CMPT 413
Computational Linguistics

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Finite-state transducers

- Many applications in computational linguistics
- Popular applications of FSTs are in:
  - Orthography
  - Morphology
  - Phonology
- Other applications include:
  - Grapheme to phoneme
  - Text normalization
  - Transliteration
  - Edit distance
  - Word segmentation
  - Tokenization
  - Parsing

Orthography and Phonology

- Orthography: written form of the language (affected by morpheme combinations)

  move + ed → moved

  swim + ing → swimming S W IH1 M IH0 NG

- Phonology: change in pronunciation due to morpheme combinations (changes may not be confined to morpheme boundary)

  intent IH2 N T EH1 N T + ion

  → intention IH2 N T EH1 N CH AH0 N

Orthography and Phonology

- Phonological alternations are not reflected in the spelling (orthography):
  - Newton Newtonian
  - maniac maniacal
  - electric electricity
- Orthography can introduce changes that do not have any counterpart in phonology:
  - picnic picnicking
  - happy happiest
  - gooey gooiest

Segmentation and Orthography

- To find entries in the lexicon we need to segment any input into morphemes
- Looks like an easy task in some cases:

  looking → look + ing

  rethink → re + think
- However, just matching an affix does not work:

  **thing* → th + ing

  **read* → re + ad
- We need to store valid stems in our lexicon

  what is the stem in *assassination* (*assassin* and not *nation*)

Porter Stemmer

- A simpler task compared to segmentation is simply stripping out all affixes (a process called **stemming**, or finding the stem)
- Stemming is usually done without reference to a lexicon of valid stems
- The Porter stemming algorithm is a simple composition of FSTs, each of which strips out some affix from the input string
  - input=..*ational*, produces output=..*ate* (*relational* → *relate*)
  - input=..V..*ing*, produces output=ε (*motoring* → *motor*)

Porter Stemmer

- False positives (stemmer gives incorrect stem): *doing* → *doe*, *policy* → *police*
- False negatives (should provide stem but does not): *European* → *Europe*, *matrices* → *matrix*

I'm a rageaholic. *I can't live without rageahol*.

Homer Simpson, from *The Simpsons*

- Despite being linguistically unmotivated, the Porter stemmer is used widely due to its simplicity (easy to implement) and speed

Segmentation and orthography

- More complex cases involve alterations in spelling

  foxes → fox + s [***e*-insertion**]

  loved → love + ed [***e*-deletion**]

  flies → fly + s [***i* to *y*, *e*-deletion**]

  panicked → panic + ed [**k-insertion**]

  chugging → chug + ing [**consonant doubling**]

  **singging* → sing + ing

  impossible → in + possible [***n* to *m***]
- Called *morphographemic* changes.
- Similar to but not identical to changes in pronunciation due to morpheme combinations

Morphological Parsing with FSTs

- Think of the process of decomposing a word into its component morphemes in the reverse direction: as *generation* of the word from the component morphemes
- Start with an abstract notion of each morpheme being simply combined with the stem using concatenation
  - Each stem is written with its part of speech, e.g. cat+N
  - Concatenate each stem with some suffix information, e.g. cat+N+PL
  - e.g. cat+N+PL goes through an FST to become *cats* (also works in reverse!)

Morphological Parsing with FSTs

- Retain simple morpheme combinations with the stem by using an intermediate representation:
  - e.g. cat+N+PL becomes *cat^s#*
- Separate rules for the various spelling changes. Each spelling rule is a different FST
- Write down a separate FST for each spelling rule

foxes → fox^s# [***e*-insertion FST**]

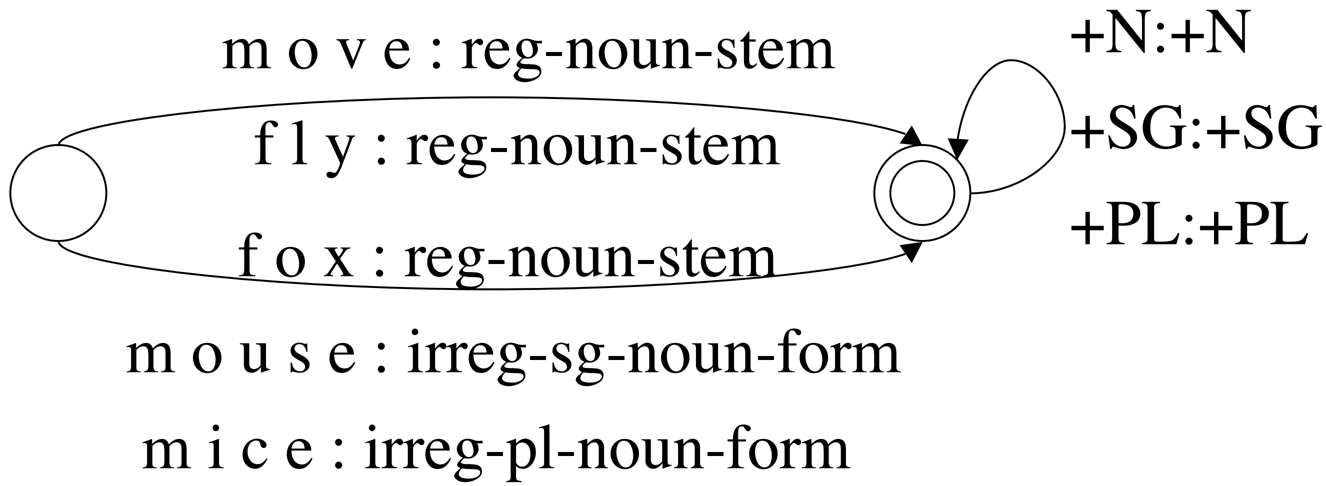
loved → love^ed# [***e*-deletion FST**]

