Finite State Transducers
Morphological Parsing & Tokenization

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(Based on slides by Jurafsky & Martin,
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Morphology:
What is a word?

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 have no blanks

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*

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 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) 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 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,...

Lexeme, Lemma, Stem, Root

- A **lexeme** is a unit of lexical meaning underlying a set of words that are related through inflection
- A **lemma** is a word that stands at the head of a definition in a dictionary.
- A **root** is the central (free) morpheme to which other bound morphemes are added to form a word.
- A **stem** is the portion of strings that are common in all the inflections of a word.
  - *reproduce, reproduces* and *reproducing* are forms of the same lexeme, for which
    - *reproduce* is the lemma.
    - *reproduc* is the stem.
    - *duce(?)* is the root.

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:

– Number: singular (book) vs. plural (books)
– Plural: books
– Possessive (~ genitive case): book's, 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

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*)

- *Infixes* are inserted inside the stem.
- *Circumfixes* (German gesehen) 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

There are many *irregular* word forms:

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

Morphemes are abstract categories

Examples: plural morpheme, past tense morpheme

The same morpheme (e.g. for plural nouns) can be realized as different surface forms (morphs):

-s/-es/-ren

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

Morphological parsing

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

Morphological generation

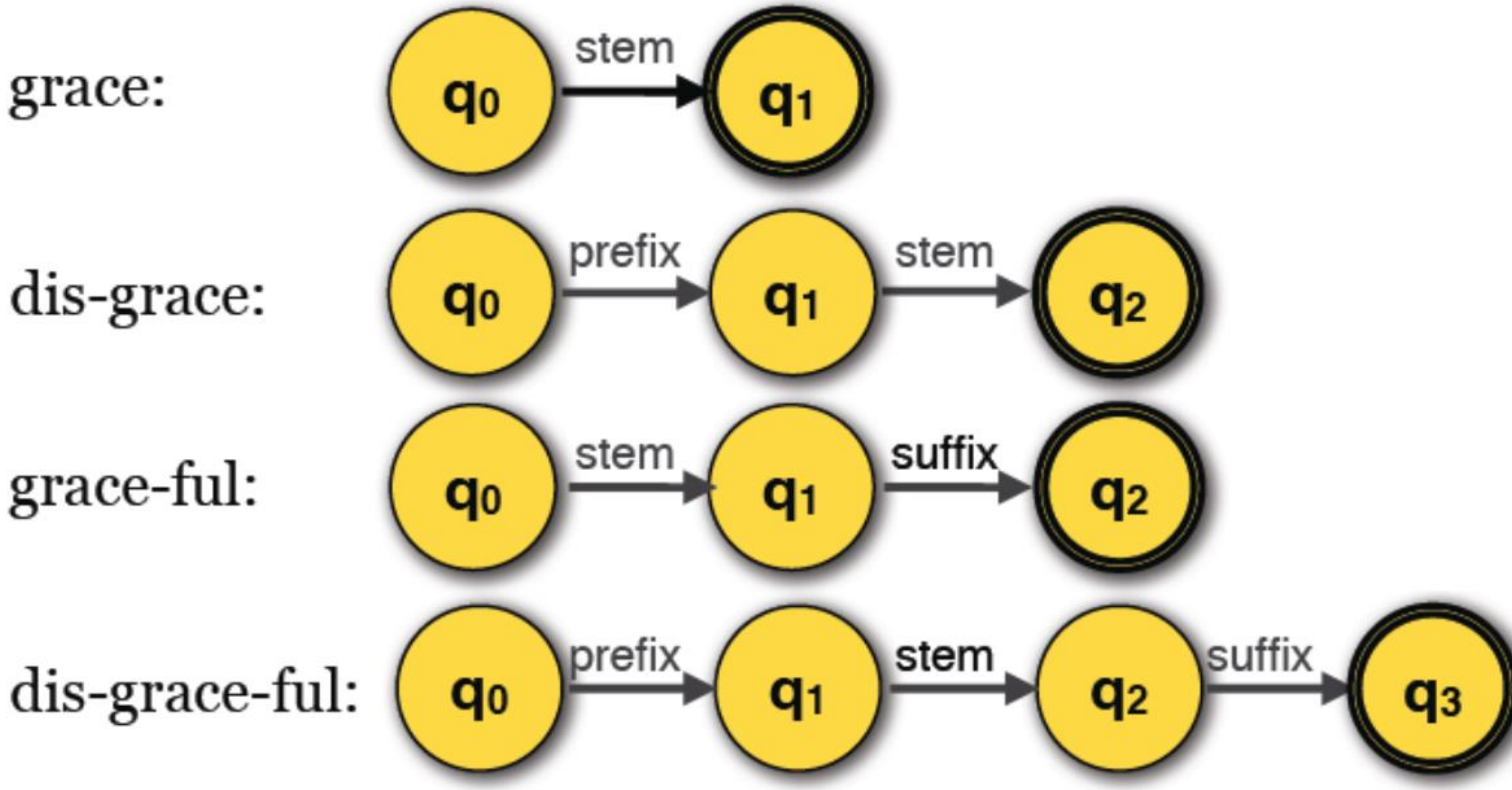
Generate possible English words:

