CS 498 JH: **Introduction to NLP** (Fall ’10)

Lecture 2: Finite State Transducers and Morphology

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Office Hour: Tuesdays, 2:00-3:00pm

http://cs.illinois.edu/class/fa10/cs498jh/

Today's lecture

What are words? How many words are there?

What is the structure of words?
(in English, Chinese, Arabic,…)

Morphology is the area of linguistics that deals with this.

How can we identify the structure of words?

We need to build a **morphological analyzer** (parser).

We will use **finite-state transducers** for this task.

Finite-State Automata and Regular Languages

(Revision)

Revision:
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 $\omega = abcbab$.
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** $L \subseteq \sum^*$ 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 which reads an **input string**, and **changes its internal state** depending on the current input symbol.
It can either **accept or reject** the input string.

Every automaton defines a language
(the set of strings it accepts).

Different automata define different classes of language:
- **Finite-state** automata define **regular** languages
- **Pushdown** automata define **context-free** languages
- **Turing machines** define **recursively enumerable** languages

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. $\Sigma = \{a, b, c, ...\}$)
- A designated **start state** $q_0 \in Q$
- A set of **final states** $F \subseteq Q$
- A **transition function** δ:

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'

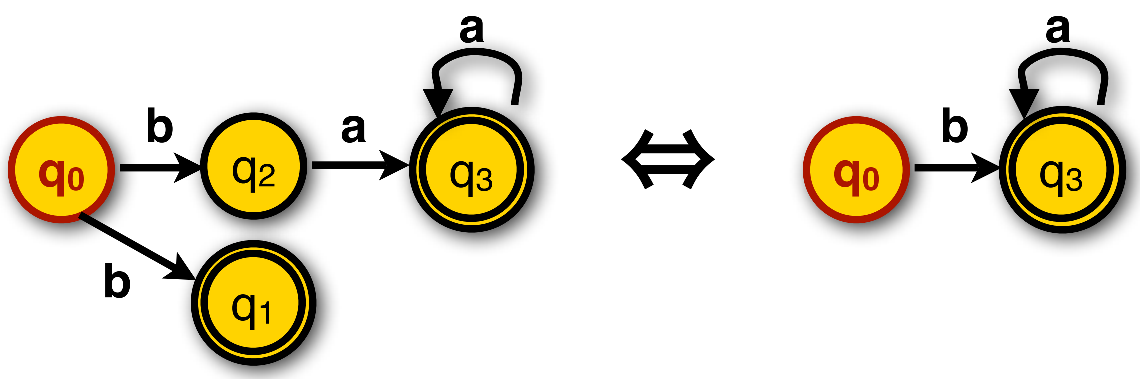
Nondeterministic (N)FSA: $Q \times \Sigma \rightarrow 2^Q$

$\delta(q,w) = Q'$ 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 Automata (FSAs)

