CS447: Natural Language Processing
http://courses.grainger.illinois.edu/cs447

Lecture 3: Morphology and Finite-State Methods

Julia Hockenmaier
juliahmr@illinois.edu

ILLINOIS

What is a word?

How many different words are there in English?

How large is the **vocabulary** of English
(or any other language)?

Vocabulary size = the number of distinct word types

Google N-gram corpus: 1 trillion tokens,
13 million word types that appear 40+ times

[here, we're treating inflected forms (took, taking) as distinct]

You may have heard statements such as
"*adults know about 30,000 words*"
"*you need to know at least 5,000 words to be fluent*"

Such statements do not refer to inflected word forms (take/takes/taking/take/takes/took) but to lemmas or dictionary forms (take), and assume if you know a lemma, you know all its inflected forms too.

Which words appear in this text?

> Of course he wants to take the advanced course too. He already took two beginners' courses.

Actual text doesn't consist of dictionary entries:

wants is a form of want
took is a form of take
courses is a form of course

Linguists distinguish between

— the **(surface) forms** that occur in text:
want, wants, beginners', took,...

— and the **lemmas** that are the uninflected forms of these words:
want, beginner, take, ...

In NLP, we sometimes map words to lemmas (or simpler "stems"), but the raw data always consists of surface forms

How many different words are there?

Inflection creates different forms of the same word:

Verbs: to be, being, I am, you are, he is, I was,
Nouns: one book, two books

Derivation creates different words from the same lemma:

grace ⇒ disgrace ⇒ disgraceful ⇒ disgracefully

Compounding combines two words into a new word:

cream ⇒ ice cream ⇒ ice cream cone ⇒ ice cream cone bakery

Word formation is productive:

New words are subject to all of these processes:
Google ⇒ Googler, to google, to ungoogle, to misgoogle, googlification, ungooglification, googlified, Google Maps, Google Maps service,...

A Turkish word

uygarlaştıramadıklarımızdanmışsınızcasına
uygar_laş_tır_ama_dık_lar_ımız_dan_mış_sınız_casına

“as if you are among those whom we were not able to civilize (=*cause to become civilized*)”
uygar: *civilized*
_laş: *become*
_tır: *cause somebody to do something*
_ama: *not able*
_dık: past participle
_lar: plural
_ımız: 1st person plural possessive (our)
_dan: *among* (ablative case)
_mış: past
_sınız: 2nd person plural (you)
_casına: *as if* (forms an adverb from a verb)

K. Oflazer pc to J&M

Inflectional morphology in English

Verbs:

Infinitive/present tense: walk, go

3rd person singular present tense (s-form): walks, goes

Simple past: walked, went

Past participle (ed-form): walked, gone

Present participle (ing-form): walking, going

Nouns:

Common nouns inflect for number:
singular (book) vs. plural (books)

Personal pronouns inflect for person, number, gender, case:

I saw him; he saw me; you saw her; we saw them; they saw us.

Derivational morphology in English

Nominalization:

V + -ation: computeriz<u>ation</u>

V+ -er: kill<u>er</u>

Adj + -ness: fuzzi<u>ness</u>

Negation:

un-: <u>un</u>do, <u>un</u>seen, ...

mis-: <u>mis</u>take,...

Adjectivization:

V+ -able: do<u>able</u>

N + -al: nation<u>al</u>

Morphemes: stems, affixes

dis-grace-ful-ly
prefix-stem-suffix-suffix

Many word forms consist of a *stem*
plus a number of *affixes* (*prefixes* or *suffixes*)

Exceptions: *Infixes* are inserted inside the stem
Circumfixes (German *ge*seh*en*) surround the stem

Morphemes: the smallest (meaningful/grammatical) parts of words.

Stems (grace) are often free morphemes.

Free morphemes can occur by themselves as words.

Affixes (dis-, -ful, -ly) are usually bound morphemes.

Bound morphemes *have* to combine with others to form words.

Morphemes and morphs

The same information (plural, past tense, …) is often expressed in different ways in the same language.

One way may be more common than others,
and exceptions may depend on specific words:

- Most plural nouns: add ***-s*** to singular: book-book**s**,
  but: box-box**<u>es</u>**, fly-fl**<u>ies</u>**, child-child**<u>ren</u>**
- Most past tense verbs add ***-ed*** to infinitive: walk-walk**ed**,
  but: like-like**<u>d</u>**, leap-leap**<u>t</u>**

Such exceptions are called *irregular* word forms

Linguists say that there is one underlying morpheme (e.g. for plural nouns) that is "realized" as different "surface" forms (morphs) (e.g. -s/-es/-ren)

Allomorphs: two different realizations (-s/-es/-ren) of the same underlying morpheme (plural)

Side note: “Surface”?

This terminology comes from Chomskyan Transformational Grammar.

- Dominant early approach in theoretical linguistics, superseded by other approaches (“minimalism”).
- Not computational, but has some historical influence on computational linguistics (e.g. Penn Treebank)

“Surface” = standard English (Chinese, Hindi, etc.).

“Surface string” = a written sequence of characters or words

vs. “Deep”/“Underlying” structure/representation:

A more abstract representation.
Might be the same for different sentences/words with the same meaning.

Finite-State Automata and Regular Languages

Formal languages

An alphabet $\sum$ is a set of symbols:

e.g. $\sum = \{a, b, c\}$

A string ω is a sequence of symbols, e.g $\omega = abcb$.

The empty string ε consists of zero symbols.

The Kleene closure $\sum^*$ ('sigma star') is the (infinite) set of all strings that can be formed from $\sum$:

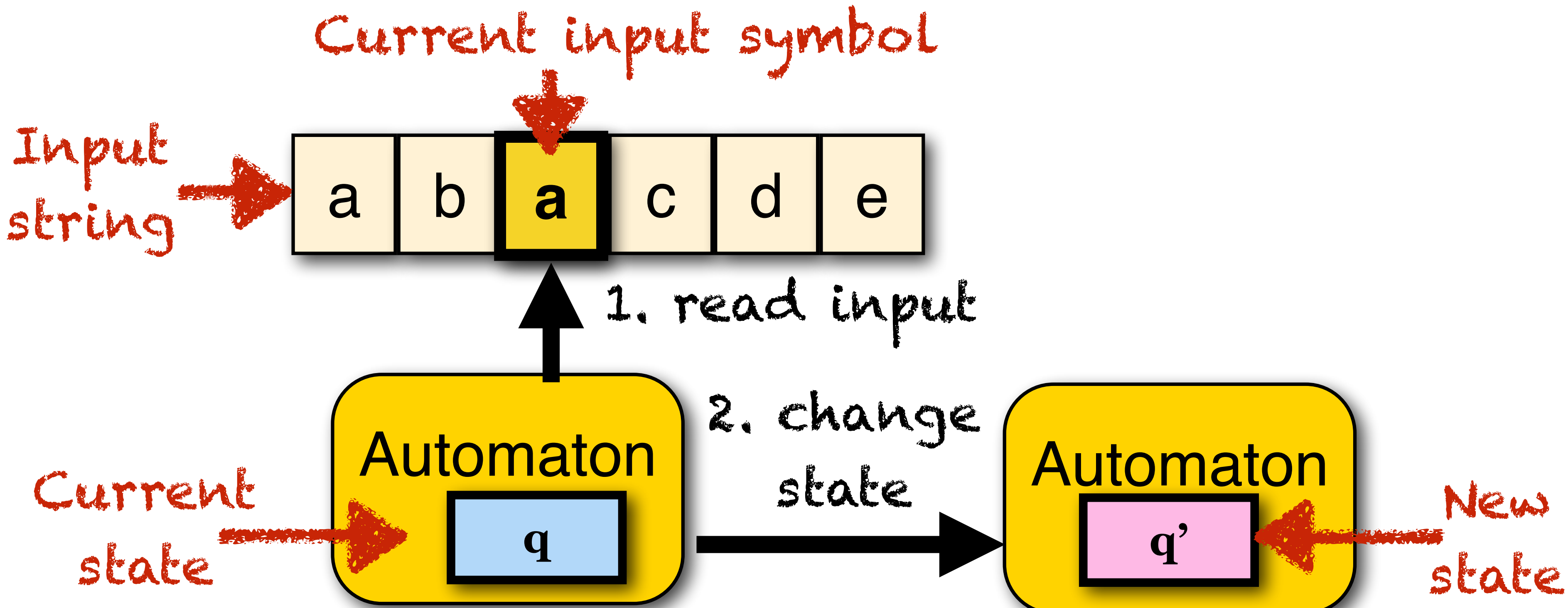
$\sum^* = \{\varepsilon, a, b, c, aa, ab, ba, aaa, ...\}$