flies → fly^s# [***i* to *y*, *e*-deletion FST**]

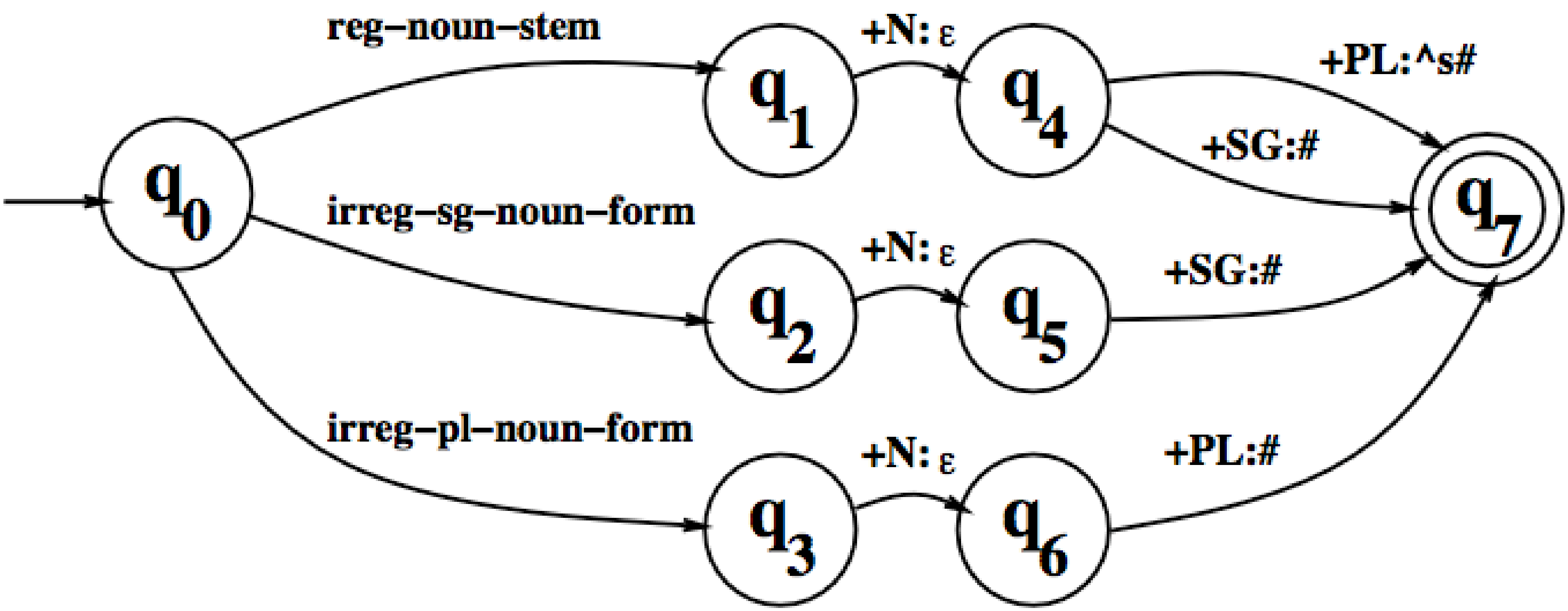
panicked → panic^ed# [**k-insertion FST**]

etc.