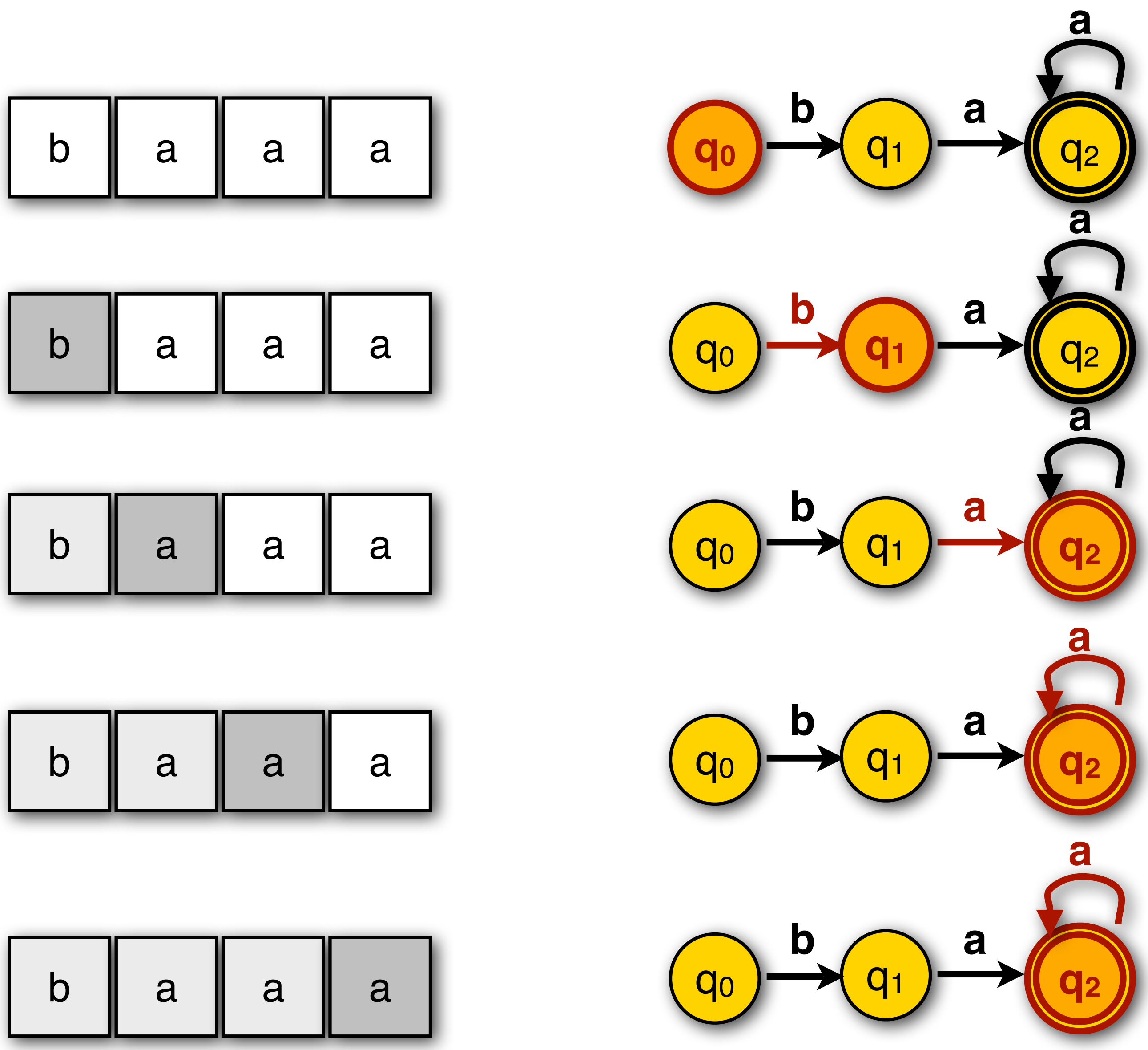
Every NFA can be transformed into an equivalent DFA:



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

Finite-state automata define the class of **regular languages**

- $L_1 = \{ a^n b^m \} = \{\text{ab, aab, abb, aaab, abb,} \ldots \}$ *is a regular language,*
  $L_2 = \{ a^n b^n \} = \{\text{ab, aabb, aaabbb,} \ldots\}$ *is not (it's context-free).*
- *You can't construct an FSA that accepts all the strings in* L_2 *and nothing else.*



b a a a
q0 q1 q2
b
a
a

Regular Expressions

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:

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

Examples: ^[A-Z]([a-z])+\s

Using Regular Expressions

```
>>> import re                      %% Import re package
>>> ex = re.compile('a.c')         %% '…': reg.expression
>>> m = ex.search('ab')            %% Does 'ab' contain ex?
>>> print m                        %% No.
None
>>> m = ex.search('abc')           %% Does 'abc' contain ex?
>>> print m                        %% Yes.
<_sre.SRE_Match object at 0x70640>
```

More about this in the homework.

http://docs.python.org/dev/howto/regex.html

http://docs.python.org/lib/module-re.html

Morphology:
What is a word?

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

Basic word classes (parts of speech)

Content words (open-class):

Nouns: *student, university, knowledge,...*
Verbs: *write, learn, teach,...*
Adjectives: *difficult, boring, hard, ...*
Adverbs: *easily, repeatedly,...*

Function words (closed-class):

Prepositions: *in, with, under,...*
Conjunctions: *and, or,...*
Determiners: *a, the, every,...*

How many words are there?

