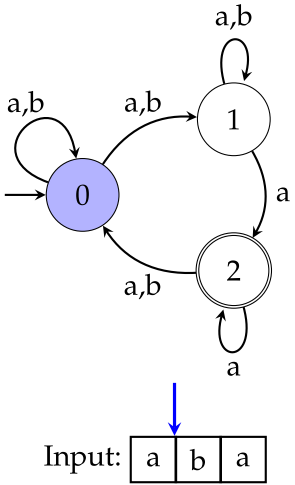


1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_0, 1)$
$(q_1, 1)$

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

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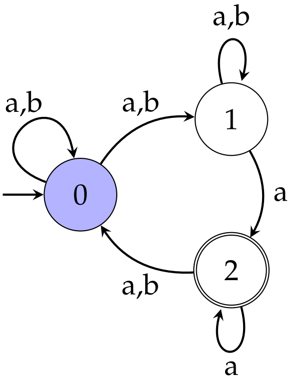


Agenda
$(q_0, 1)$
$(q_1, 1)$

Input:

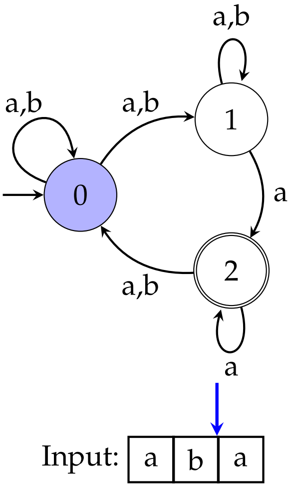
a	b	a

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

as search (with backtracking)



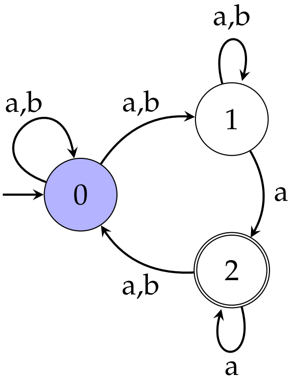
Agenda
$(q_0, 2)$
$(q_1, 2)$
$(q_1, 1)$

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_0, 2)$
$(q_1, 2)$
$(q_1, 1)$

Input: | a | b | a |

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

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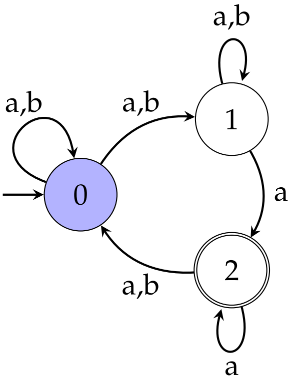


Agenda
$(q_0, 3)$
$(q_1, 3)$
$(q_1, 2)$
$(q_1, 1)$

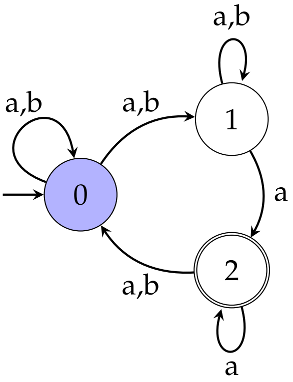
Input: | a | b | a |

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
Reject not in accepting state & agenda empty
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_0, 3)$
$(q_1, 3)$
$(q_1, 2)$
$(q_1, 1)$

Input: | a | b | a |

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
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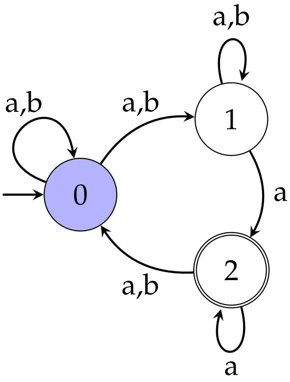
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_1, 3)$
$(q_1, 2)$
$(q_1, 1)$

Input:

a	b	a

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

Accept if in an accepting state
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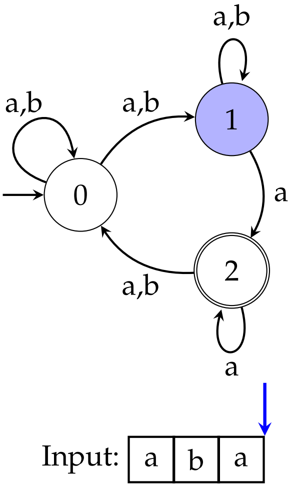
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_1, 3)$
$(q_1, 2)$
$(q_1, 1)$