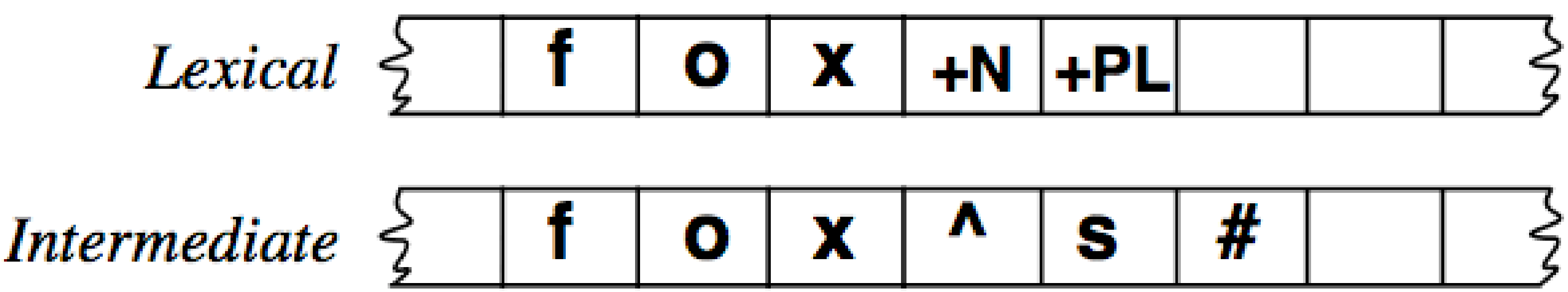
Lexicon FST (stores stems)



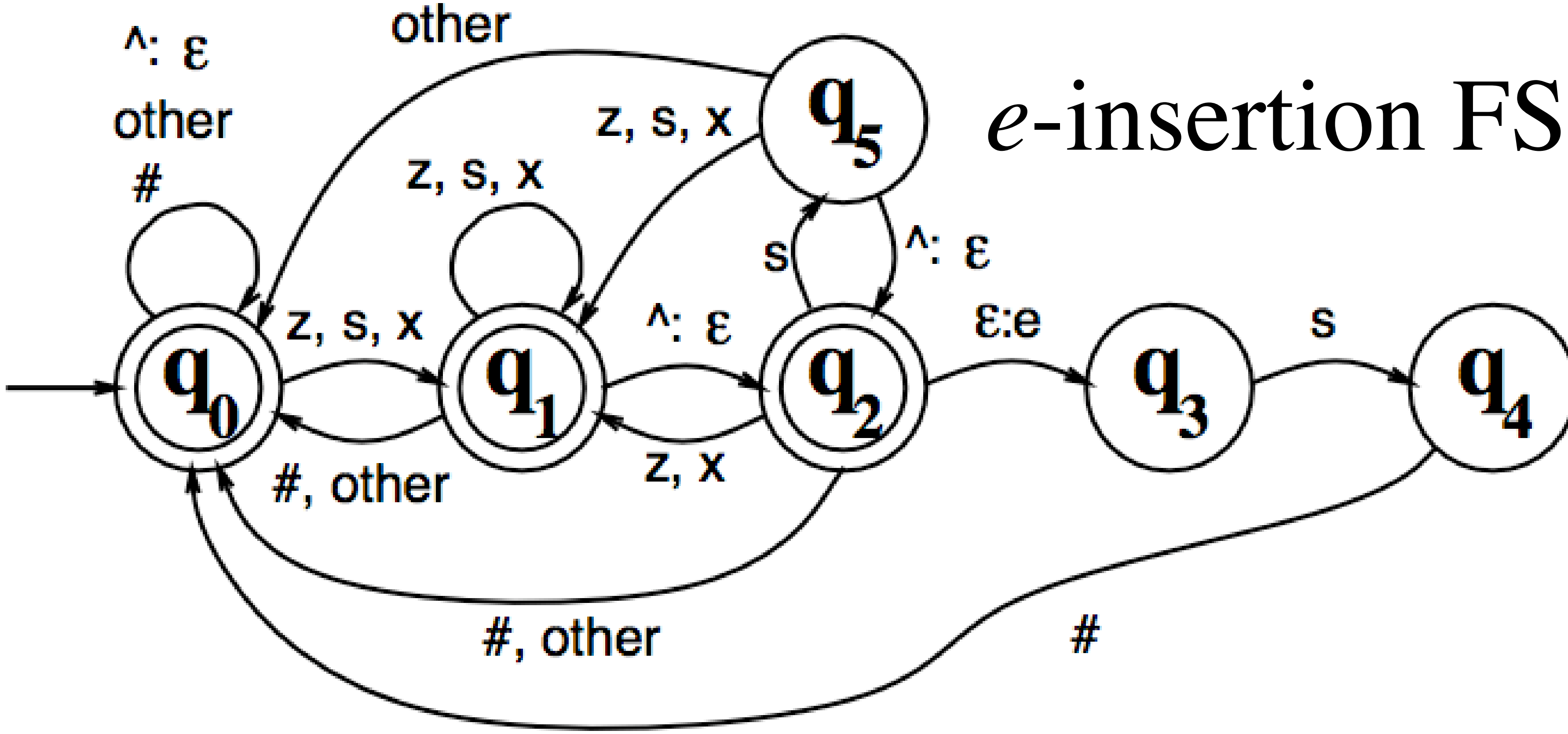
Compose the above lexicon FST with some inflection FST