The Unix command ***"wc -w"*** counts the words in a file.

```
> cat example.txt
This company isn't New York-based anymore
We moved to Chicago

> wc -w example.txt
     10 example.txt
```

"wc -w" uses blanks to identify words:

This$_1$ ***company***$_2$ ***isn't***$_3$ ***New***$_4$ ***York-based***$_5$ ***anymore***$_6$

We$_7$ ***moved***$_8$ ***to***$_9$ ***Chicago***$_{10}$

Words aren't just defined by blanks

Problem 1: Compounding

"ice cream", "website", "web site", "New York-based"

Problem 2: Other writing systems

Chinese: 我开始写小说 **=** 我 开始 写 小说

I start(ed) writing novel(s)

Problem 3: Clitics

English: ***"doesn't" , "I'm"*** ,

Italian: ***"dirglielo"*** = **dir** + **gli(e)** + **lo**

tell + him + it

Written vs. spoken words

Even in alphabetic writing systems, there may not be a one-to-one mapping between sounds and letters:

I have a spelling checker I disk covered four my PC.
It plane lee marks four my revue miss steaks aye can knot see.

Sometimes, **phonetic transcripts** are used instead:

- *review*	*r.Ivy'u r+ivy'u r'ivy+u*
- *revue*	*r.Ivy'u*
- *project*	*pr'aJ.Ekt pr.xJ'Ekt*
- *cats*	*k'@ts*
- *dogs*	*d'cgz*

NB: we'll work with standard writing

How many *different* words are there?

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

- **The same (underlying) word can take different forms:**
  course/courses, take/took

  We distinguish concrete **word forms** (*take, taking, took*) from abstract **lemmas** or dictionary forms (*take*)

- **Different words may be spelled (pronounced) the same**:
  of course vs. *advanced course*
  two vs. *too*

How many words are there?

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

This is a bad question. Did I mean:

- **How many word tokens are there?**
  (16 to 19, depending on how we count punctuation)

- **How many word types are there?**
  (i.e. How many *different* words are there?
  Again, this depends on how you count, but it’s usually much less than the number of tokens)

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,...

Inflectional morphology

English verb forms:

Infinitive/present tense: *walk, go*

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

Past participle (*ed*-form): *walked, gone*

Present participle (*ing*-form): *walking, going*

English noun forms:

Singular: *book*

Plural: *books*

Possessive: *book's, books'*

Personal pronouns

I *saw* ***him*** *and* ***he*** *saw* ***me****.*
You *saw* ***her*** *and* ***she*** *saw* ***you****.*
We *saw* ***them*** *and* ***they*** *saw* ***us****.*

Personal pronouns inflect for

- **person:** (1st: *I/we*, 2nd: *you/you*, 3rd: *he/she/it/they*),
- **number:** (singular: *I/you/he/she/it,* plural: *we/you/they*),
- **gender:** masculine: *he*, feminine: *she*, neuter: *it*)
- **case:** nominative: *I/he/she/it/we*,
  accusative: *me/him/her/us*)

In many languages, all nouns inflect for number, gender and case

Derivational morphology

Nominalization:

V + -ation: *computerization*

V+ -er: *killer*

Adj + -ness: *fuzziness*

Negation:

un-: *undo, unseen, ...*

mis-: *mistake,...*

Adjectivization:

V+ -able: *doable*

N + -al: *national*

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**)

Infixes are inserted inside the stem.
Circumfixes (German <u>ge</u>seh<u>en</u>) surround the stem

We call the smallest (meaningful or grammatical) parts of words **morphemes**.

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

There are many *irregular* word forms:

- **Plural nouns** add ***s*** to singular noun: *book-book**s**,*
  but: *box-box**es**, fly-fl**ies**, child-child**ren***

- **Past tense verbs** add ***ed*** to infinitive: *walk-walk**ed**,*
  but: *like-like**d**, leap-leap**t***

Morphemes are abstract categories

- Examples: plural morpheme, past tense morpheme

The same morpheme can be realized as different surface forms (morphs).

