Chapter 3. Morphology and Finite-State Transducers

From: Chapter 3 of *An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition,* by Daniel Jurafsky and James H. Martin

Background

- The problem of recognizing that *foxes* breaks down into the two morphemes *fox* and *-es* is called ***morphological parsing***.
- Similar problem in the information retrieval domain: ***stemming***
- Given the **surface** or **input form** *going*, we might want to produce the parsed form: `VERB-go + GERUND-ing`
- In this chapter
  - morphological knowledge and
  - The **finite-state transducer**
- It is quite inefficient to list all forms of noun and verb in the dictionary because the productivity of the forms.
- Morphological parsing is necessary more than just IR, but also
  - Machine translation
  - Spelling checking

Survey of (Mostly) English Morphology

- Morphology is the study of the way words are built up from smaller meaning-bearing units, **morphemes**.
- Two broad classes of morphemes:
  - **The stems:** the "main" morpheme of the word, supplying the main meaning, while
  - **The affixes:** add "additional" meaning of various kinds.
- Affixes are further divided into **prefixes**, **suffixes**, **infixes**, and **circumfixes**.
  - Suffix: *eat-s*
  - Prefix: *un-buckle*
  - Circumfix: *ge-sag-t* (said) *sagen* (to say) (in German)
  - Infix: *hingi* (borrow) ***h**um**ingi*** (the agent of an action))in Philippine language Tagalog)

Survey of (Mostly) English Morphology

- Prefixes and suffixes are often called **concatenative morphology.**
- A number of languages have extensive **non-concatenative morphology**
  - The Tagalog infixation example
  - **Templatic morphology** or **root-and-pattern morphology**, common in Arabic, Hebrew, and other Semitic languages
- Two broad classes of ways to form words from morphemes:
  - **Inflection:** the combination of a word stem with a grammatical morpheme, usually resulting in a word of the same class as the original tem, and usually filling some syntactic function like agreement, and
  - **Derivation**: the combination of a word stem with a grammatical morpheme, usually resulting in a word of a *different* class, often with a meaning hard to predict exactly.

Survey of (Mostly) English Morphology
Inflectional Morphology

- In English, only nouns, verbs, and sometimes adjectives can be inflected, and the number of affixes is quite small.
- Inflections of nouns in English:
  - An affix marking **plural**,
    - `cat(-s), thrush(-es), ox (oxen), mouse (mice)`
    - `ibis(-es), waltz(-es), finch(-es), box(-es), butterfly(-lies)`
  - An affix marking **possessive**
    - `llama’s, children’s, llamas’, Euripides’ comedies`

Survey of (Mostly) English Morphology
Inflectional Morphology

- Verbal inflection is more complicated than nominal inflection.
  – English has three kinds of verbs:
    - **Main verbs**, *eat*, *sleep*, *impeach*
    - **Modal verbs**, *can will, should*
    - **Primary verbs**, *be, have, do*
  – Morphological forms of regular verbs

stem	walk	merge	try	map
-*s* form	walks	merges	tries	maps
-*ing* principle	walking	merging	trying	mapping
Past form or –*ed* participle	walked	merged	tried	mapped

  – These regular verbs and forms are significant in the morphology of English because of their *majority* and being *productive*.

Survey of (Mostly) English Morphology
Inflectional Morphology

– Morphological forms of irregular verbs

stem	eat	catch	cut
-*s* form	eats	catches	cuts
-*ing* principle	eating	catching	cutting
Past form	ate	caught	cut
–*ed* participle	eaten	caught	cut

Survey of (Mostly) English Morphology
Derivational Morphology

- **Nominalization** in English:
  - The formation of new nouns, often from verbs or adjectives

Suffix	Base Verb/Adjective	Derived Noun
-action	computerize (V)	computerization
-ee	appoint (V)	appointee
-er	kill (V)	killer
-ness	fuzzy (A)	fuzziness

  - Adjectives derived from nouns or verbs

Suffix	Base Noun/Verb	Derived Adjective
-al	computation (N)	computational
-able	embrace (V)	embraceable
-less	clue (A)	clueless

Survey of (Mostly) English Morphology

Derivational Morphology

- Derivation in English is more complex than inflection because
  - Generally less productive
    - A nominalizing affix like –*ation* can not be added to absolutely every verb. *eatation*(*)
  - There are subtle and complex meaning differences among nominalizing suffixes. For example, *sincerity* has a subtle difference in meaning from *sincereness*.