A language $\mathrm{L} \subseteq \sum^*$ over $\sum$ is also a set of strings.

Typically we only care about proper subsets of $\sum^*$ $(L \subset \Sigma)$.

Automata and languages

An automaton is an abstract model of a computer.
It *reads* an input string symbol by symbol.
It *changes* its internal state depending on
the current input symbol and its current internal state.

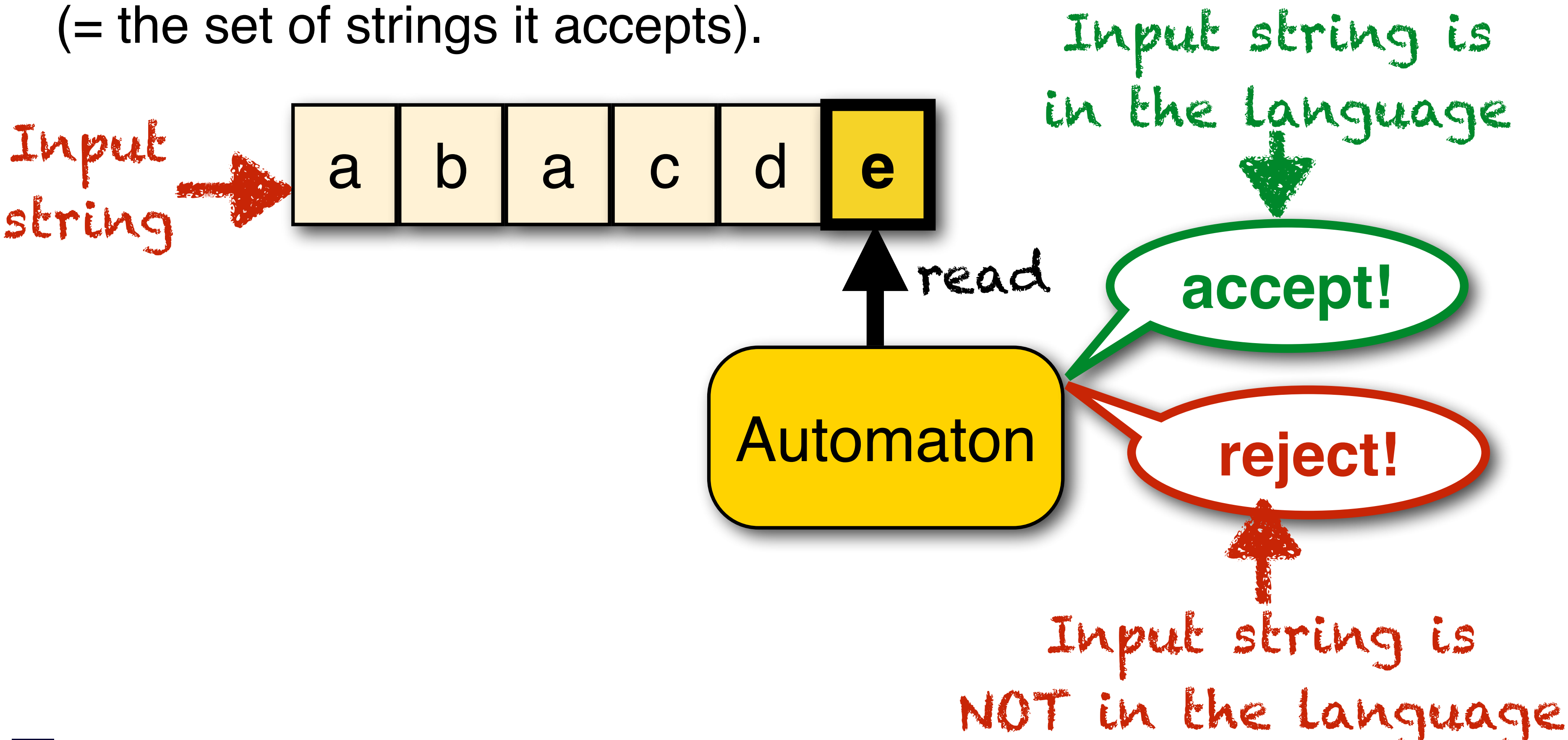


Automata and languages

The automaton either *accepts* or *rejects* the input string.

Every automaton defines a language

(= the set of strings it accepts).