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
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4. At the end of input

Accept if in an accepting state
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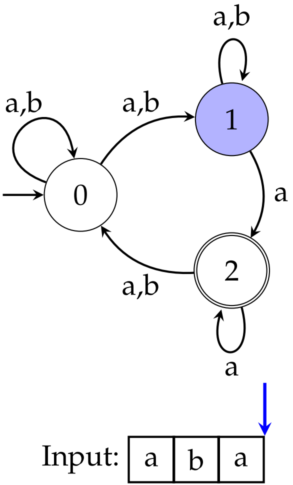
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_1, 2)$
$(q_1, 1)$

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

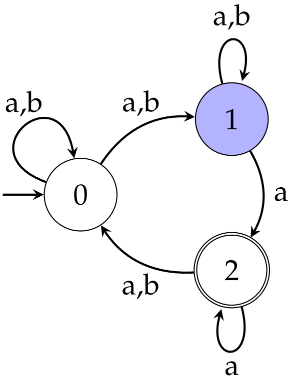
Accept: if in an accepting state

Reject: not in accepting state & agenda empty

Backtrack: otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_1, 2)$
$(q_1, 1)$

Input:

a	b	a

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
4. At the end of input

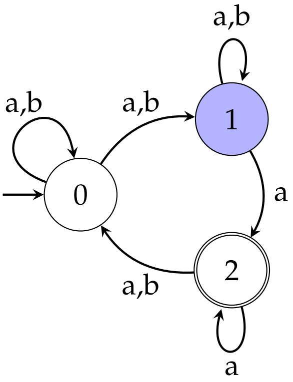
Accept if in an accepting state

Reject not in accepting state & agenda empty

Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_2, 3)$
$(q_1, 3)$
$(q_1, 1)$

Input:

a	b	a

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
3. Get the next action from the agenda, act
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Accept if in an accepting state
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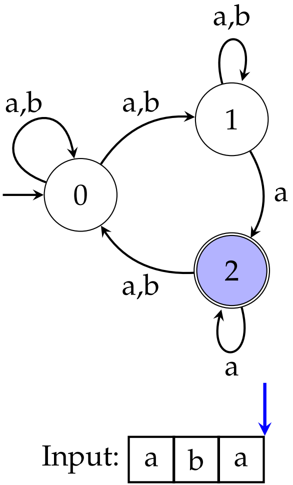
Backtrack otherwise

NFA recognition

as search (with backtracking)



Agenda
$(q_2, 3)$
$(q_1, 3)$
$(q_1, 1)$

1. Start at q_0
2. Take the next input, place all possible actions to an *agenda*
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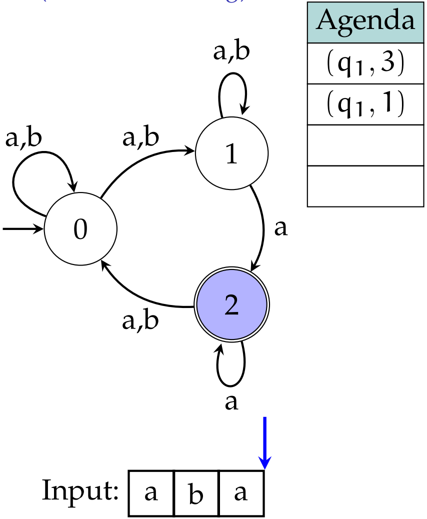
NFA recognition

as search (with backtracking)



1. Start at q_0
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3. Get the next action from the agenda, act
4. At the end of input

Accept: if in an accepting state
Reject: not in accepting state & agenda empty
Backtrack: otherwise

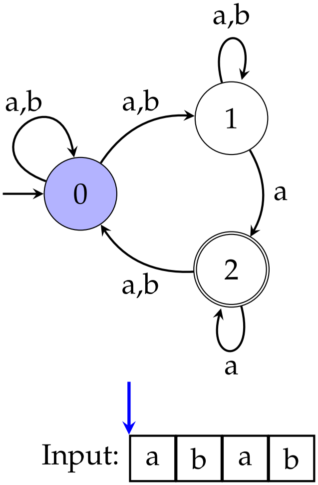
NFA recognition as search

summary

- Worst time complexity is exponential
  - Complexity is worse if we want to enumerate all derivations
- We used a stack as *agenda*, performing a depth-first search
- A queue would result in breadth-first search
- If we have a reasonable heuristic A* search may be an option
- Machine learning methods may also guide finding a fast or the best solution