This machine relates intermediate forms like `fox^s#` to underlying lexical forms like `fox+N+PL`



e-insertion FST



- The label *other* means pairs not use anywhere in the transducer.
- Since # is used in a transition, q_0 has a transition on # to itself
- States q_0 and q_1 accept default pairs like (*cat^s#*, *cats#*)
- State q_5 rejects incorrect pairs like (*fox^s#*, *foxs#*)

e-insertion FST

- Run the e-insertion FST on the following pairs:

  (*fir#*, *fir#*)

  (*fir^s#*, *firs#*)

  (*fir^s#*, *fires#*)

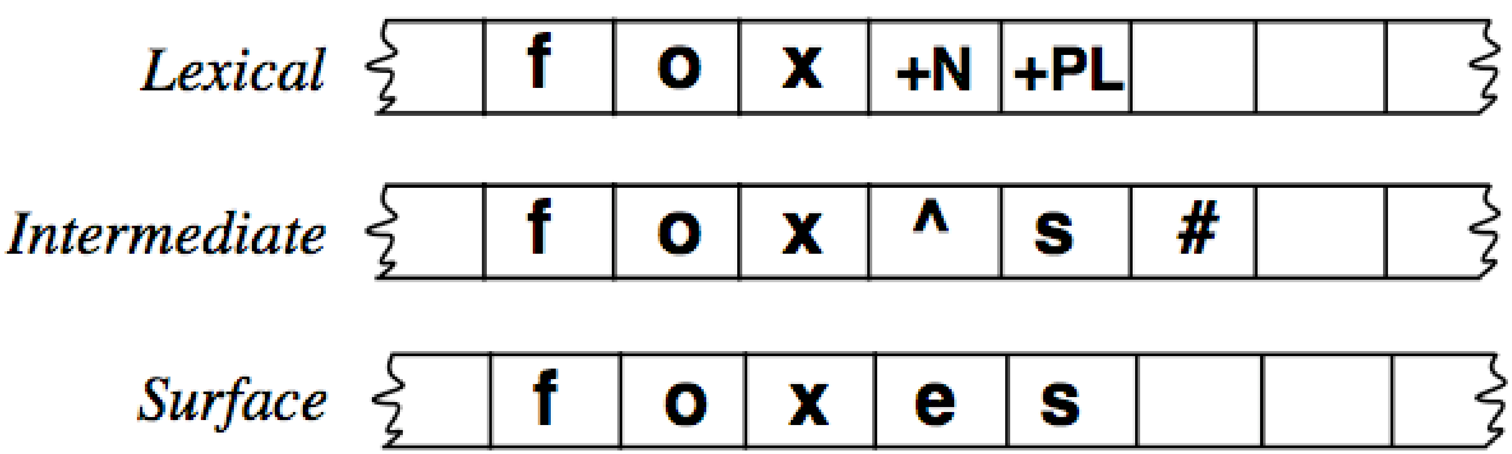
  (*fizz^s#*, *fizzs#*)

  (*fizz^s#*, *fizzes#*)

  (*fizz^ing#*, *fizzing#*)

- Find the state the FST reaches after attempting to accept each of the above pairs
- Is the state a final state, i.e. does the FST accept the pair or reject it

• We first use an FST to convert the lexicon containing the stems and affixes into an intermediate representation
• We then apply a spelling rule that converts the intermediate form into the surface form
• **Parsing**: takes the surface form and produces the lexical representation
• **Generation**: takes the lexical form and produces the surface form
• But how do we handle multiple spelling rules?