Finite-State Morphological Parsing

- Parsing English morphology

Input	Morphological parsed output
cats	cat +N +PL
cat	cat +N +SG
cities	city +N +PL
geese	goose +N +PL
goose	(goose +N +SG) or (goose +V)
gooses	goose +V +3SG
merging	merge +V +PRES-PART
caught	(caught +V +PAST-PART) or (catch +V +PAST)

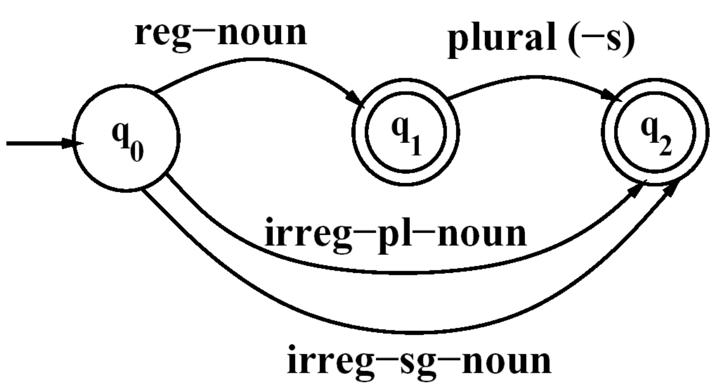
Finite-State Morphological Parsing

- We need at least the following to build a morphological parser:
  1. **Lexicon**: the list of stems and affixes, together with basic information about them (Noun stem or Verb stem, etc.)
  2. **Morphotactics**: the model of morpheme ordering that explains which classes of morphemes can follow other classes of morphemes inside a word. E.g., the rule that English plural morpheme follows the noun rather than preceding it.
  3. **Orthographic rules**: these **spelling rules** are used to model the changes that occur in a word, usually when two morphemes combine (e.g., the *y→ie* spelling rule changes *city* + *-s* to *cities*).

Finite-State Morphological Parsing

The Lexicon and Morphotactics

- A lexicon is a repository for words.
  - The simplest one would consist of an explicit list of every word of the language. ***Incovenient or impossible!***
  - Computational lexicons are usually structured with
    - a list of each of the stems and
    - Affixes of the language together with a representation of morphotactics telling us how they can fit together.
  - The most common way of modeling morphotactics is the finite-state automaton.

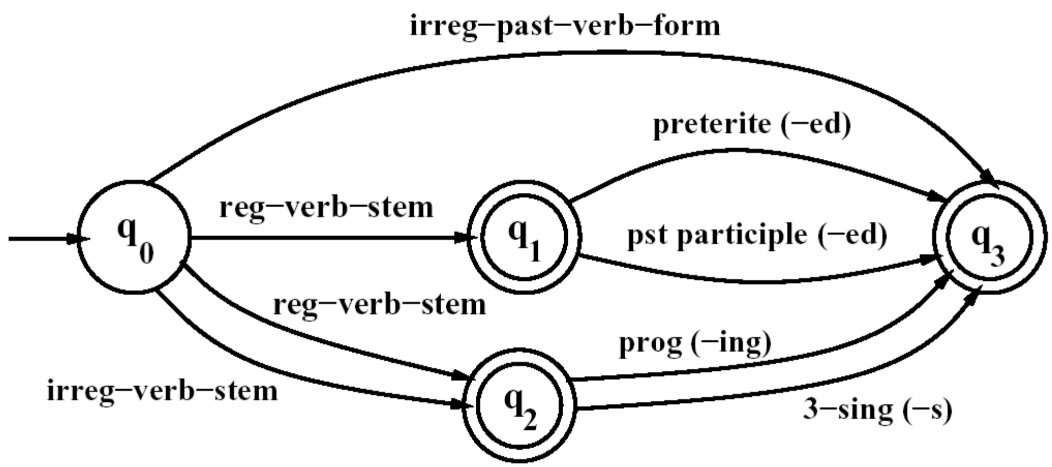


An FSA for English nominal inflection

Reg-noun	Irreg-pl-noun	Irreg-sg-noun	plural
fox fat fog fardvark	geese sheep Mice	goose sheep mouse	-s

Finite-State Morphological Parsing

The Lexicon and Morphotactics



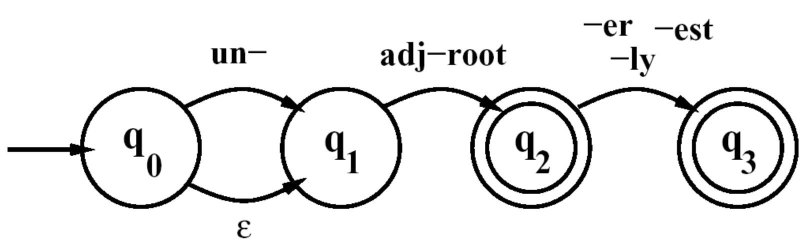
An FSA for English verbal inflection

Reg-verb-stem	Irreg-verb-stem	Irreg-past-verb	past	Past-part	Pres-part	3sg
walk fry talk impeach	cut speak sing sang spoken	caught ate eaten	-ed	-ed	-ing	-s

Finite-State Morphological Parsing

The Lexicon and Morphotactics

- English derivational morphology is more complex than English inflectional morphology, and so automata of modeling English derivation tends to be quite complex.
  - Some even based on CFG
- A small part of morphosyntactics of English adjectives