Automata and languages

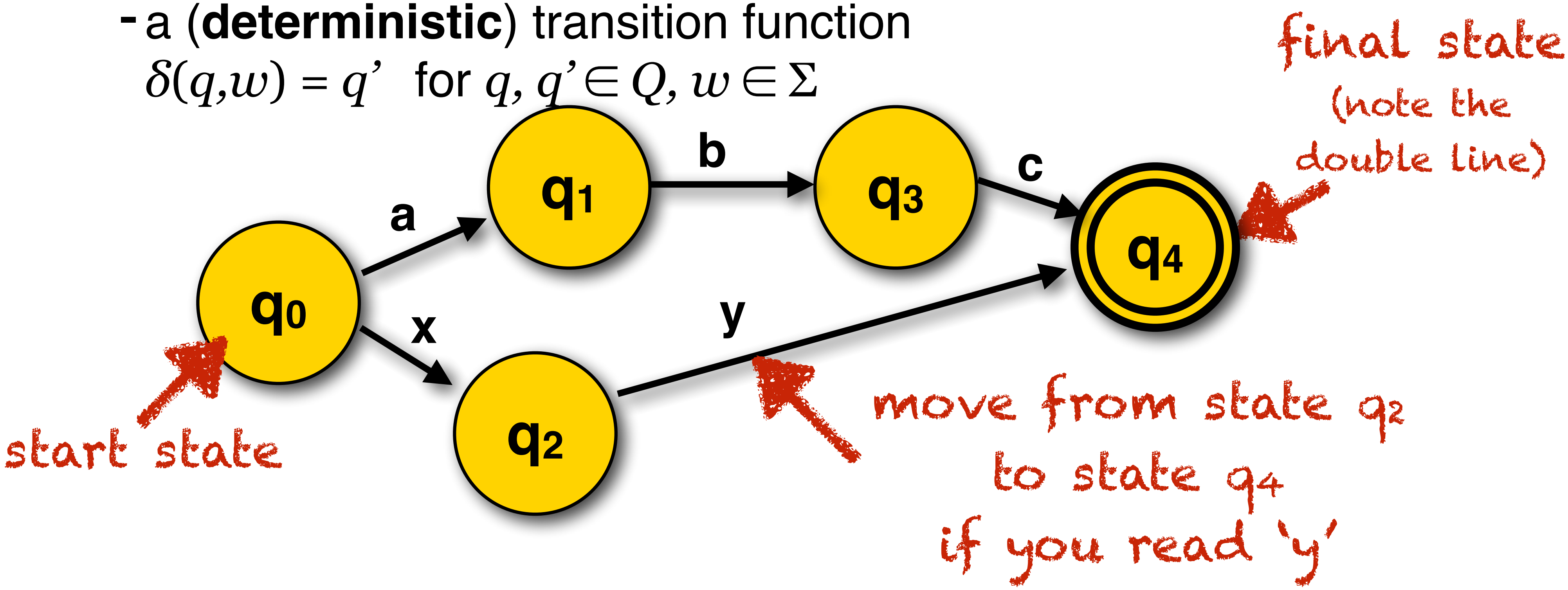
Different types of automata define different language classes:

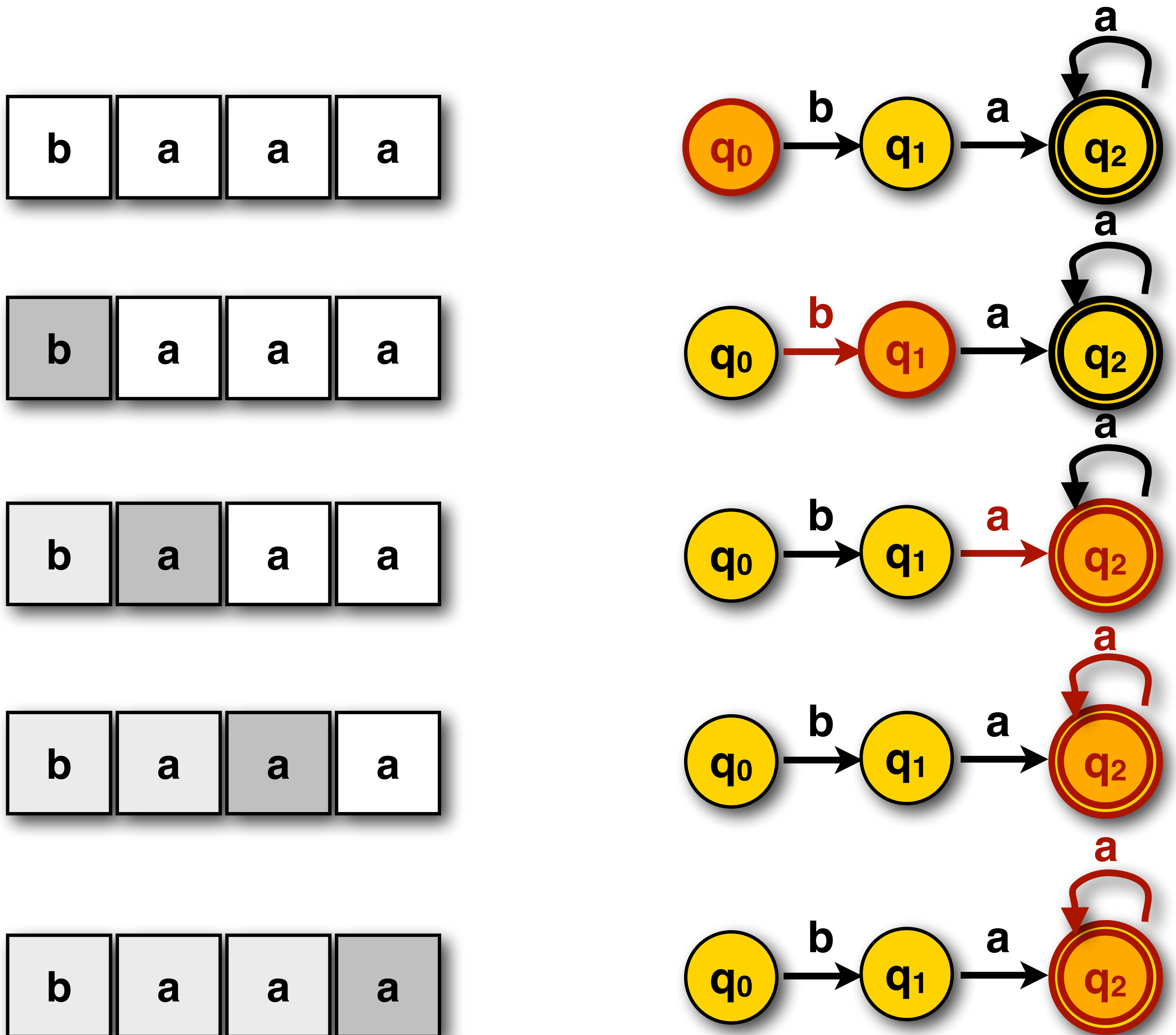
- **Finite-state** automata define **regular** languages
- **Pushdown** automata define **context-free** languages
- **Turing machines** define **recursively enumerable** languages

Finite-state automata

A (deterministic) finite-state automaton (FSA) consists of:

- a **finite set of states** $Q = \{q_0 \ldots . q_N\}$, including **a start state** q_0 and one (or more) **final (=accepting) states** (say, q_N)
- a (**deterministic**) transition function $\delta(q,w) = q'$ for $q, q' \in Q, w \in \Sigma$