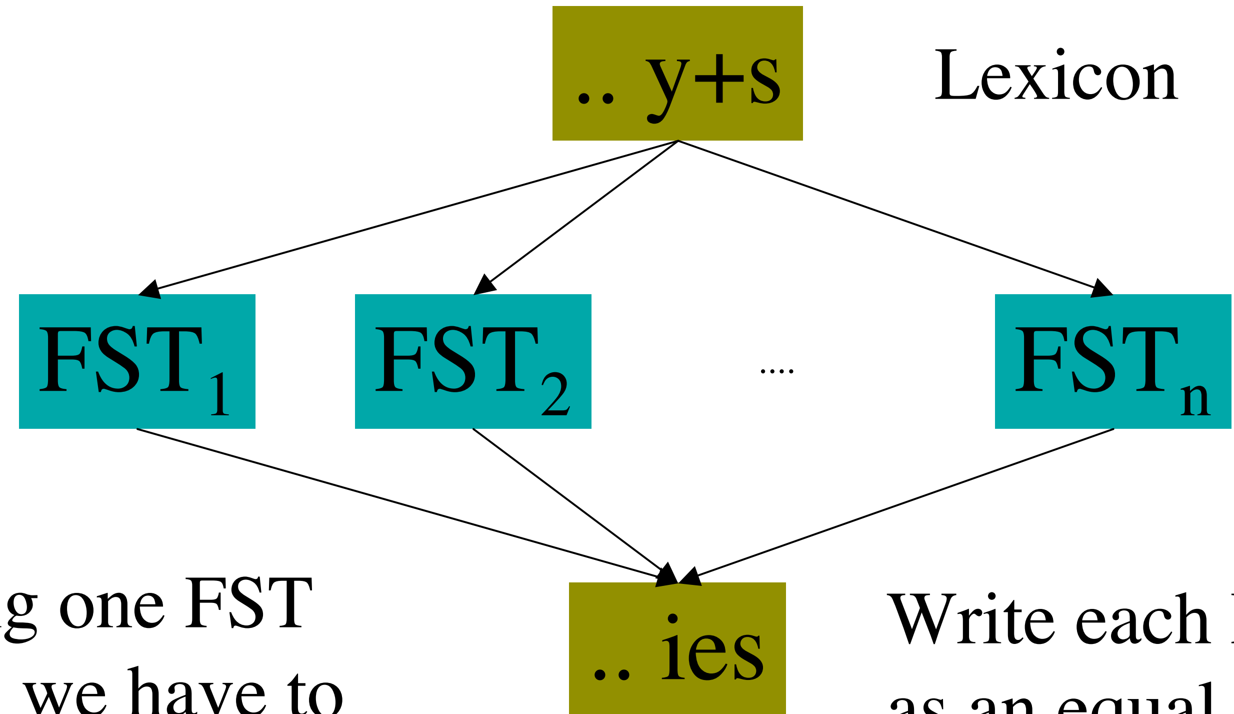
Method 1: Composition

FST composition: creates one FST for all rules

Lexicon

write one FST for each spelling rule: each FST has to provide input to next stage

Method 2: Intersection



Creating one FST implies we have to do **FST intersection** (but there's a catch: *what is it?*)

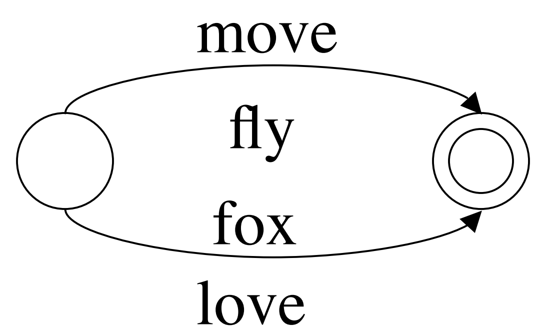
Write each FST as an equal length mapping (ε is taken to be a real symbol)

Intersecting/Composing FSTs

- Implement each spelling rule as a separate FST
- We need slightly different FSTs when using Method 1 (composition) vs. using Method 2 (intersection)
  - In Method 1, each FST implements a spelling rule if it matches, and transfers the remaining affixes to the output (composition can then be used)
  - In Method 2, each FST computes an equal length mapping from input to output (intersection can then be used). Finally compose with lexicon FST and input.
- In practice, composition can create large FSTs