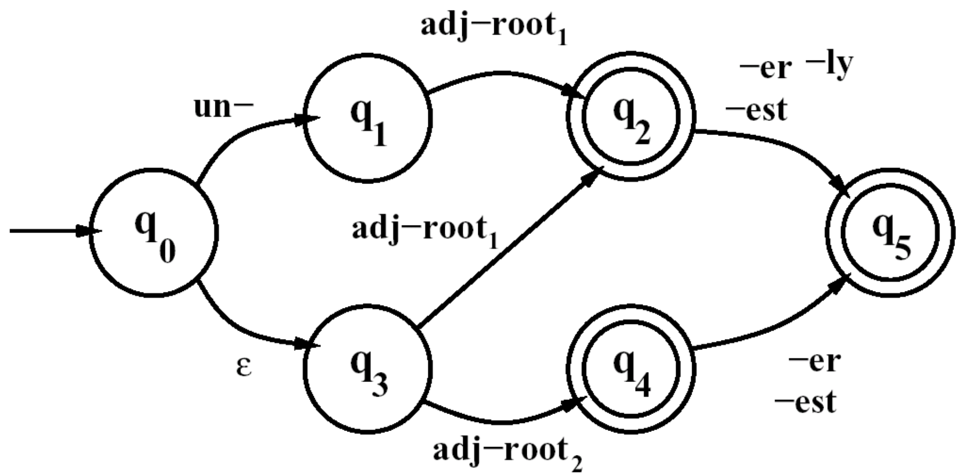


An FSA for a fragment of English adjective Morphology #1

big, bigger, biggest
cool, cooler, coolest, coolly
red, redder, reddest
clear, clearer, clearest, clearly, unclear, unclearly
happy, happier, happiest, happily
unhappy, unhappier, unhappiest, unhappily
real, unreal, really

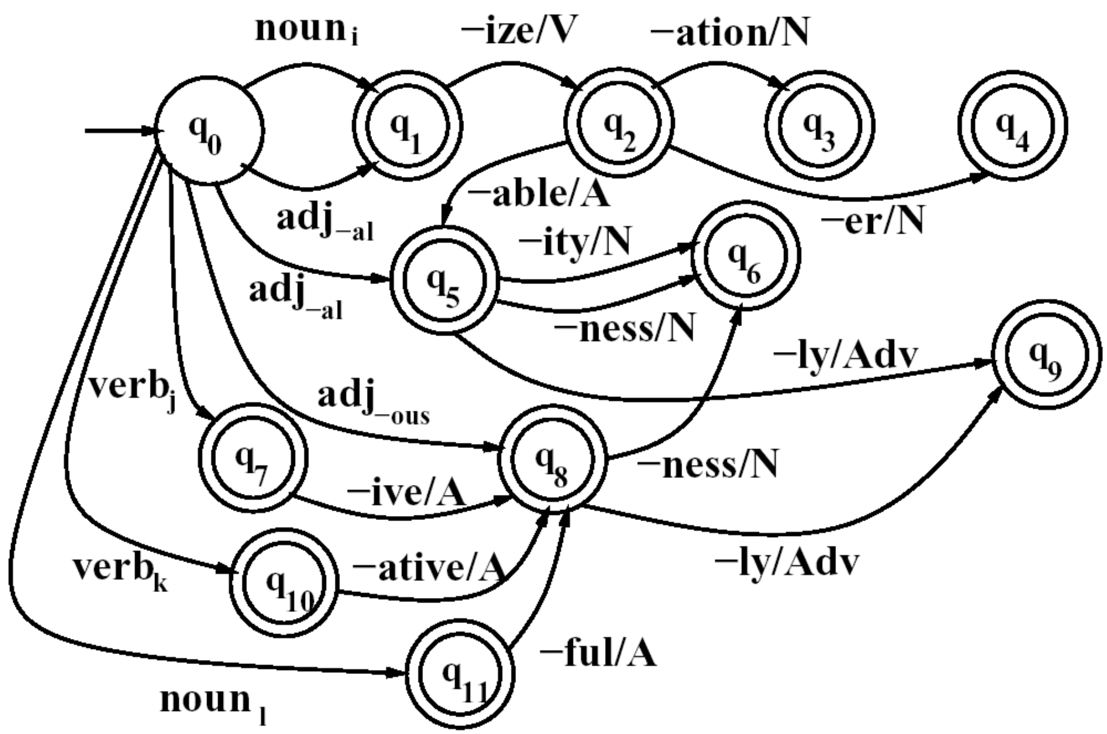
Finite-State Morphological Parsing

- The FSA#1 recognizes all the listed adjectives, and ungrammatical forms like *unbig, redly,* and *realest.*
- Thus #1 is revised to become #2.
- The complexity is expected from English derivation.