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

Don't generate impossible English words:

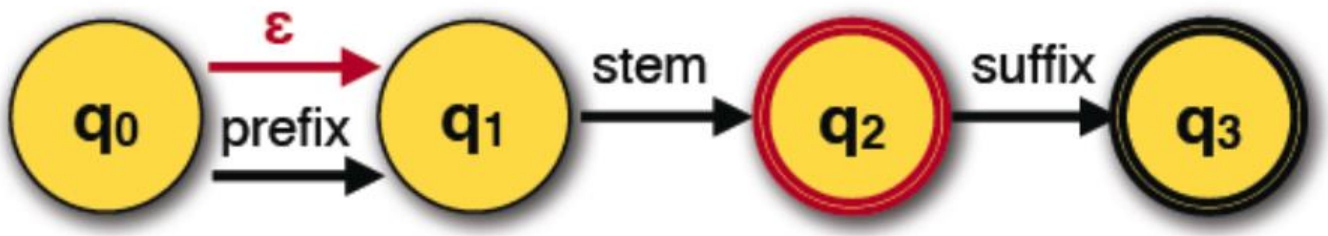
*gracelyful, *gracefuly, *disungracefully,...

Finite state automata for morphology



Union: merging automata

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

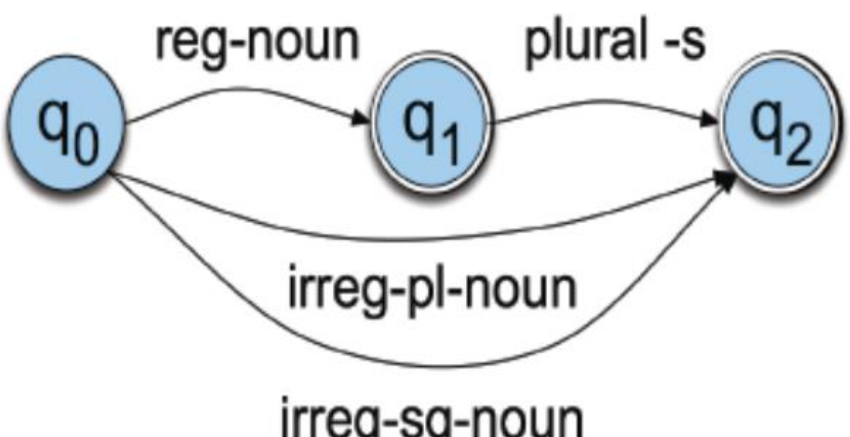


Stem changes

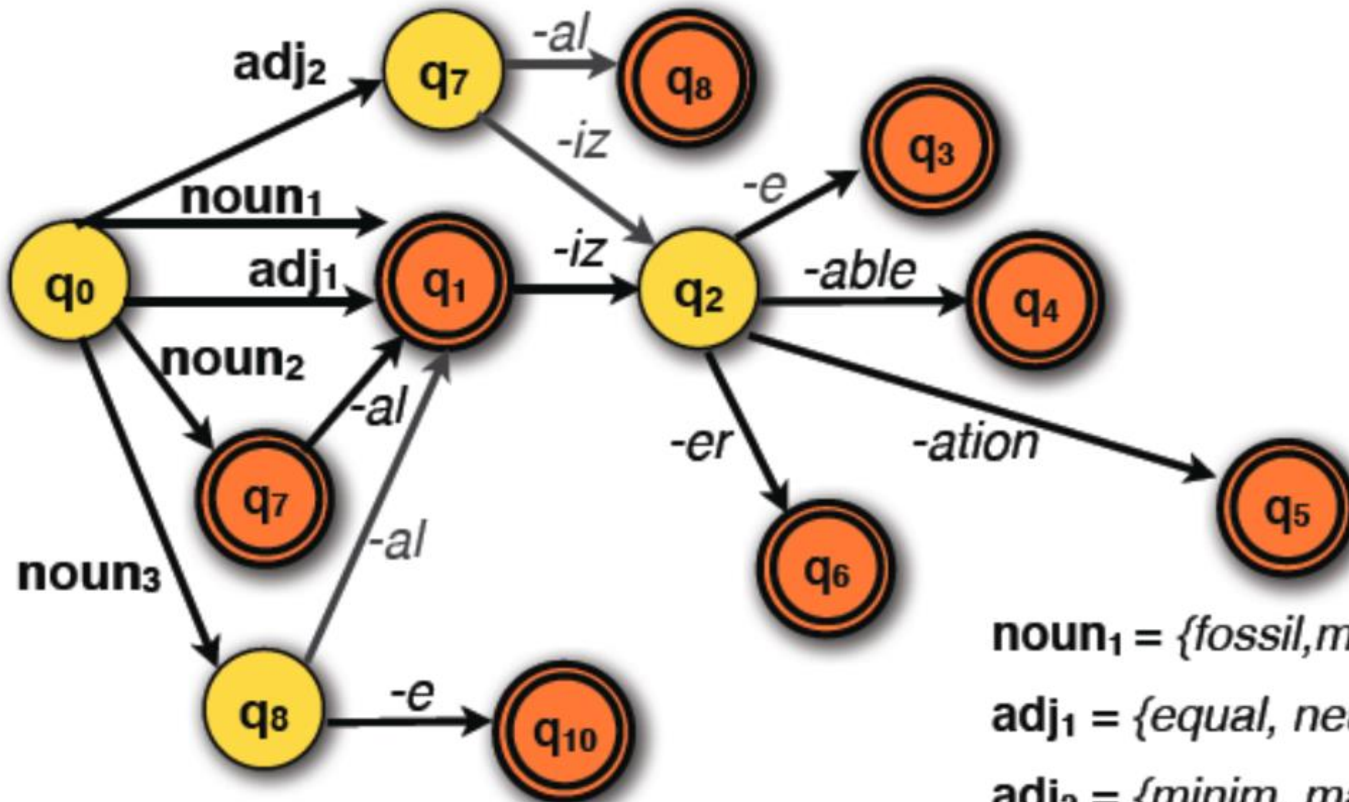
Some irregular words require stem changes:

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

Plural nouns:
mouse-mice, foot-feet, wife-wives



FSAs for derivational morphology



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

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

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

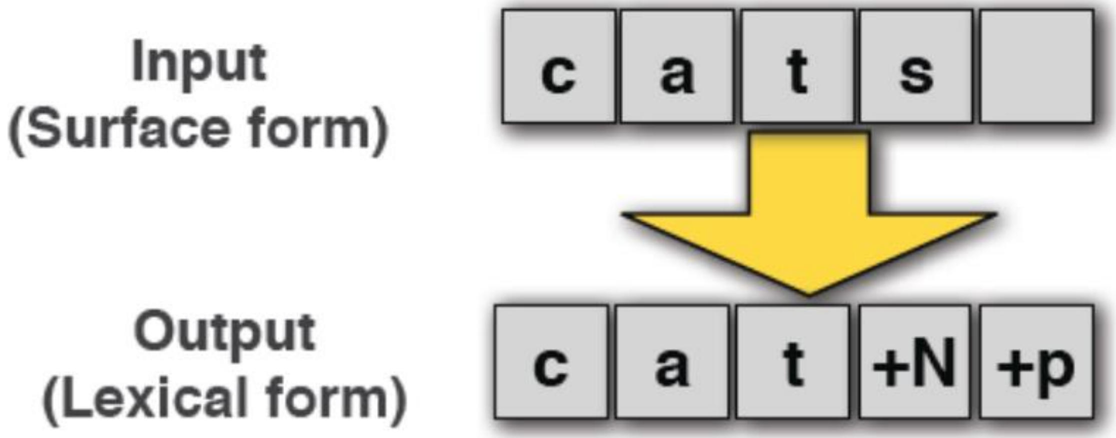
noun$_2$ **=** *{nation, form,…}*

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.

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

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

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

We define an intermediate representation which captures morpheme boundaries (^) and word boundaries (#):

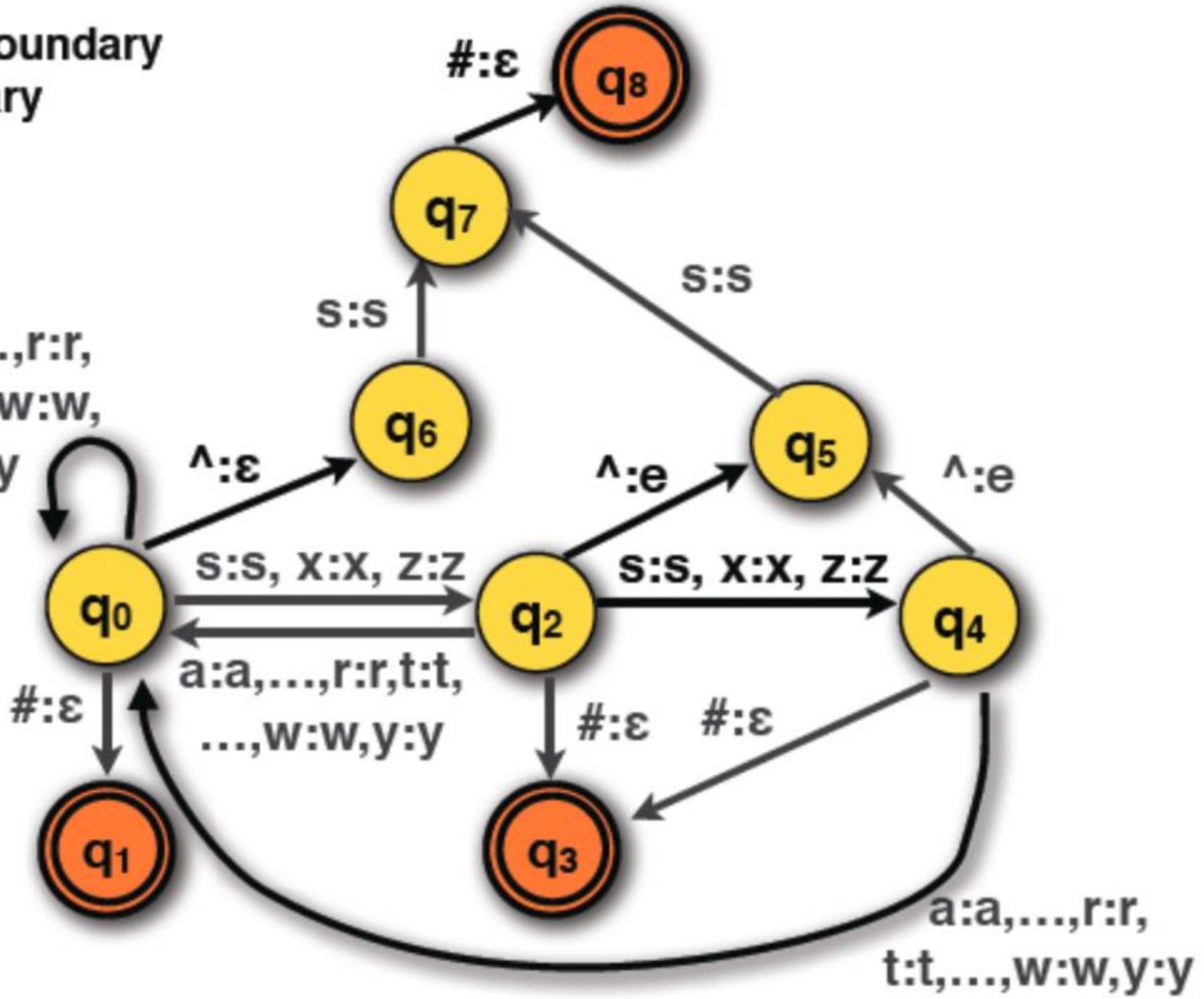
Lexicon:	***cat+N+PL***	***fox+N+PL***
⇒ *Intermediate representation:*	***cat^s#***	***fox^s#***
⇒ *Surface string:*	***cats***	***foxes***