NFA recognition

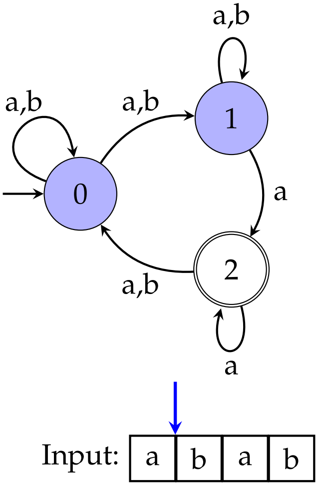
parallel version



1. Start at q_0
2. Take the next input, mark all possible next states
3. If an accepting state is marked at the end of the input, accept

NFA recognition

parallel version



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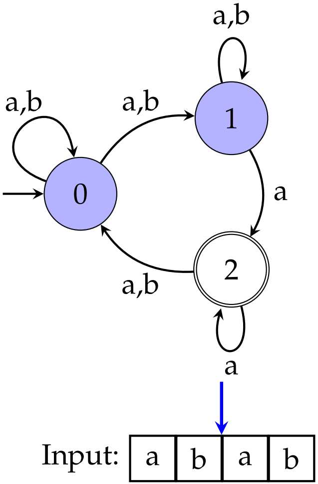
NFA recognition
parallel version



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NFA recognition

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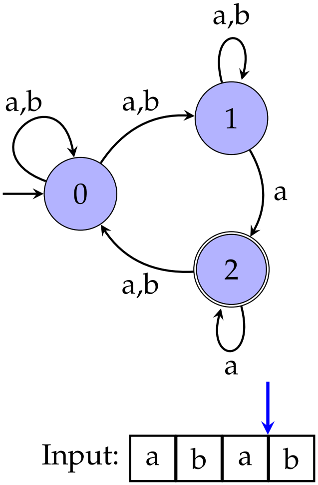

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NFA recognition

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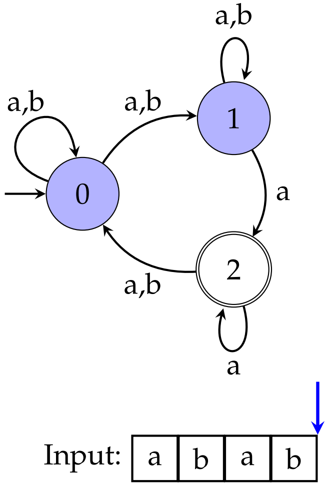

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NFA recognition

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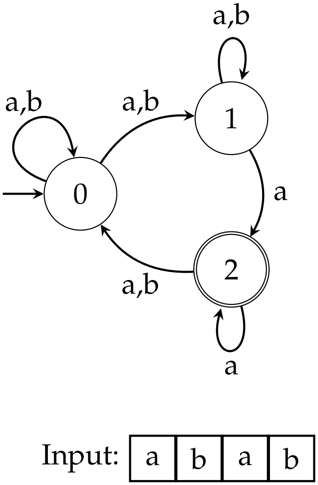

1. Start at q_0
2. Take the next input, mark all possible next states
3. If an accepting state is marked at the end of the input, accept

Note: the process is *deterministic*, and *finite-state*.

An exercise

Construct an NFA and a DFA for the language over $\Sigma = \{a, b\}$ where all sentences end with ab.

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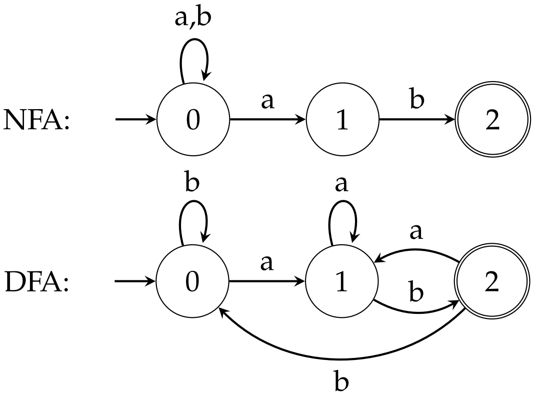
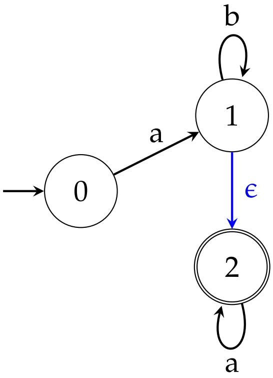
Construct an NFA and a DFA for the language over $\Sigma = \{a, b\}$ where all sentences end with ab.