An FSA for a fragment of English adjective Morphology #2

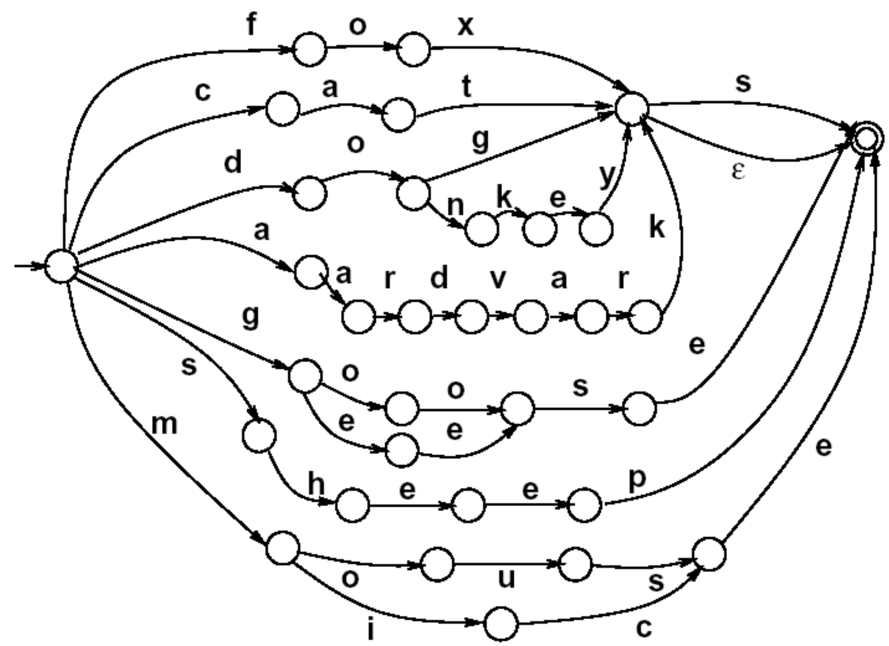
Finite-State Morphological Parsing



An FSA for another fragment of English derivational morphology

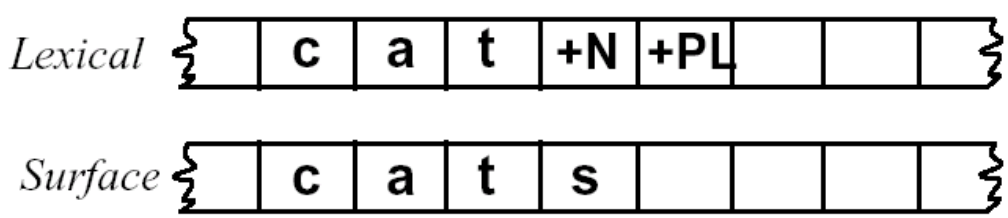
Finite-State Morphological Parsing

- We can now use these FSAs to solve the problem of **morphological recognition**:
  - Determining whether an input string of letters makes up a legitimate English word or not
  - We do this by taking the morphotactic FSAs, and plugging in each "sub-lexicon" into the FSA.
  - The resulting FSA can then be defined as the level of the individual letter.



Finite-State Morphological Parsing
Morphological Parsing with FST

- Given the input, for example, *cats*, we would like to produce `cat +N +PL`.
- Two-level morphology, by Koskenniemi (1983)
  - Representing a word as a correspondence between a **lexical level**
    - Representing a simple concatenation of morphemes making up a word, and
  - The **surface level**
    - Representing the actual spelling of the final word.
- Morphological parsing is implemented by building mapping rules that maps letter sequences like *cats* on the surface level into morpheme and features sequence like `cat +N +PL` on the lexical level.



Finite-State Morphological Parsing

Morphological Parsing with FST

- The automaton we use for performing the mapping between these two levels is the **finite-state transducer** or **FST**.
  - A transducer maps between one set of symbols and another;
  - An FST does this via a finite automaton.
- Thus an FST can be seen as a two-tape automaton which **recognizes** or **generates** ***pairs*** of strings.
- The FST has a more general function than an FSA:
  - An FSA defines a formal language
  - An FST defines a relation between sets of strings.
- Another view of an FST:
  - A machine reads one string and generates another.

Finite-State Morphological Parsing

Morphological Parsing with FST

- **FST as recognizer:**
  - a transducer that takes a pair of strings as input and output *accept* if the string-pair is in the string-pair language, and a *reject* if it is not.
- **FST as generator:**
  - a machine that outputs pairs of strings of the language. Thus the output is a yes or no, and a pair of output strings.
- **FST as transducer:**
  - A machine that reads a string and outputs another string.
- **FST as set relater:**
  - A machine that computes relation between sets.

Finite-State Morphological Parsing

Morphological Parsing with FST

- A formal definition of FST (based on the **Mealy machine** extension to a simple FSA):
  - Q: a finite set of N states $q_0, q_1, \ldots, q_N$
  - Σ: a finite alphabet of complex symbols. Each complex symbol is composed of an input-output pair $i : o$; one symbol I from an input alphabet I, and one symbol o from an output alphabet O, thus $\Sigma \subseteq I \times O$. I and O may each also include the epsilon symbol ε.
  - q_0: the start state
  - F: the set of final states, $F \subseteq Q$
  - $\delta(q, i{:}o)$: the transition function or transition matrix between states. Given a state $q \in Q$ and complex symbol $i{:}o \in \Sigma$, $\delta(q, i{:}o)$ returns a new state q' $\in Q$. δ is thus a relation from $Q \times \Sigma$ to Q.