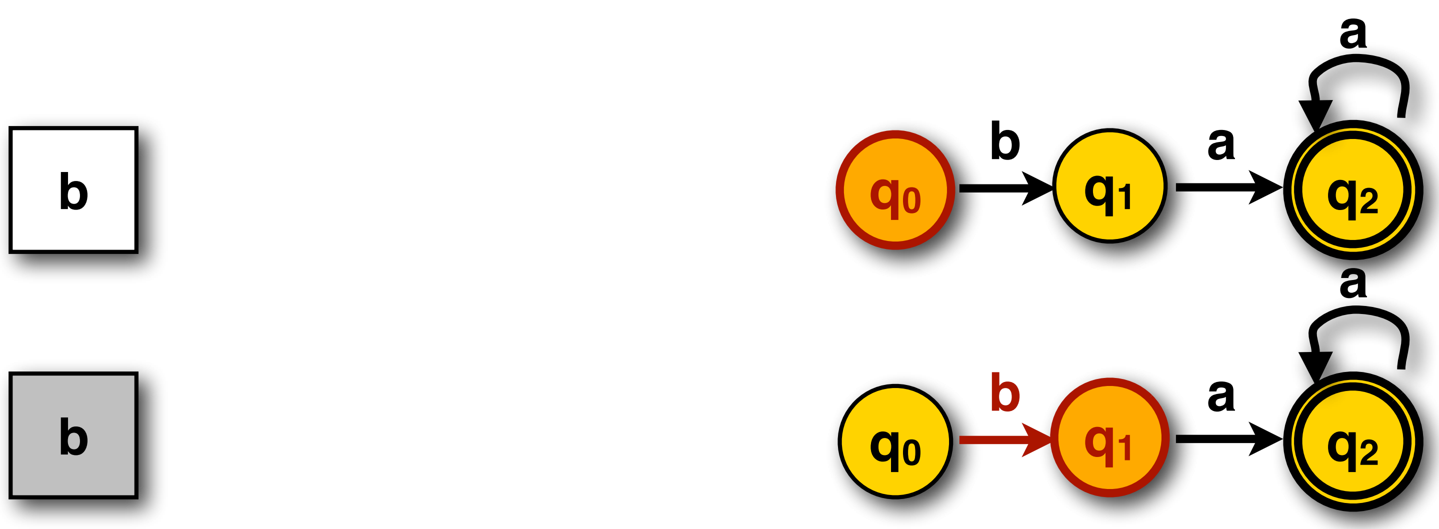


Start in q_0

Accept!

We've reached the end of the string, and are in an accepting state.

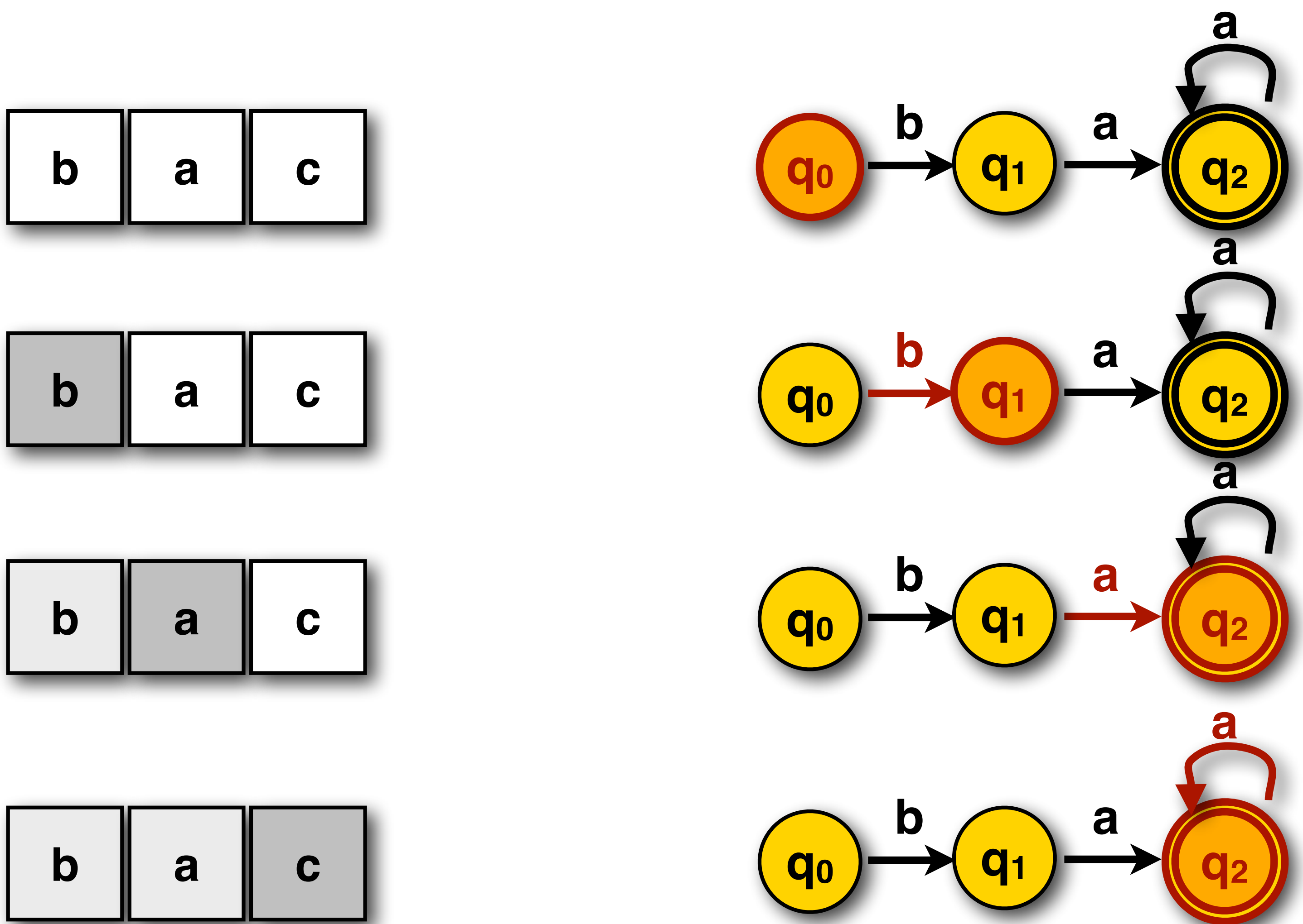
Rejection: Automaton does not end up in accepting state



Start in q_0

Reject!
(q_1 is not a final state)

Rejection: Transition not defined

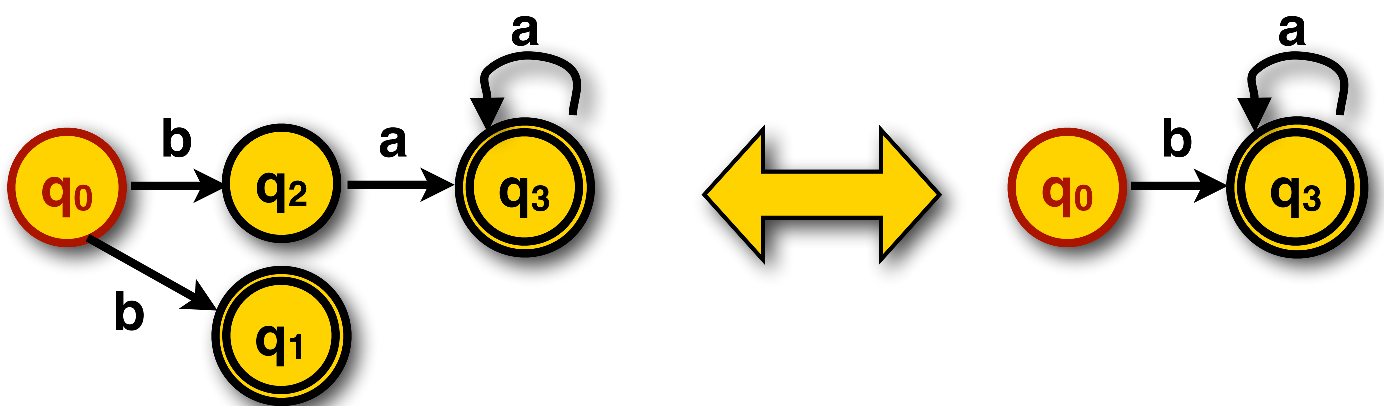


Start in q_0

Reject!
(There is no transition labeled ‘c’)