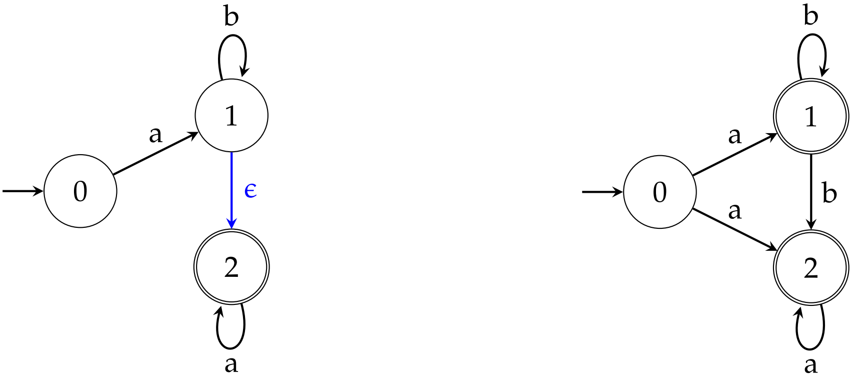
One more complication: ϵ transitions

- An extension of NFA, ϵ-NFA, allows moving without consuming an input symbol, indicated by an ϵ-transition (sometimes called a λ-transition)
- Any ϵ-NFA can be converted to an NFA

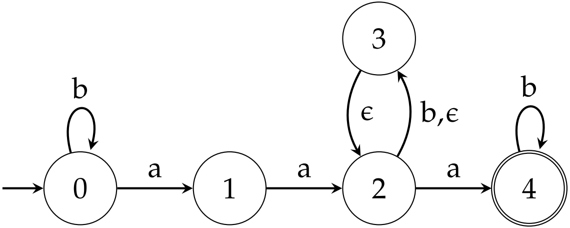


One more complication: ϵ transitions

- An extension of NFA, ϵ-NFA, allows moving without consuming an input symbol, indicated by an ϵ-transition (sometimes called a λ-transition)
- Any ϵ-NFA can be converted to an NFA



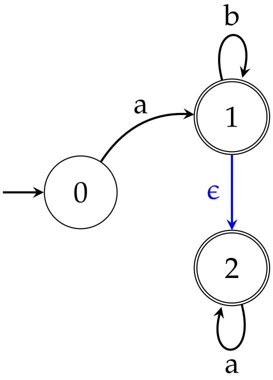
ϵ-transitions need attention



- How does the (depth-first) NFA recognition algorithm we described earlier work on this automaton?
- Can we do without ϵ transitions?

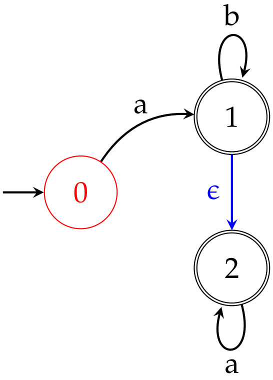
ϵ removal

- We start with finding the ϵ-*closure* of all states



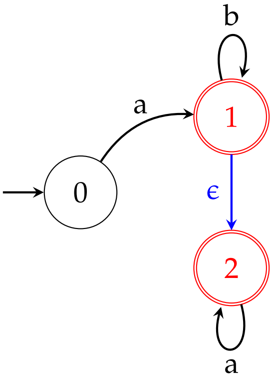
ϵ removal

- We start with finding the ϵ-*closure* of all states
  - $\epsilon\text{-closure}(q_0) = \{q0\}$



ϵ removal

- We start with finding the ϵ-*closure* of all states
  - ϵ-closure$(q_0) = \{q0\}$
  - ϵ-closure$(q_1) = \{q1, q2\}$