Finite-State Morphological Parsing

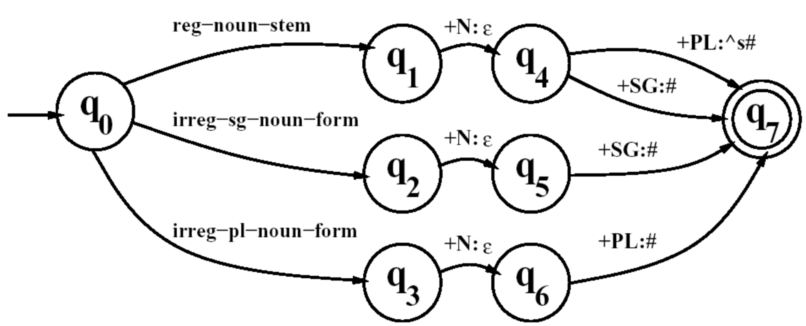
Morphological Parsing with FST

- FSAs are isomorphic to regular languages, FSTs are isomorphic to **regular relations.**
- Regular relations are sets of pairs of strings, a natural extension of the regular language, which are sets of strings.
- FSTs are closed under union, but generally they are not closed under difference, complementation, and intersection.
- Two useful closure properties of FSTs:
  - **Inversion:** If T maps from I to O, then the inverse of T, T^{-1} maps from O to I.
  - **Composition:** If T_1 is a transducer from I_1 to O_1 and T_2 a transducer from I_2 to O_2, then $T_1 \circ T_2$ maps from I_1 to O_2

Finite-State Morphological Parsing

Morphological Parsing with FST

- Inversion is useful because it makes it easy to convert a FST-as-parser into an FST-as-generator.
- Composition is useful because it allows us to take two transducers than run in series and replace them with one complex transducer.
  - $T_1 \circ T_2(S) = T_2(T_1(S))$

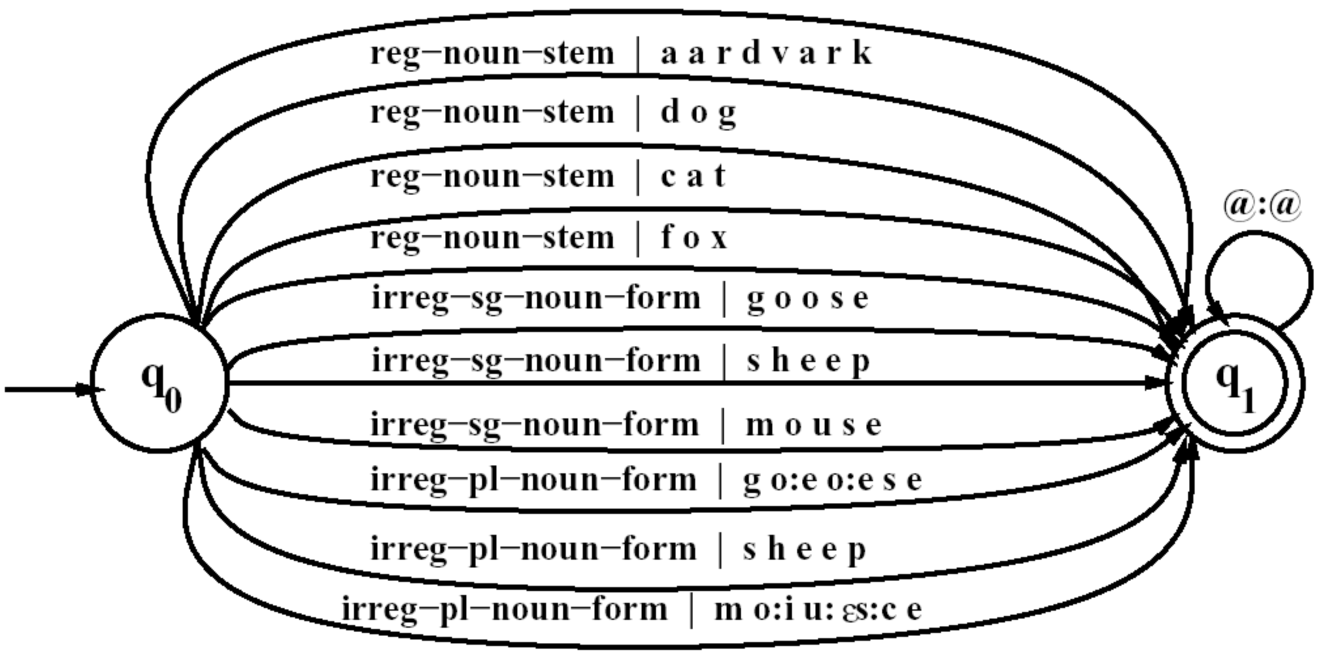


A transducer for English nominal number inflection T_{num}

Reg-noun	**Irreg-pl-noun**	**Irreg-sg-noun**
fox	g o:e o:e s e	goose
fat	sheep	sheep
fog	m o:i u:εs:c e	mouse
aardvark		