Finite State Automata (FSAs)

Every NFA can be transformed into an equivalent DFA:



Recognition of a string *w* with a DFA is linear in the length of *w*

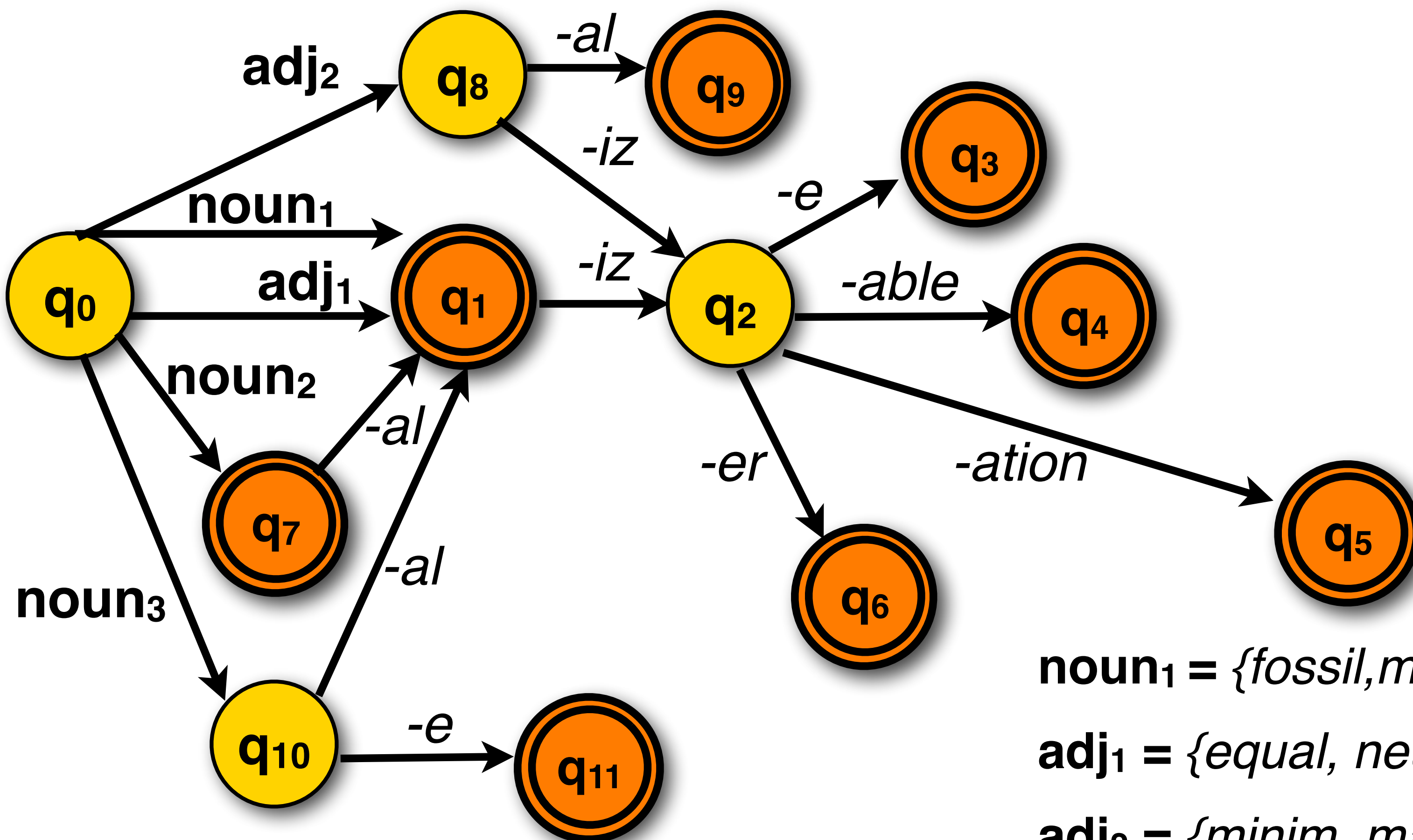
Finite-state automata define the class of regular languages

$L_1 = \{ a^n b^m \} = \{ab, aab, abb, aaab, abb, \ldots \}$ is a regular language,

$L_2 = \{ a^n b^n \} = \{ab, aabb, aaabbb, \ldots\}$ is not (it's context-free).

You cannot construct an FSA that accepts all the strings in L_2 and nothing else.

FSAs for derivational morphology



noun$_1$ = *{fossil,mineral,...}*

adj$_1$ = *{equal, neutral}*

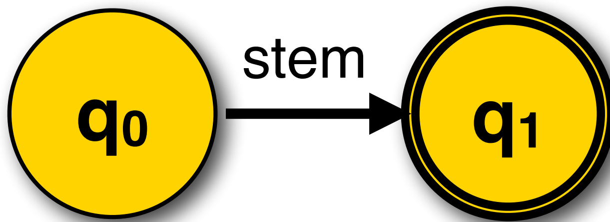
adj$_2$ = *{minim, maxim}*

noun$_2$ = *{nation, form,…}*

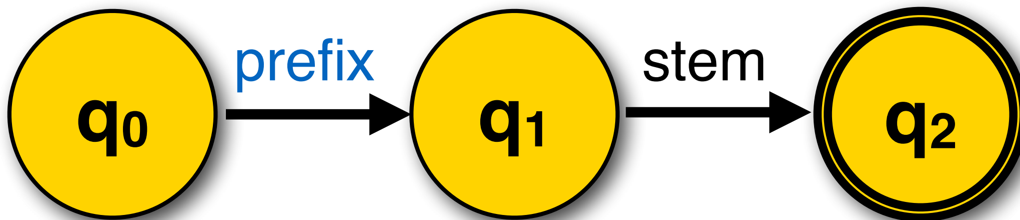
noun$_3$ = *{natur, structur,…}*

Finite state automata for morphology

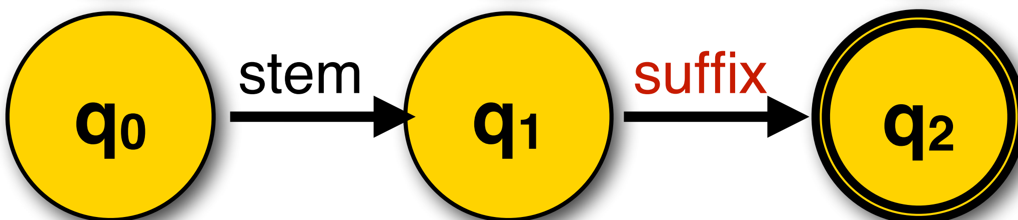
grace:



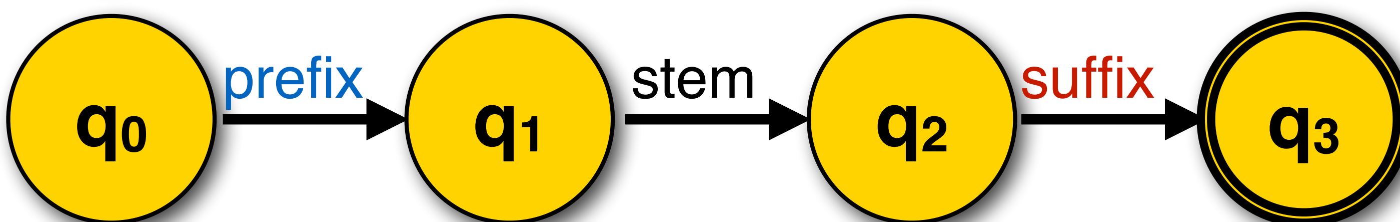
dis-grace:



grace-ful:

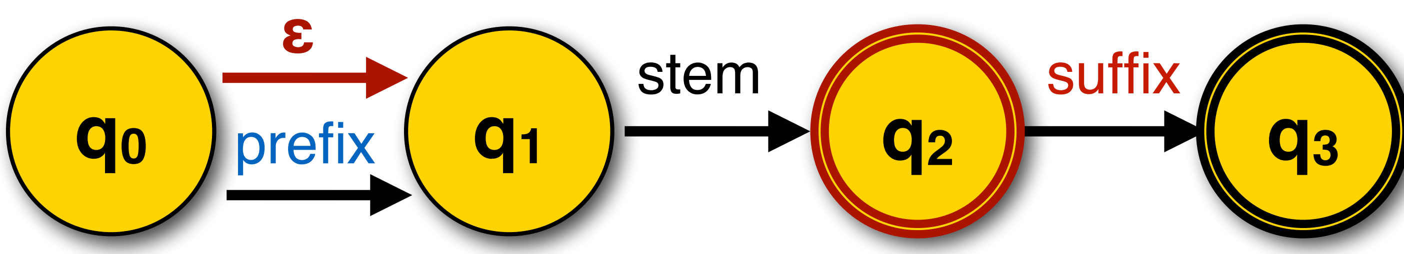


dis-grace-ful:



Union: merging automata

grace,
dis-grace,
grace-ful,
dis-grace-ful



Regular Expressions

Regular expressions (regexes) can also be used to define a regular language.

Simple patterns:

- **Standard characters** match themselves: '*a*', '1'
- **Character classes**: '[*abc*]', '[0-9]', **negation:** '[^*aeiou*]'
  (Predefined: *s* (whitespace), *w* (alphanumeric), etc.)
- **Any character** (except newline) is matched by '.'

Complex patterns: (e.g. ^[*A-Z*]([*a-z*])+\s)

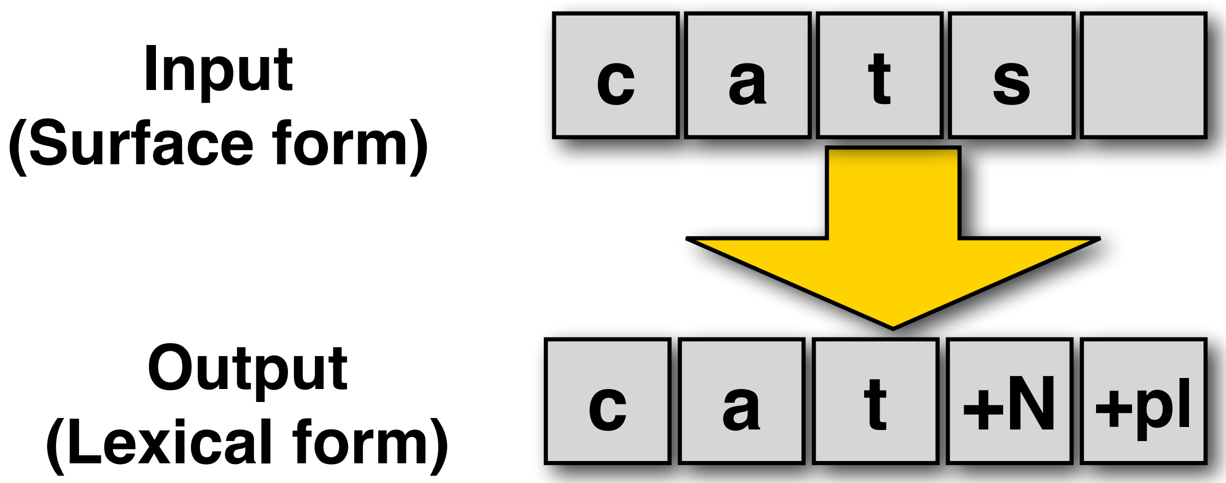
- **Group:** '(…)'
- **Repetition:** 0 or more times: '*', 1 or more times: '+'
- **Disjunction:** '...|...'
- **Beginning of line** '^' and **end of line** '$'

Finite-State Transducers for Morphology

Recognition vs. Analysis

FSAs can recognize (accept) a string,
but they don't tell us its internal structure.

We need is a machine that maps (transduces)
the input string into an output string
that encodes its structure:



Morphological parsing

disgracefully

dis	grace	ful	ly
prefix	*stem*	*suffix*	*suffix*
NEG	grace*+N*	*+ADJ*	*+ADV*

Morphological generation

We cannot enumerate all possible English words, but we would like to capture the rules that define whether a string *could* be an English word or not.

That is, we want a procedure that can generate (or accept) *possible* English words…

grace, graceful, gracefully
disgrace, disgraceful, disgracefully,
ungraceful, ungracefully,
undisgraceful, undisgracefully,…

without generating/accepting impossible English words

*gracelyful, *gracefuly, *disungracefully,…

NB: * is linguists' shorthand for "this is ungrammatical"

Finite State Automata (FSAs)

A finite-state automaton $M = \langle Q, \Sigma, q_0, F, \delta \rangle$ consists of:

- A finite set of **states** $Q = \{q_0, q_1, .., q_n\}$
- A finite **alphabet** Σ of input symbols (e.g. $\Sigma = \{a, b, c, \ldots\}$)
- A designated **start state** $q_0 \in Q$
- A set of **final states** $F \subseteq Q$
- A **transition function** δ:

  For a **deterministic (D)FSA**: $Q \times \Sigma \rightarrow Q$

  $\delta(q,w) = q'$ for $q, q' \in Q, w \in \Sigma$

  If the current state is q and the current input is w, go to q'

  For a **nondeterministic (N)FSA**: $Q \times \Sigma \rightarrow 2^Q$

  $\delta(q,w) = Q'$ for $q \in Q, Q' \subseteq Q, w \in \Sigma$

  If the current state is q and the current input is w, go to any $q' \in Q'$

Finite-state transducers

A **finite-state transducer** $T = \langle Q, \Sigma, \Delta, q_0, F, \delta, \sigma \rangle$ consists of:

— A finite **set of states** $Q = \{q_0, q_1, .., q_n\}$

— A finite alphabet Σ of **input symbols** (e.g. $\Sigma = \{a, b, c, ...\}$)

— A finite alphabet Δ of **output symbols** (e.g. $\Delta = \{+N, +pl, \ldots\}$)

— A designated **start state** $q_0 \in Q$

— A set of **final states** $F \subseteq Q$

— A **transition function** $\delta\colon Q \times \Sigma \rightarrow 2^Q$

$\delta(q,w) = Q'$ *for* $q \in Q, Q' \subseteq Q, w \in \Sigma$

— An **output function** $\sigma\colon Q \times \Sigma \rightarrow \Delta^*$

$\sigma(q,w) = \omega$ for $q \in Q, w \in \Sigma, \omega \in \Delta^*$

If the current state is q and the current input is w, write ω.