Length Preserving “two-level” FST for *e-deletion*

Stems/Lexicon

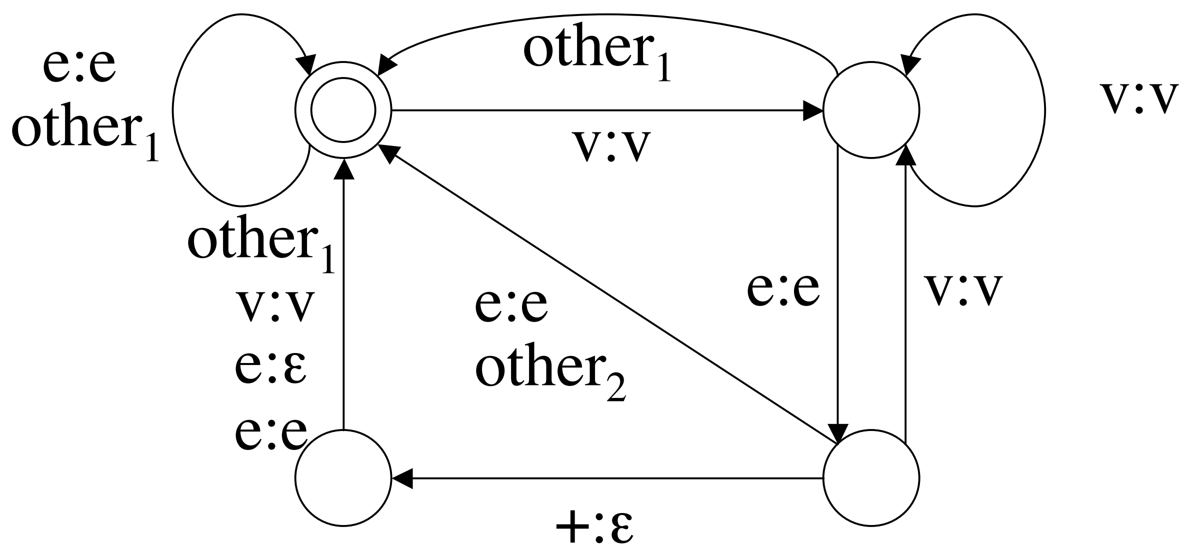


move + ed

move ε εd

$other_1 = \Sigma$ - {e,v}

$other_2 = \Sigma$ - {e,v,+}



Rewrite Rules

left context   right context

- Context dependent rewrite rules: $\alpha \rightarrow \beta$ / λ __ ρ
  - ($\lambda\ \alpha\ \rho \rightarrow \lambda\ \beta\ \rho$; that is α becomes β in context λ __ ρ)
  - α, β, λ, ρ are regular expressions, α = input, β = output
- How to apply rewrite rules:
  - Consider rewrite rule: a $\rightarrow$ b / ab __ ba
  - Apply rule on string *abababababa*
  - Three different outcomes are possible:
    - *abbbabbbaba* (left to right, iterative)
    - *ababbbabbba* (right to left, iterative)
    - *abbbbbbbbba* (simultaneous)

Rewrite Rules

$u \rightarrow i \,/\, i\ C^*\ \_\_$

$(u \rightarrow i \,/\, \Sigma^*\ i\ C^*\ \_\_\ \Sigma^*)$

Input: kikukuku

from *(R. Sproat slides)*

Rewrite Rules

$u \rightarrow i \,/\, i\, C^* \,\_\_$

kikukuku

kikukuku

kikikuku

kikikuku

kikikiku

kikikiku

kikikiki

output of one application *feeds* next application

left to right application

Rewrite Rules

$u \rightarrow i \ / \ i \ C^* \ \_\_$

kikukuku
kikukuku
kikukuku
kikukuku
kikikuku
kikikiku
kikikiki

← *right to left application*

Rewrite Rules

$u \rightarrow i \ / \ i \ C^* \ \_\_$

kikukuku

kikukuku

kikikuku

simultaneous application
(context rules apply to input string only)

Rewrite Rules

- Example of the e-insertion rule as a rewrite rule:

  $\varepsilon \rightarrow e \,/\, (x \mid s \mid z)\hat{}\ \_\_\ s\#$

- Rewrite rules can be optional or obligatory
- Rewrite rules can be ordered wrt each other
- This ensures exactly one output for a set of rules

Rewrite Rules

- Rule 1: iN → im / __ (p | b | m)
- Rule 2: iN → in / __
- Consider input *iNpractical* (N is an abstract nasal phoneme)
- Each rule has to be obligatory or we get two outputs: *impractical* and *inpractical*
- The rules have to be ordered wrt to each other so that we get *impractical* rather than *inpractical* as output
- The order also ensures that *intractable* gets produced correctly

Rewrite Rules

- Under some conditions, these rewrite rules are equivalent to FSTs
- We cannot apply output of a rule as input to the rule itself iteratively:

  $\varepsilon \rightarrow ab$ / a __ b

  If we allow this, the above rewrite rule will produce $a^n\ b^n$ for $n >= 1$ which is not regular

  Why? Because we rewrite the ε in aεb which was introduced in the previous rule application

  Matching the a__b as left/right context in aεb is ok

Rewrite Rules

- In a rewrite rule: $\alpha \rightarrow \beta$ / λ __ ρ
- Rewrite rules are interpreted so that the **input** α does not match something introduced in the previous rule appliction
- However, we are free to match the **context** either λ or ρ or both with something introduced in the previous rule application (see previous examples)
- In this case, we can convert them into FSTs

Rewrite rules to FSTs

$u \rightarrow i \,/\, \Sigma^* \; i \; C^* \; \_\_ \; \Sigma^*$ (example from R. Sproat's slides)

- Input: kikukupapu (use left-right iterative matching)
- Mark all possible right contexts