Intermediate-to-Surface Spelling Rule:

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

FST: intermediate to surface level

^ = morpheme boundary
# = word boundary



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.

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

Practical Uses

- This kind of parsing is normally called morphological analysis
- Can be
  - An important stand-alone component of an application (spelling correction, information retrieval, part-of-speech tagging,…)
  - Or simply a link in a chain of processing (machine translation, parsing,…)

FST-based Tokenization

```
#!/usr/bin/perl

$letternumber = "[A-Za-z0-9]";
$notletter = "[^A-Za-z0-9]";
$alwayssep = "[\\?!()\";/\\|`]";
$clitic = "('|:|-|'S|'D|'M|'LL|'RE|'VE|N'T|'s|'d|'m|'ll|'re|'ve|n't)";

$abbr{"Co."} = 1; $abbr{"Dr."} = 1; $abbr{"Jan."} = 1; $abbr{"Feb."} = 1;

while ($line = <>){ # read the next line from standard input

    # put whitespace around unambiguous separators
    $line =~ s/$alwayssep/ $& /g;

    # put whitespace around commas that aren't inside numbers
    $line =~ s/([^0-9]),/$1 , /g;
    $line =~ s/,([^0-9])/ , $1/g;

    # distinguish singlequotes from apostrophes by
    # segmenting off single quotes not preceded by letter
    $line =~ s/^'/$& /g;
    $line =~ s/($notletter)'/$1 '/g;

    # segment off unambiguous word-final clitics and punctuation
    $line =~ s/$clitic$/ $&/g;
    $line =~ s/$clitic($notletter)/ $1 $2/g;

   # now deal with periods.  For each possible word
   @possiblewords=split(/\s+/,$line);
   foreach $word (@possiblewords) {
      # if it ends in a period,
      if (($word =~ /$letternumber\./)
             && !($abbr{$word})  # and isn't on the abbreviation list
                # and isn't a sequence of letters and periods (U.S.)
                # and doesn't resemble an abbreviation (no vowels: Inc.)
             && !($word =~
                 /^([A-Za-z]\.([A-Za-z]\.)+|[A-Z][bcdfghj-nptvxz]+\.)$/)) {
          # then segment off the period
          $word =~ s/\.$/ \./;
      }
      # expand clitics
      $word =~s/'ve/have/;
      $word =~s/'m/am/;
      print $word," ";
   }
 print "\n";
}
```