ϵ removal

- We start with finding the ϵ-*closure* of all states
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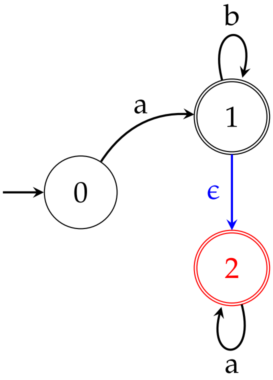
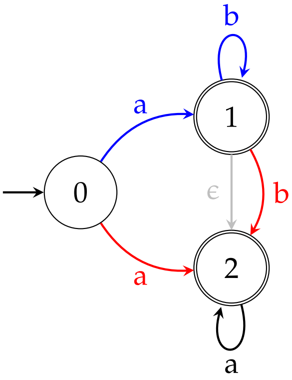


ϵ removal

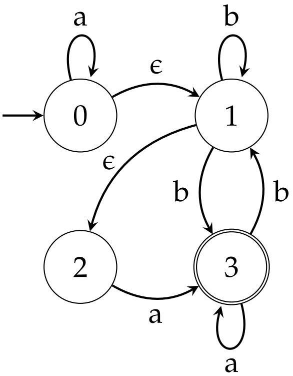
- We start with finding the ϵ-*closure* of all states
  - $\epsilon\text{-closure}(q_0) = \{q0\}$
  - $\epsilon\text{-closure}(q_1) = \{q1, q2\}$
  - $\epsilon\text{-closure}(q_2) = \{q2\}$
- Replace each arc to each state with arc(s) to all states in the ϵ-closure of the state



ϵ removal

a(nother) solution with the transition table

transition table

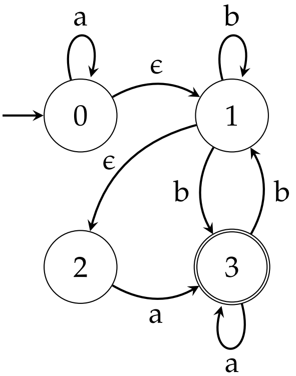


ϵ removal

a(nother) solution with the transition table

transition table

		symbol		
		a	**b**	**ϵ**
state	**→0**	0	∅	1
	1	∅	1,3	2
	2	3	∅	∅
	***3**	3	1	∅

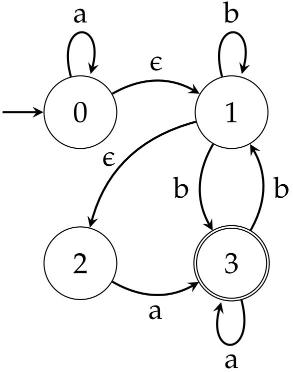


ϵ removal

a(nother) solution with the transition table

transition table

		symbol			
		a	**b**	$\boldsymbol{\epsilon}$	$\boldsymbol{\epsilon}^*$
state	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	
	2	3	∅	∅	
	***3**	3	1	∅	

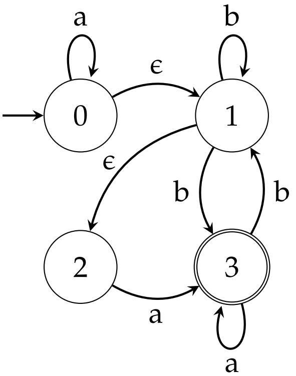


ϵ removal

a(nother) solution with the transition table

transition table

		symbol			
		a	**b**	ϵ	ϵ^*
state	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	



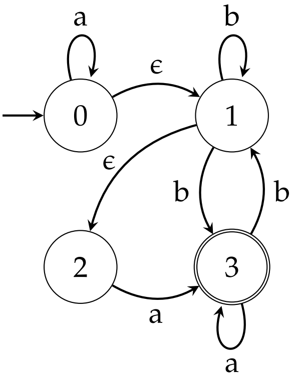
ϵ removal

a(nother) solution with the transition table

transition table

			symbol	
	a	**b**	ϵ	ϵ^*
→**0**	0	∅	1	0,1,2
1	∅	1,3	2	1,2
2	3	∅	∅	2
***3**	3	1	∅	3

state



ϵ removal

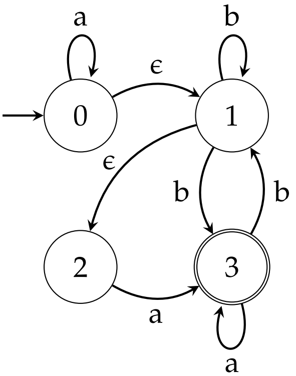
a(nother) solution with the transition table

transition table

state		a	b	ϵ	ϵ^*
	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	a	b
→**0**		
1		
2		
***3**		