(NB: Jurafsky&Martin (2nd ed.) define $\sigma\colon Q \times \Sigma^* \rightarrow \Delta^*$. Why is this equivalent?)

Finite-state transducers

An FST $T = L_{in} \times L_{out}$ defines a **relation between two regular languages** L_{in} and L_{out}:

L_{in} = {**cat, cats, fox, foxes, ...**}

L_{out} = {*cat+N+sg, cat+N+pl, fox+N+sg, fox+N+pl ...*}

T = { ⟨**cat**, *cat+N+sg*⟩,
⟨**cats**, *cat+N+pl*⟩,
⟨**fox**, *fox+N+sg*⟩,
⟨**foxes**, *fox+N+pl*⟩ }

Some FST operations

Inversion T^{-1}:

The inversion (T^{-1}) of a transducer switches input and output labels.

This can be used to switch from parsing words to generating words.

Composition ($T \circ T'$): *(Cascade)*

Two transducers $T = L_1 \times L_2$ and $T' = L_2 \times L_3$ can be composed into a third transducer $T'' = L_1 \times L_3$.

Sometimes intermediate representations are useful

English spelling rules

Peculiarities of English spelling (orthography)

The same underlying morpheme (e.g. *plural-s*) can have different orthographic "surface realizations" (-s, -es)

This leads to spelling changes at morpheme boundaries:

E-insertion: fox +s = fox**e**s

E-deletion: mak**e** +ing = making

Intermediate representations

English plural -s: cat ⇒ cats dog ⇒ dogs
but: fox ⇒ foxes, bus ⇒ buses buzz ⇒ buzzes

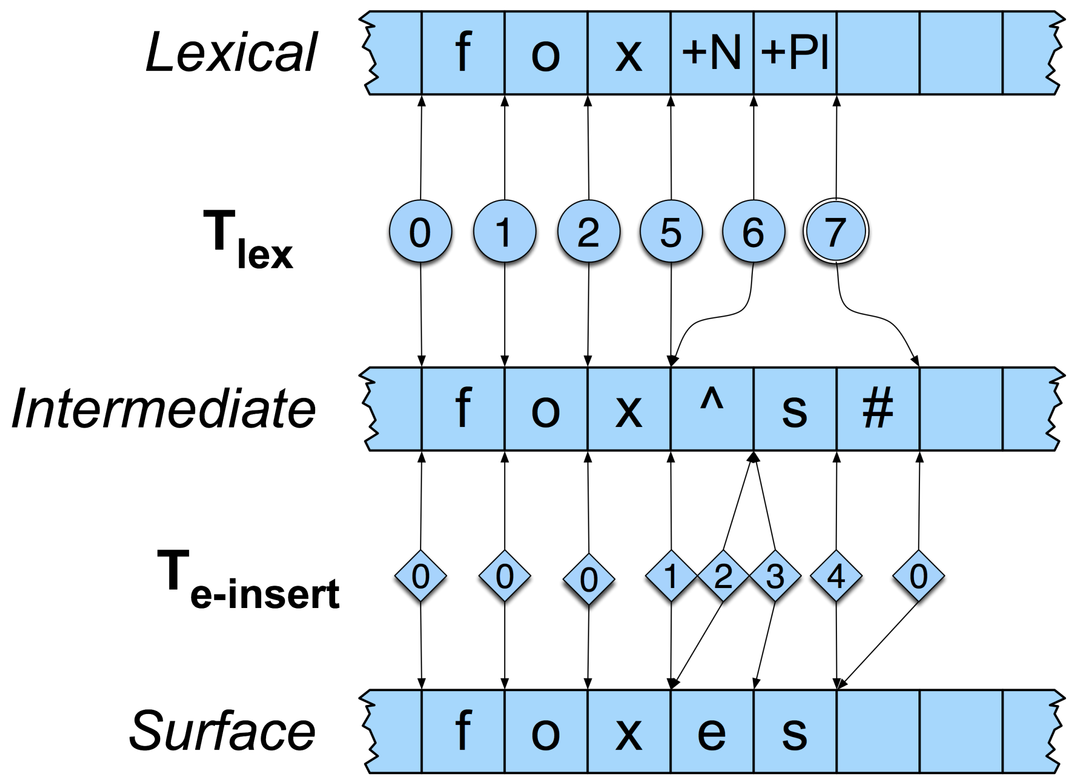
We define an intermediate representation to capture morpheme boundaries (^) and word boundaries (#):

Lexicon:	***cat+N+PL***	***fox+N+PL***
⇒ *Intermediate representation:*	***cat^s#***	***fox^s#***
⇒ *Surface string:*	***cats***	***foxes***