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

Morphological parsing

Morphological parsing

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

Morphological generation

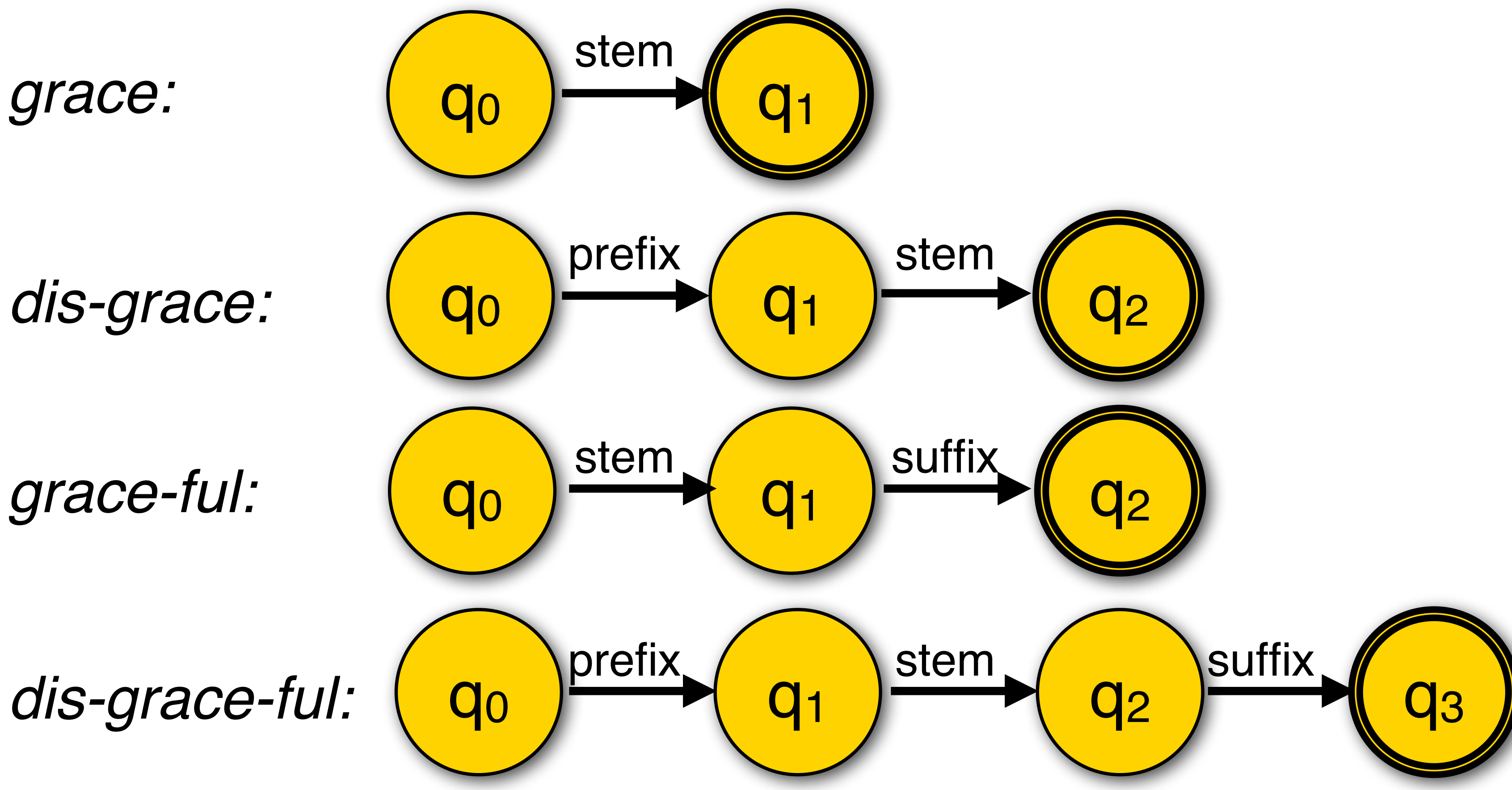
Generate possible English words:

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

Don't generate impossible English words:

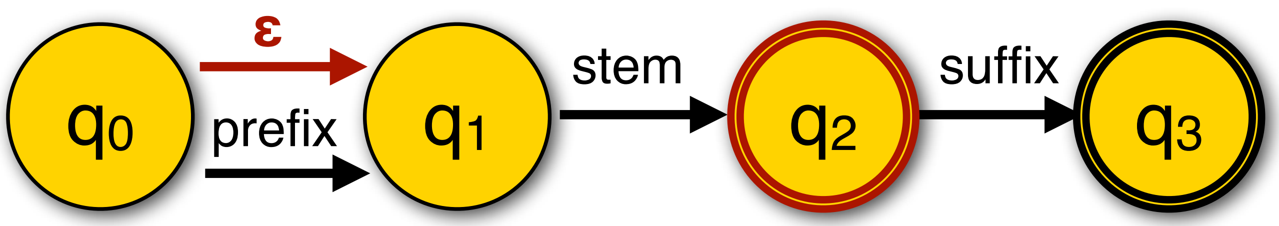
**gracelyful, *gracefuly, *disungracefully,...*