Finite-State Morphological Parsing

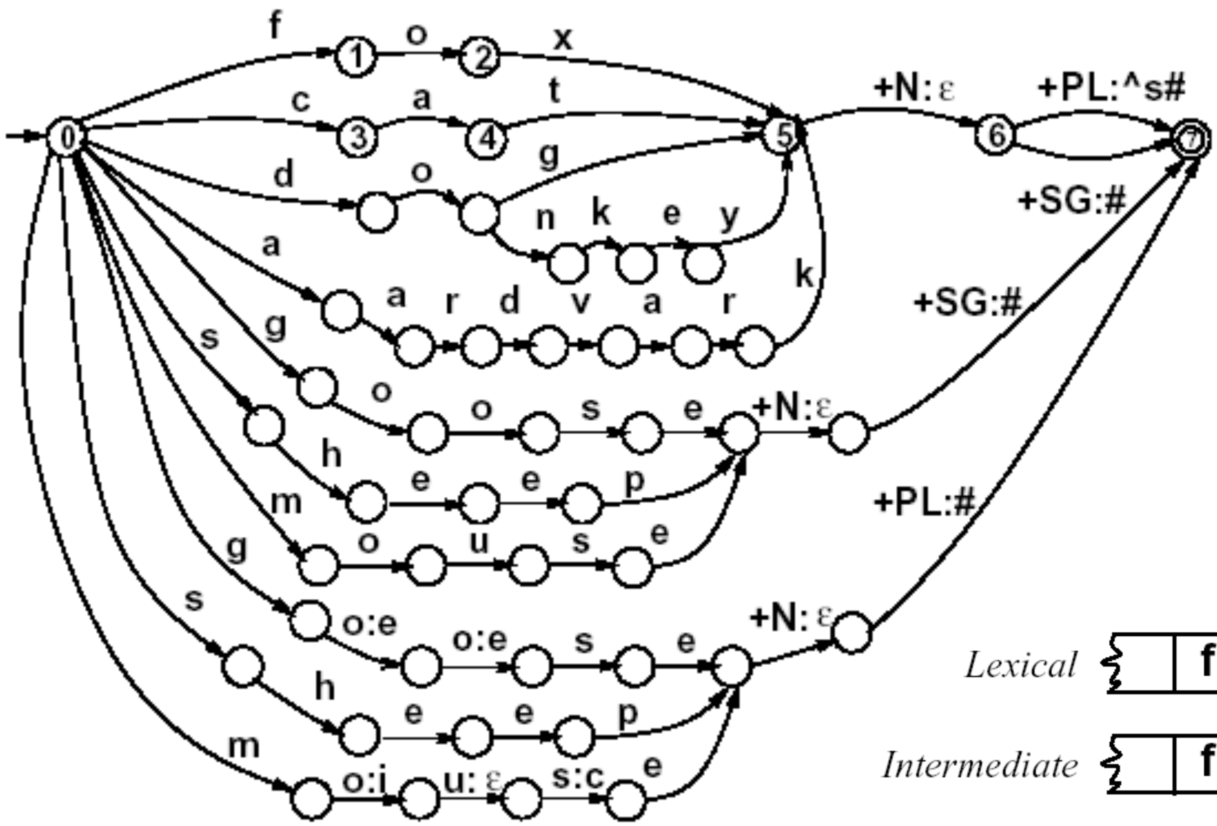
Morphological Parsing with FST



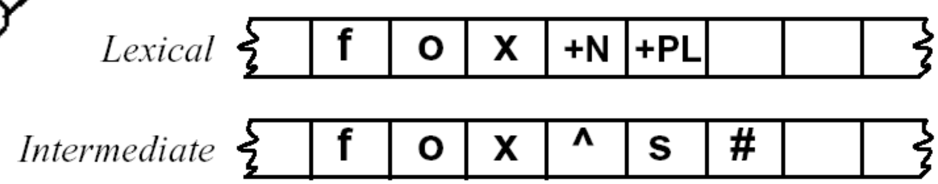
The transducer T_{stems}, which maps roots to their root-class

Finite-State Morphological Parsing

Morphological Parsing with FST



^: morpheme boundary
#: word boundary



A fleshed-out English nominal inflection FST

$T_{lex} = T_{num} \circ T_{stems}$

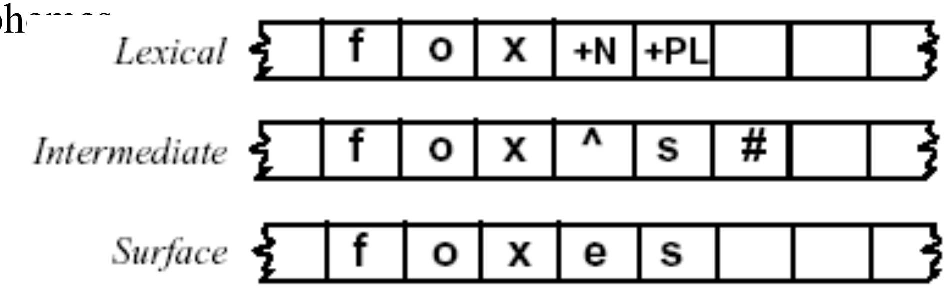
Finite-State Morphological Parsing

Orthographic Rules and FSTs

- **Spelling rules** (or **orthographic rules**)

Name	**Description of Rule**	**Example**
Consonant doubling	1-letter consonant doubled before *-ing/-ed*	beg/begging
E deletion	Silent e dropped before *-ing* and *-ed*	make/making
E insertion	e added after *-s*, *-z*, *-x*, *-ch*, *-sh*, before *-s*	watch/watches
Y replacement	*-y* changes to *-ie* before *-s*, *-i* before *-ed*	try/tries
K insertion	Verb ending with *vowel* + *-c* add *-k*	panic/panicked

  – These spelling changes can be thought as taking as input a simple concatenation of morphemes and producing as output a slightly-modified concatenation of morphemes.