  > k > i > k > u > k > u > p > a > p > u >

- Mark all possible left contexts

  > k > i <> k <> u > k > u > p > a > p > u >

- Change u to i when delimited by <>

  > k > i <> k <> i > k > u > p > a > p > u >

- But the next u is not delimited by <> and so cannot be changed even though the rule matches

Rewrite rules to FSTs

$u \rightarrow i \,/\, \Sigma^* \; i \; C^* \; \_\_ \; \Sigma^*$

- Input: kikukupapu
- Mark all possible right contexts

  $> k > i > k > u > k > u > p > a > p > u >$
- Mark all *u* followed by > with $<_1$ and $<_2$

  $k > i > k <_1 > u > k <_1 > u > p > a > p <_1 > u >$

  $\quad <_2 \quad u \qquad <_2 \quad u \qquad\qquad <_2 \quad u$
- Change all *u* to *i* when delimited by $<_1 >$

  $k > i > k <_1 > i > k <_1 > i > p > a > p <_1 > i >$

  $\quad <_2 \quad u \qquad <_2 \quad u \qquad\qquad <_2 \quad u$

$u \rightarrow i \,/\, \Sigma^* \; i \; C^* \;\_\_\; \Sigma^*$

Rewrite rules to FSTs

$k > i > k <_1 > i > k <_1 > i > p > a > p <_1 > i >$

$<_2 \quad u \quad <_2 \quad u \quad <_2 \quad u$

- Delete >

$k\ i\ k <_1 i\ k <_1 i\ p\ a\ p <_1 i$

$<_2 u \quad <_2 u \quad <_2 u$

- Only allow *i* where $<_1$ is preceded by iC*, delete $<_1$

$k\ i\ k \quad i\ k \quad i\ p\ a\ p$

$<_2 u \quad <_2 u \quad <_2 u$

- Allow only strings where $<_2$ is **not** preceded by iC*, delete $<_2$

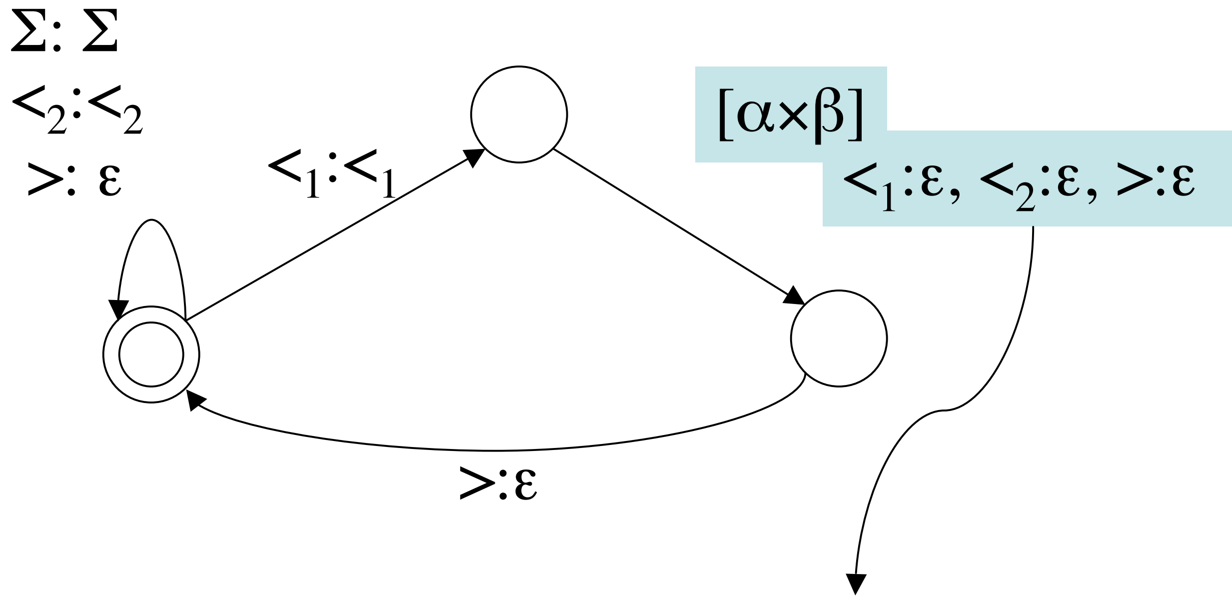
$k\ i\ k\ i\ k\ i\ p\ a\ p\ u$

Rewrite rules to FST

- For every rewrite rule: $\alpha \rightarrow \beta / \lambda \,\_\_\, \rho$:
  - FST *r* that inserts $>$ before every ρ
  - FST *f* that inserts $<_1$ & $<_2$ before every α followed by $>$
  - FST *replace* that replaces α with β between $<_1$ and $>$ and deletes $>$
  - FST λ_1 that only allows all $<_1 \beta$ preceded by λ and deletes $<_1$
  - FST λ_2 that only allows all $<_2 \beta$ **not** preceded by λ and deletes $<_2$
- Final FST = $r \circ f \circ \mathit{replace} \circ \lambda_1 \circ \lambda_2$
- This is only for left-right iterative obligatory rewrite rules: similar construction for other types