Finite state automata for morphology



Union: merging automata

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

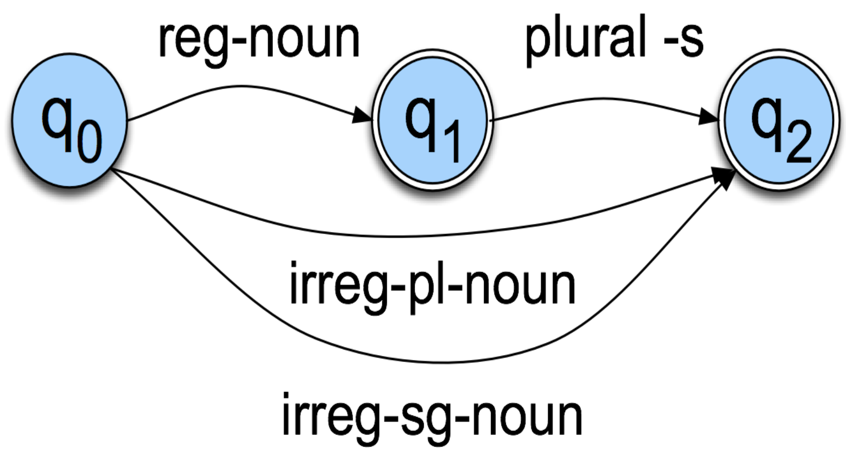


Stem changes

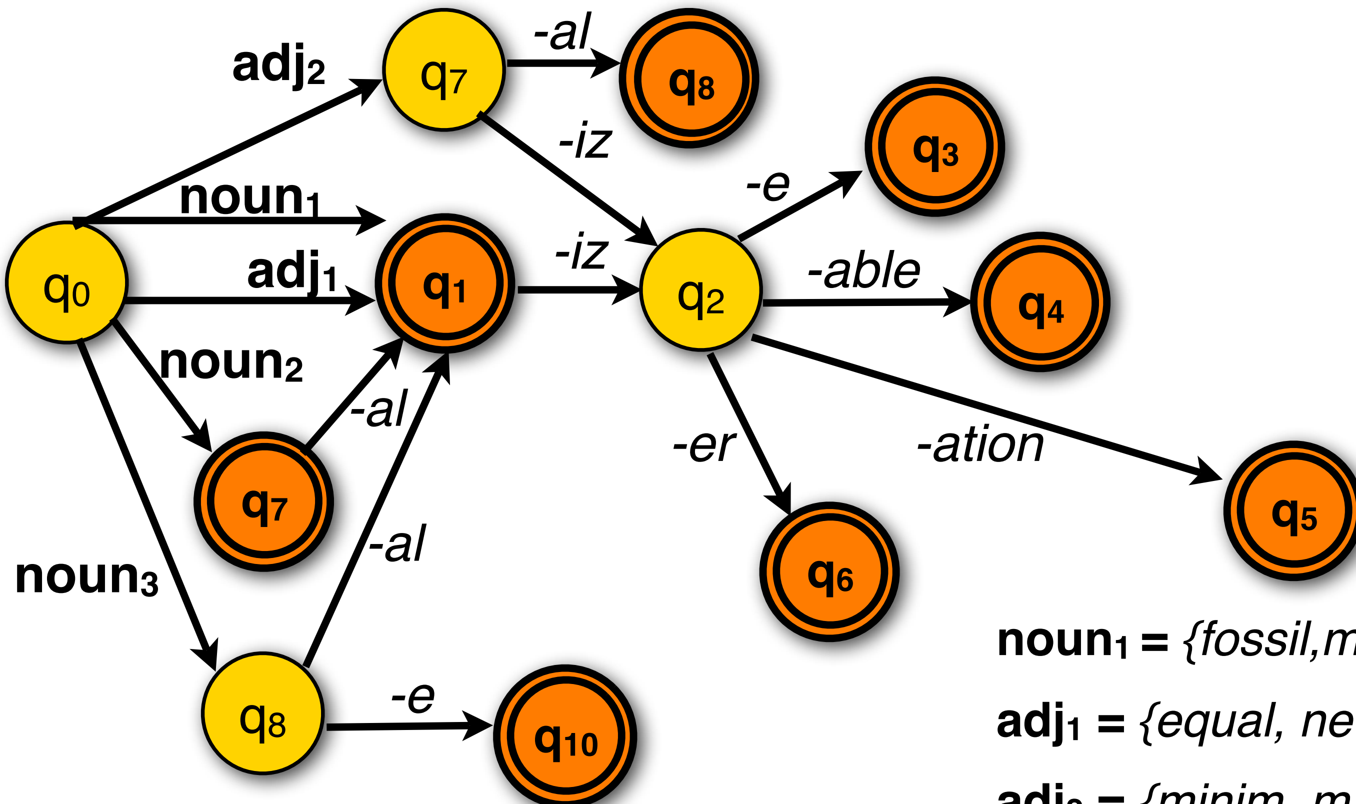
Some irregular words require stem changes:

- **Past tense verbs**:
  *teach-**taught**, go-**went**, write-**wrote***

- **Plural nouns**:
  *mouse-**mice**, foot-**feet**, wife-wi**ves***



FSAs for derivational morphology



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

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

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

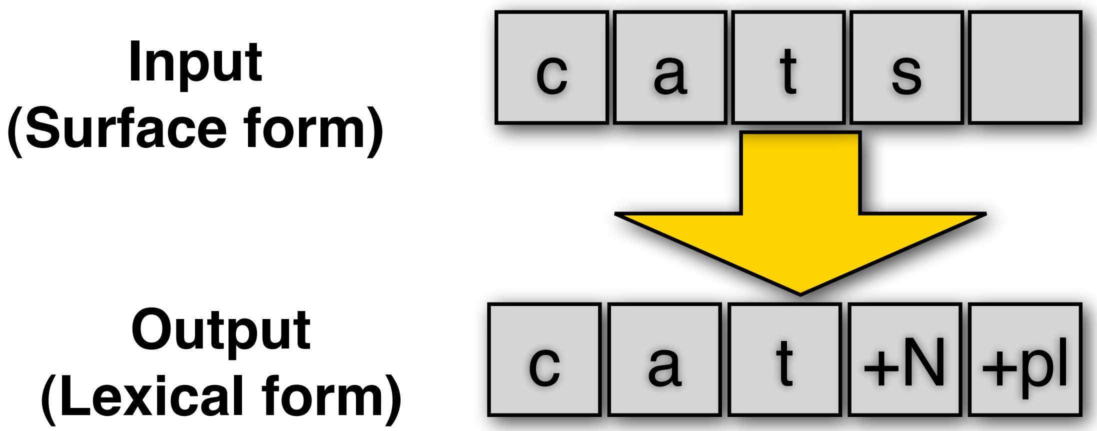
noun$_2$ = *{nation, form,…}*

noun$_3$ = *{natur, structur,…}*

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:



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. $\Delta = \{+N, +pl,...\}$)
- A designated **start state** $q_0 \in Q$
- A set of **final states** $F \subseteq Q$
- A **transition function** $\delta: Q \times \Sigma \rightarrow 2^Q$

  $\delta(q,w) = Q'$ for $q \in Q$, $Q' \subseteq Q$, $w \in \Sigma$
- **An output function** $\sigma: Q \times \Sigma \rightarrow \Delta^*$

  $\sigma(q,w) = \omega$ 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 define $\sigma: Q \times \Sigma^* \rightarrow \Delta^*$. Why is this equivalent?)

Finite-state transducers

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

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

$\boldsymbol{L_{out}}$ = {*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

English spelling (orthography) is funny:

The underlying morphemes (*plural-s*, etc.) can have different orthographic surface realizations (-s, -es)

Spelling changes at morpheme boundaries:

- **E insertion** fox +s = fox**e**s
- **E deletion** *mak**e** +ing = making*

Intermediate representations

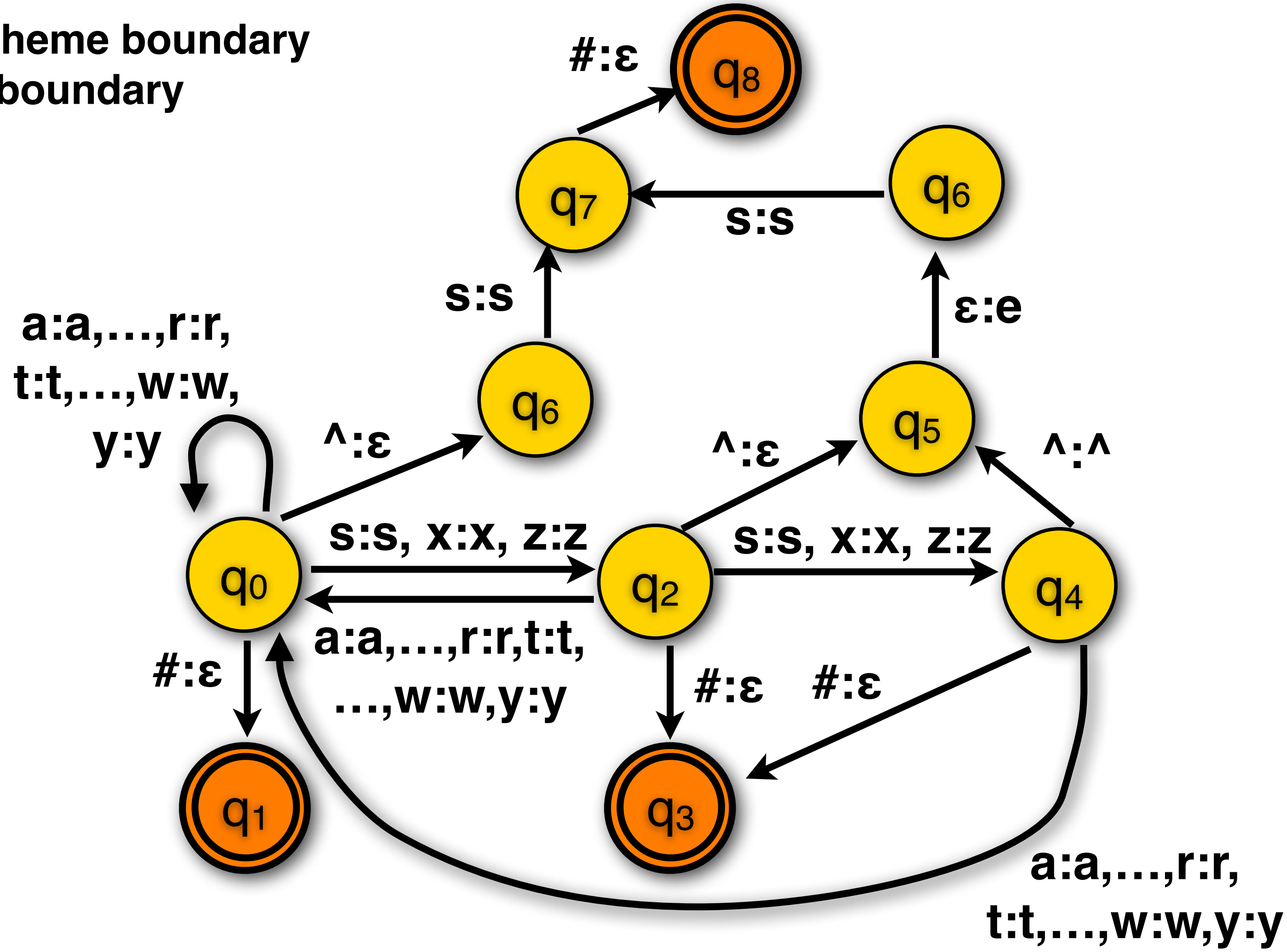
In order to capture these spelling rules,
we use an **intermediate level** which captures
morpheme boundaries (^) and word boundaries (#):

Lexicon: ***fox+N+PL*** ⇒ **Intermed.:** ***fox^s#*** ⇒ **Surface:** ***foxes***

Intermediate-to-Surface Spelling Rule:
If '***s***' follows a morpheme ending in '***x***', insert '***e***'

Intermediate to surface level

^ = morpheme boundary
# = word boundary



Dealing with ambiguity

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

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

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

ELIZA as a FST cascade

Human: *You don't argue with me.*
Computer: *WHY DO YOU THINK I DON'T ARGUE WITH YOU*

1. Replace **you** with ***I*** and ***me*** with ***you:***
   I don't argue with you.
2. Replace ***<...>*** with ***Why do you think <...>:***
   Why do you think I don't argue with you.

What about other NLP tasks?

Could we write an FST for machine translation?

What about compounds?

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.

Let's recap...

Today's key concepts

Automata theory (J&M chapter 2)

- Finite state automata and regular expressions
- Finite state transducers
- Composition of finite state transducers

Morphology (J&M chapter 3.1-6)

- Morphemes (stem/affix, bound/free)
- One morpheme may have many surface realizations (morph)
- Dealing with exceptions/irregularities
- Complex words can be formed by derivation, inflection or compounding