Finite-State Morphological Parsing

Orthographic Rules and FSTs

- "insert an *e* on the surface tape just when the lexical tape has a morpheme ending in *x* (or *z,* etc) and the next morphemes is -*s*"

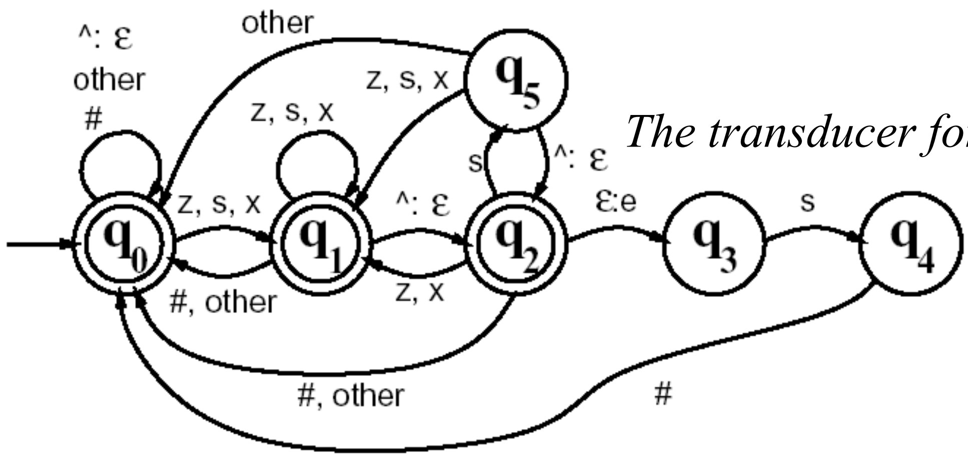
$$\varepsilon \rightarrow e / \left\{ \begin{array}{c} x \\ s \\ z \end{array} \right\} \_\_ \; s\#$$

- "rewrite *a* to *b* when it occurs between *c* and *d*"