Rewrite Rules to FST

FST for *replace*



Create a new FST by taking the cross product of the languages α and β and each state of this new FST: $[\alpha\times\beta]$ has loops for the transitions $<_1:\varepsilon$, $<_2:\varepsilon$, $>:\varepsilon$

Ambiguity (in parsing)

- Global ambiguity: (de+light+ed *vs*. delight+ed)

  foxes → fox+N+PL (*I saw two foxes*)

  foxes → foxes+V+3SG (*Clouseau foxes them again*)

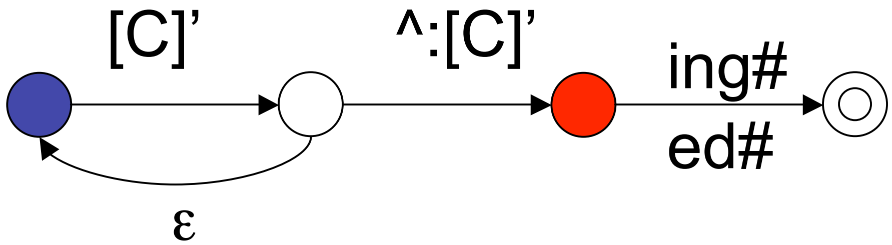
- Local ambiguity:

  assess has a prefix string *asses* that has a valid analysis:
  asses → ass+N+PL

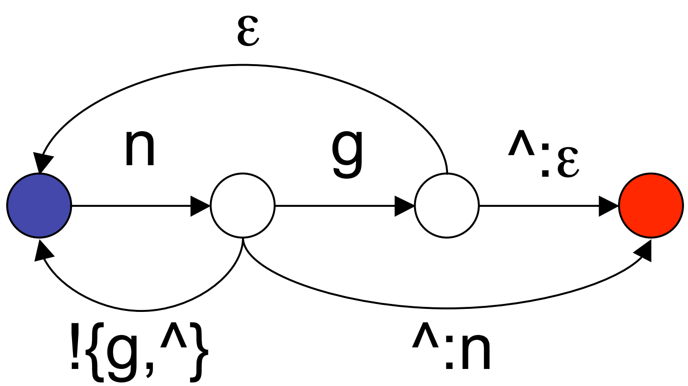
- Global ambiguity results in two valid answers, but local ambiguity returns only one.
- However, local ambiguity can also slow things down since two analyses are considered partway through the string.

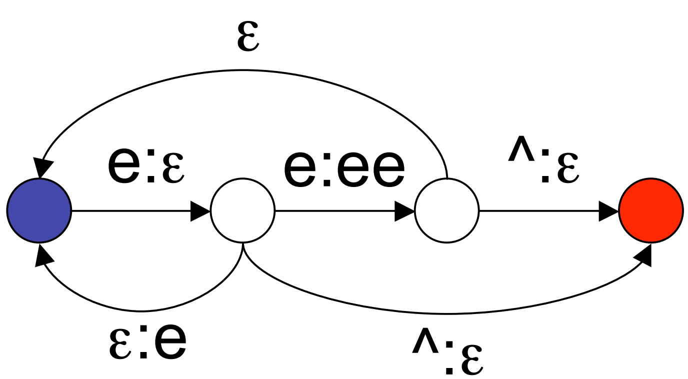
Summary

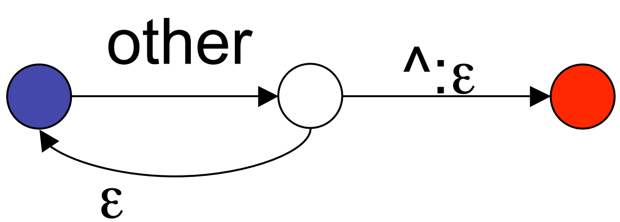
- FSTs can be applied to creating lexicons that are aware of morphology
- FSTs can be used for simple stemming
- FSTs can also be used for morphographemic changes in words (spelling rules), e.g. fox+N+PL becomes foxes
- Multiple FSTs can be composed to give a single FST (that can cover all spelling rules)
- Multiple FSTs that are length preserving can also be run in parallel with the intersection of the FSTs
- Rewrite rules are a convenient notation that can be converted into FSTs automatically
- Ambiguity can exists in the lexicon: both global & local



[C]' = [C]-{n}







other = Σ-[C]'-{n,e}