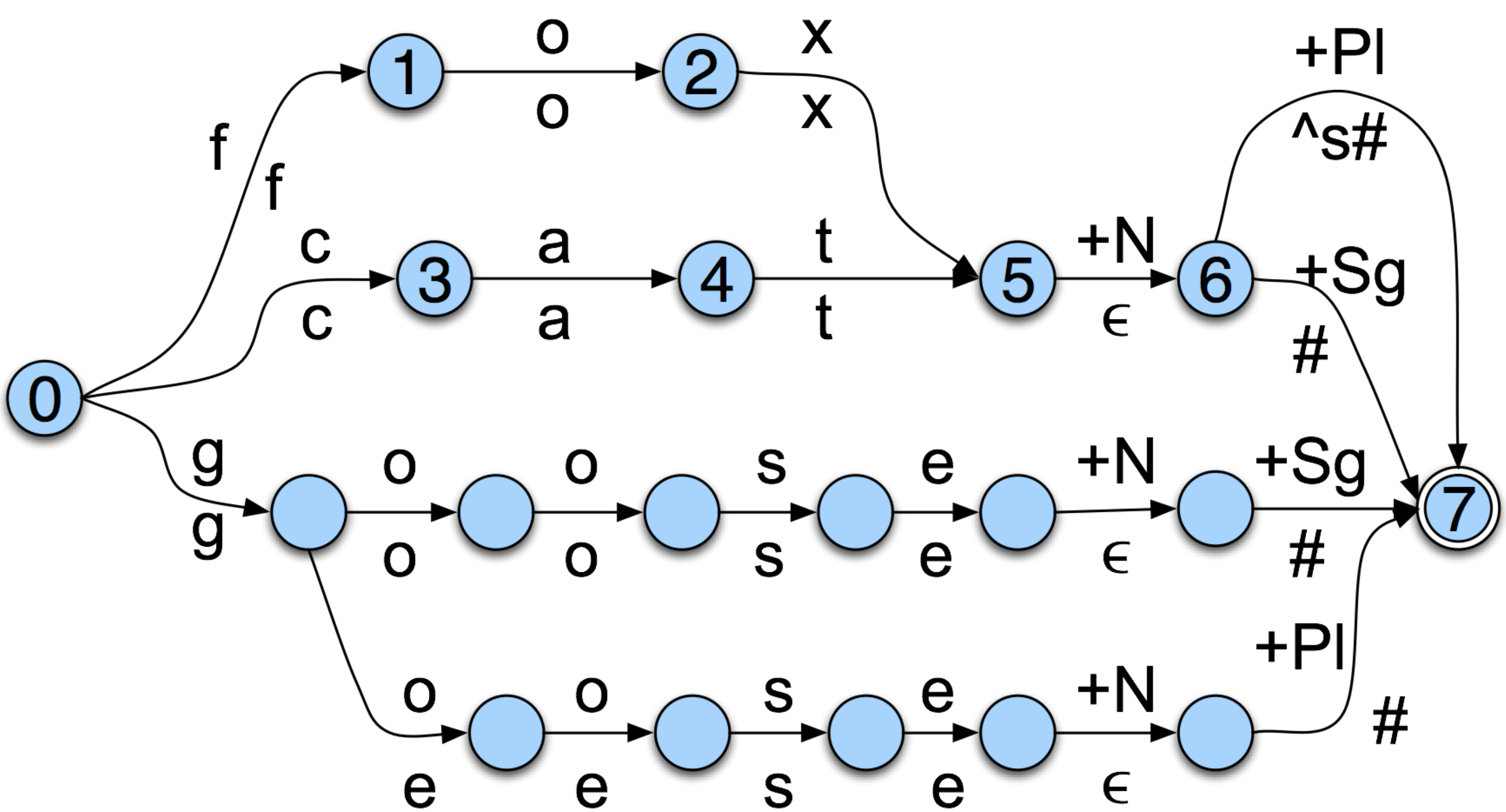
Intermediate-to-Surface Spelling Rule:

If plural ‘*s*’ follows a morpheme ending in ‘*x*’,‘*z*’ or ‘*s*’, insert ‘*e*’.

FST composition/cascade:

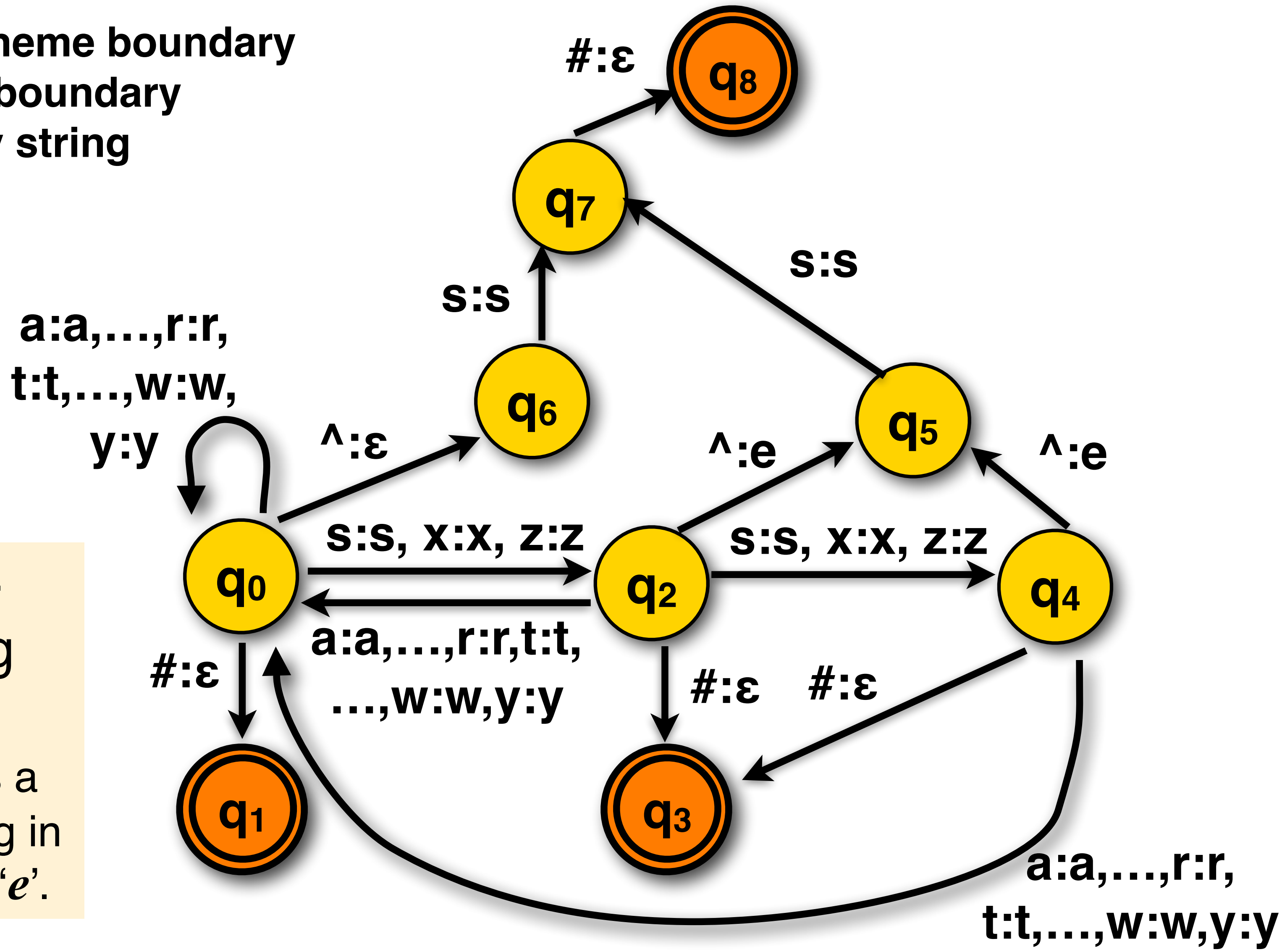


T_{lex}: Lexical to intermediate level



$T_{e\text{-insert}}$: intermediate to surface level

^ = morpheme boundary
 # = word boundary
ε = empty string



Intermediate-to-Surface Spelling Rule:

If plural '*s*' follows a morpheme ending in '*x*','*z*' or '*s*', insert '*e*'.

Dealing with ambiguity

book: *book +N +sg* or *book +V*?

Generating words is generally unambiguous,
but analyzing words often requires disambiguation.

We need a nondeterministic FST.

Efficiency problem: Not every nondeterministic FST can be translated into a deterministic one!

We also need a scoring function to identify which analysis is more likely.

We may need to know the context in which the word appears: (I read a **book** vs. I **book** flights)

What about compounds?

Semantically, compounds have hierarchical structure:

(((ice cream) cone) bakery)
not (ice ((cream cone) bakery))

((computer science) (graduate student))
not (computer ((science graduate) student))

We will need context-free grammars to capture this underlying structure.