ϵ removal

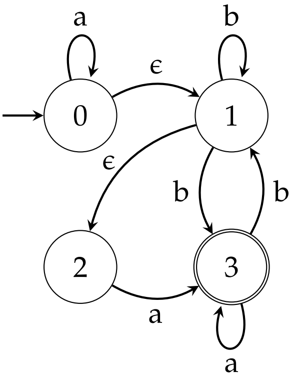
a(nother) solution with the transition table

transition table

state		*symbol* a	b	ϵ	ϵ^*
	$\rightarrow$**0**	0	$\varnothing$	1	0,1,2
	1	$\varnothing$	1,3	2	1,2
	2	3	$\varnothing$	$\varnothing$	2
	***3**	3	1	$\varnothing$	3

$\Rightarrow$

	symbol a	b
$\rightarrow$**0**	0,3	
1		
2		
***3**		



ϵ removal

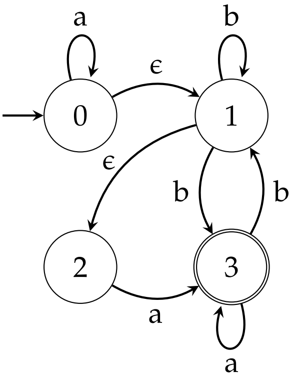
a(nother) solution with the transition table

transition table

state		*symbol* a	b	ϵ	ϵ*
	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	symbol a	b
→**0**	0,3	1,3
1		
2		
***3**		



ϵ removal

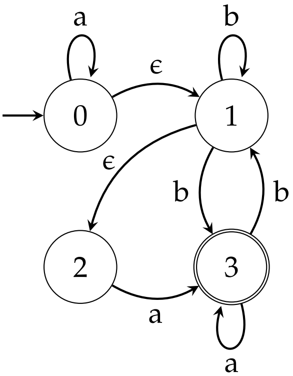
a(nother) solution with the transition table

transition table

state	a	b	ϵ	ϵ^*
→0	0	∅	1	0,1,2
1	∅	1,3	2	1,2
2	3	∅	∅	2
***3**	3	1	∅	3

⇒

state	a	b
→0	0,3	1,3
1	3	
2		
***3**		



ϵ removal

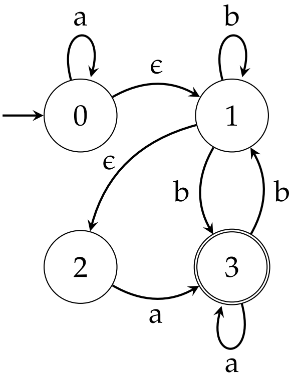
a(nother) solution with the transition table

transition table

		symbol			
		a	**b**	**ϵ**	**ϵ^***
state	**→0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

$\Rightarrow$

	symbol	
	a	**b**
→0	0,3	1,3
1	3	1,3
2		
***3**		



ϵ removal

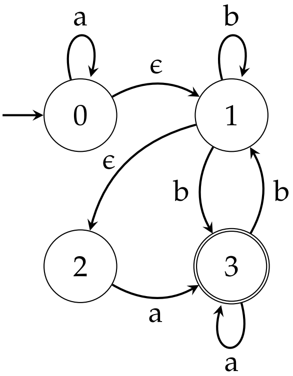
a(nother) solution with the transition table

transition table

state		*symbol*			
		a	**b**	ϵ	ϵ^*
	→0	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	symbol	
	a	**b**
→0	0,3	1,3
1	3	1,3
2	3	
***3**		



ϵ removal

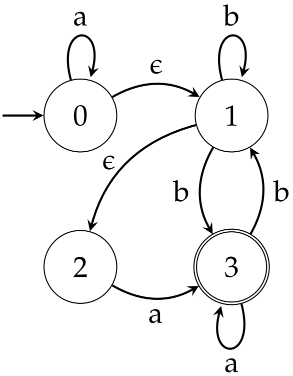
a(nother) solution with the transition table

transition table

state		*symbol* a	b	ϵ	ϵ*
	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	symbol a	b
→**0**	0,3	1,3
1	3	1,3
2	3	∅
***3**		