$$a \rightarrow b \, / \, c \, \_\_ \, d$$

Finite-State Morphological Parsing

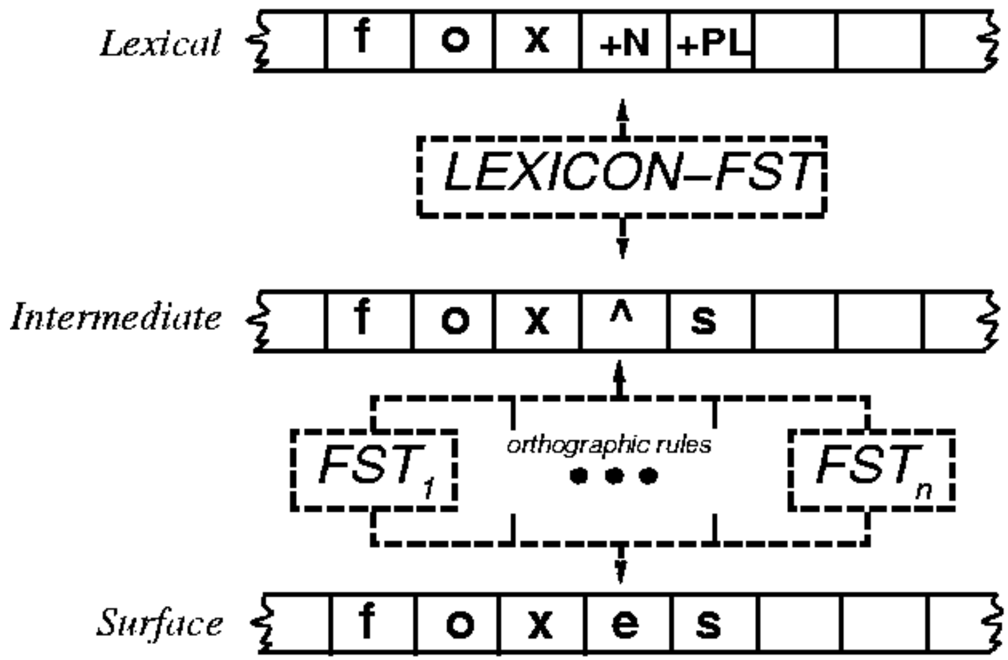
Orthographic Rules and FSTs



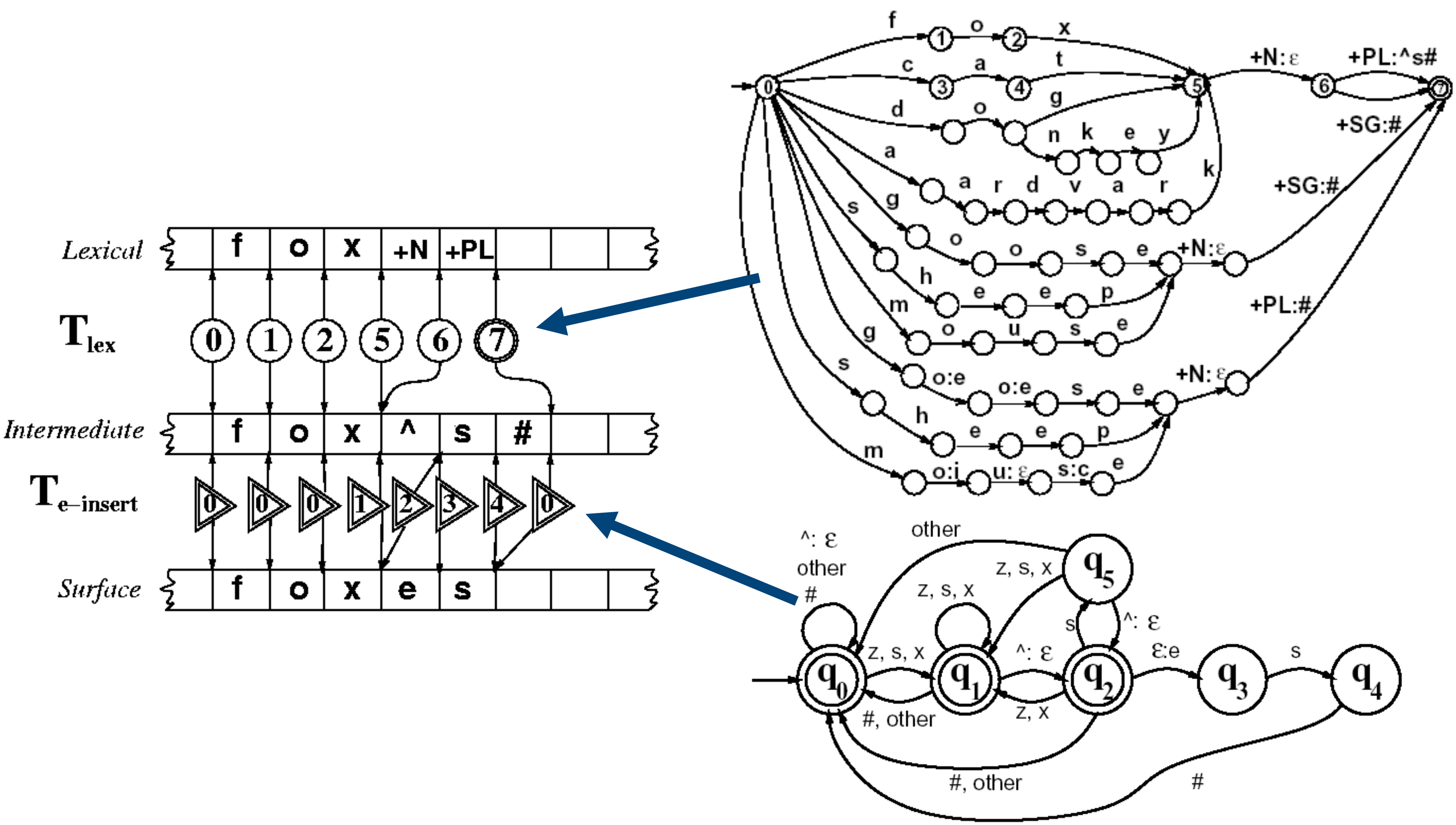
The transducer for the E-insertion rule

State\Input	s:s	x:x	z:z	^:ε	ε:e	#	other
q_0:	1	1	1	0	-	0	0
q_1:	1	1	1	2	-	0	0
q_2:	5	1	1	0	3	0	0
q_3	4	-	-	-	-	-	-
q_4	-	-	-	-	-	0	-
q_5	1	1	1	2	-	-	0

Combining FST Lexicon and Rules



Combining FST Lexicon and Rules



Combining FST Lexicon and Rules

- The power of FSTs is that the exact same cascade with the same state sequences is used
  - when machine is generating the surface form from the lexical tape, or
  - When it is parsing the lexical tape from the surface tape.
- Parsing can be slightly more complicated than generation, because of the problem of **ambiguity.**
  - For example, *foxes* could be `fox +V +3SG` as well as `fox +N +PL`

Lexicon-Free FSTs: the Porter Stemmer

- Information retrieval
- One of the mostly widely used **stemmming** algorithms is the simple and efficient Porter (1980) algorithm, which is based on a series of simple cascaded rewrite rules.
  - ATIONAL → ATE (e.g., relational → relate)
  - ING → εif stem contains vowel (e.g., motoring → motor)
- Problem:
  - Not perfect: error of commision, omission
- Experiments have been made
  - Some improvement with smaller documents
  - Any improvement is quite small