Porter Stemmer (1980)

- Common algorithm for stemming English

- Conventions + 5 phases of reductions
  - phases applied sequentially
  - each phase consists of a set of commands
  - sample convention: *Of the rules in a compound command, select the one that applies to the longest suffix.*

Porter Stemmer (1980)

- Standard, very popular and usable stemmer (IR, IE) – identify a word's stem
- Sequence of cascaded rewrite rules, e.g.
  - IZE → ε (e.g. unionize → union)
  - CY → T (e.g. frequency → frequent)
  - ING → ε , if stem contains vowel (motoring → motor)
- Can be implemented as a lexicon-free FST (many implementations available on the web)
- http://text-processing.com/demo/stem/

Eliza

User_1:	Men are all alike.
ELIZA_1:	IN WHAT WAY
User_2:	They're always bugging us about something or other.
ELIZA_2:	CAN YOU THINK OF A SPECIFIC EXAMPLE
User_3:	Well, my boyfriend made me come here.
ELIZA_3:	YOUR BOYFRIEND MADE YOU COME HERE
User_4:	He says I'm depressed much of the time.
ELIZA_4:	I AM SORRY TO HEAR YOU ARE DEPRESSED

Eliza FST

```
s/.* I'M (depressed|sad) .*/I AM SORRY TO HEAR YOU ARE \1/
s/.* I AM (depressed|sad) .*/WHY DO YOU THINK YOU ARE \1/
s/.* all .*/IN WHAT WAY/
s/.* always .*/CAN YOU THINK OF A SPECIFIC EXAMPLE/
```

RelNoun: Nominal Open IE

Constructions	**Phrase**	**Extraction**
Verb1	Francis Collins is the director of NIH	(Francis Collins; is the director of; NIH)
Verb2	the director of NIH is Francis Collins	(Francis Collins; is the director of; NIH)
Appositive1	Francis Collins, the director of NIH	(Francis Collins; [is] the director of; NIH)
Appositive2	the director of NIH, Francis Collins,	(Francis Collins; [is] the director of; NIH)
Appositive3	Francis Collins, the NIH director	(Francis Collins; [is] the director [of]; NIH)
AppositiveTitle	Francis Collins, the director,	(Francis Collins; [is]; the director)
CompoundNoun	*NIH director Francis Collins*	*(Francis Collins; [is] director [of]; NIH)*
Possessive	NIH's director Francis Collins	(Francis Collins; [is] director [of]; NIH)
PossessiveAppositive	NIH's director, Francis Collins	(Francis Collins; [is] director [of]; NIH)
AppositivePossessive	Francis Collins, NIH's director	(Francis Collins; [is] director [of]; NIH)
PossessiveVerb	NIH's director is Francis Collins	(Francis Collins; is director [of]; NIH)
VerbPossessive	Francis Collins is NIH's director	(Francis Collins; is director [of]; NIH)

Compound Noun Extraction Baseline

- NIH Director Francis Collins

  (Francis Collins, is the Director of, NIH)

- Challenges
  - New York Banker Association — ORG NAMES
  - German Chancellor Angela Merkel — DEMONYMS
  - Prime Minister Modi — COMPOUND RELATIONAL NOUNS
  - GM Vice Chairman Bob Lutz

Rule-Based System

- Classifies and filters orgs
- List of demonyms
  - appropriate location conversion
- Bootstrap a list of relational noun *prefixes*
  - vice, ex, health, …

Summing Up

- Regular expressions and FSAs can represent subsets of natural language as well as regular languages
  - Both representations may be difficult for humans to use for any real subset of a language
  - But quick, powerful and easy to use for small problems

- Finite state transducers and rules are common ways to incorporate linguistic ideas in NLP for small applications

- Particularly useful for no data setting