ϵ removal

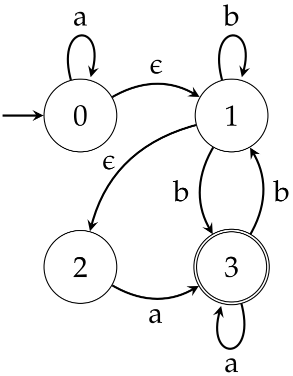
a(nother) solution with the transition table

transition table

		symbol			
		a	**b**	ϵ	ϵ^*
state	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	symbol	
	a	**b**
→**0**	0,3	1,3
1	3	1,3
2	3	∅
***3**	3	



ϵ removal

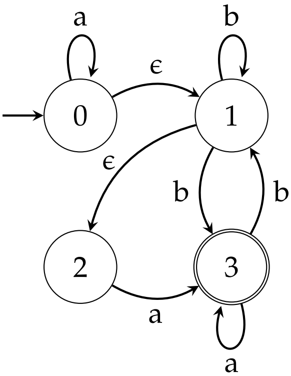
a(nother) solution with the transition table

transition table

state	*symbol* a	b	ϵ	ϵ^*
$\rightarrow$**0**	0	$\varnothing$	1	0,1,2
1	$\varnothing$	1,3	2	1,2
2	3	$\varnothing$	$\varnothing$	2
***3**	3	1	$\varnothing$	3

$\Rightarrow$

state	*symbol* a	b
$\rightarrow$**0**	0,3	1,3
1	3	1,3
2	3	$\varnothing$
***3**	3	1



ϵ removal

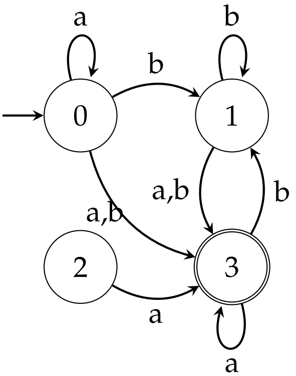
a(nother) solution with the transition table

transition table

		symbol			
		a	**b**	**ϵ**	**ϵ***
state	→**0**	0	∅	1	0,1,2
	1	∅	1,3	2	1,2
	2	3	∅	∅	2
	***3**	3	1	∅	3

⇒

	symbol	
	a	**b**
→**0**	0,3	1,3
1	3	1,3
2	3	∅
***3**	3	1



NFA–DFA equivalence

- The language recognized by every NFA is recognized by some DFA
- The set of DFA is a subset of the set of NFA (a DFA is also an NFA)
- The same is true for ϵ-NFA
- All recognize/generate regular languages
- NFA can automatically be converted to the equivalent DFA

Why do we use an NFA then?

- NFA (or ϵ-NFA) are often easier to construct
  - Intuitive for humans (cf. earlier exercise)
  - Some representations are easy to convert to NFA rather than DFA, e.g., regular expressions
- NFA may require less memory (fewer states)

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A quick exercise

1. Construct (draw) an NFA for the language over $\Sigma = \{a, b\}$, such that 4th symbol from the end is an a

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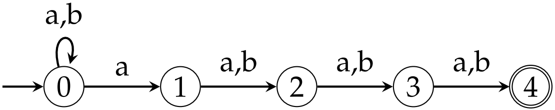

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  - Intuitive for humans (cf. earlier exercise)
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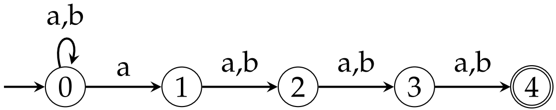
- NFA may require less memory (fewer states)

A quick exercise – and a not-so-quick one

1. Construct (draw) an NFA for the language over $\Sigma = \{a, b\}$, such that 4th symbol from the end is an a



2. Construct a DFA for the same language

Summary

- FSA are efficient tools with many applications
- FSA have two flavors: DFA, NFA (or maybe three: ε-NFA)
- DFA recognition is linear, recognition with NFA may require exponential time
- Reading suggestion: **hopcroft1979** (and its successive editions), Jurafsky and Martin (2009, Ch. 2)

Next:

- FSA determinization, minimization
- Reading suggestion: **hopcroft1979** (and its successive editions), Jurafsky and Martin (2009, Ch. 2)

Acknowledgments, credits, references

Jurafsky, Daniel and James H. Martin (2009). *Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition*. second edition. Pearson Prentice Hall. ISBN: 978-0-13-504196-3.

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