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): $doing \rightarrow doe, policy \rightarrow police$
- False negatives (should provide stem but does not): $European \rightarrow Europe, matrices \rightarrow matrix$

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 [***y* to *i*, *e*-insertion**]

  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**]

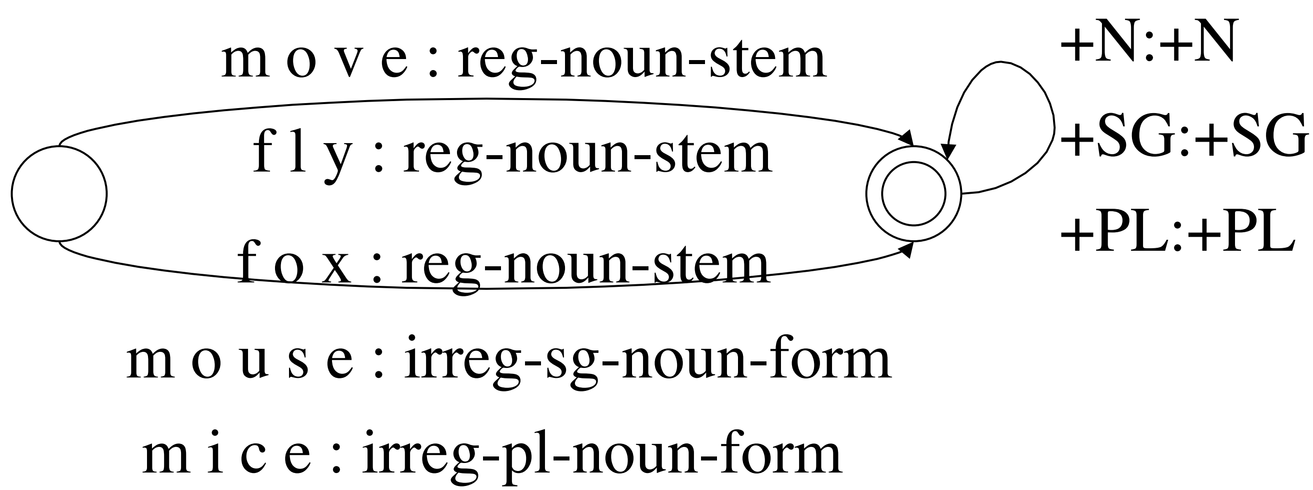
  loved :: love^ed# [***e*-deletion FST**]

  flies :: fly^s# [***y* to *i*, *e*-insertion FST**]

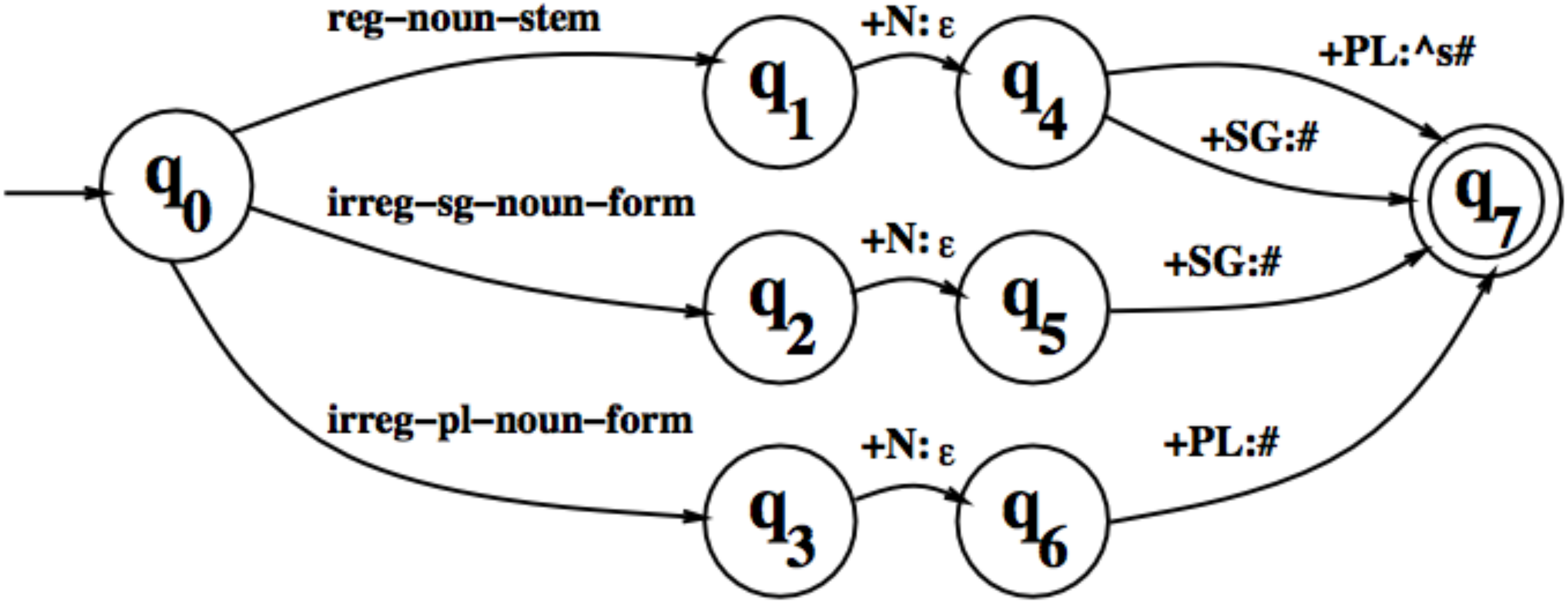
  panicked :: panic^ed# [**k-insertion FST**] (arced::arc^ed#)??

  etc.

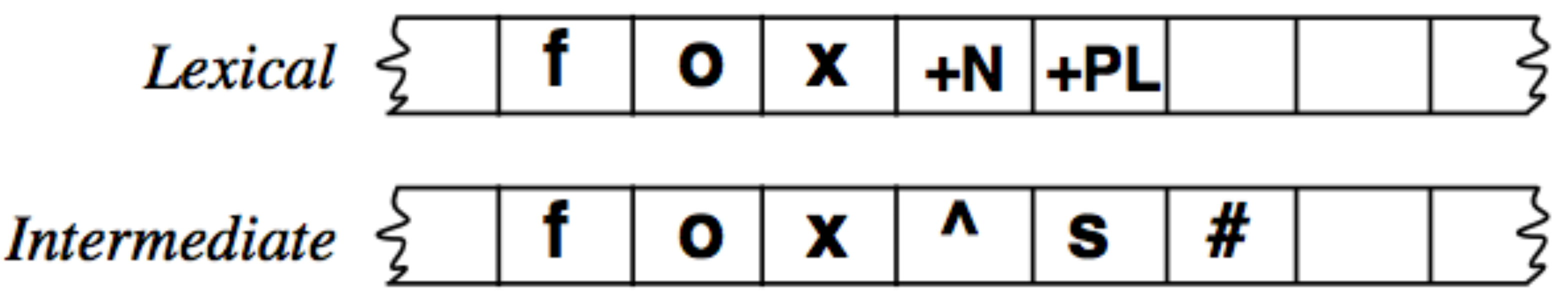
Lexicon FST (stores stems)



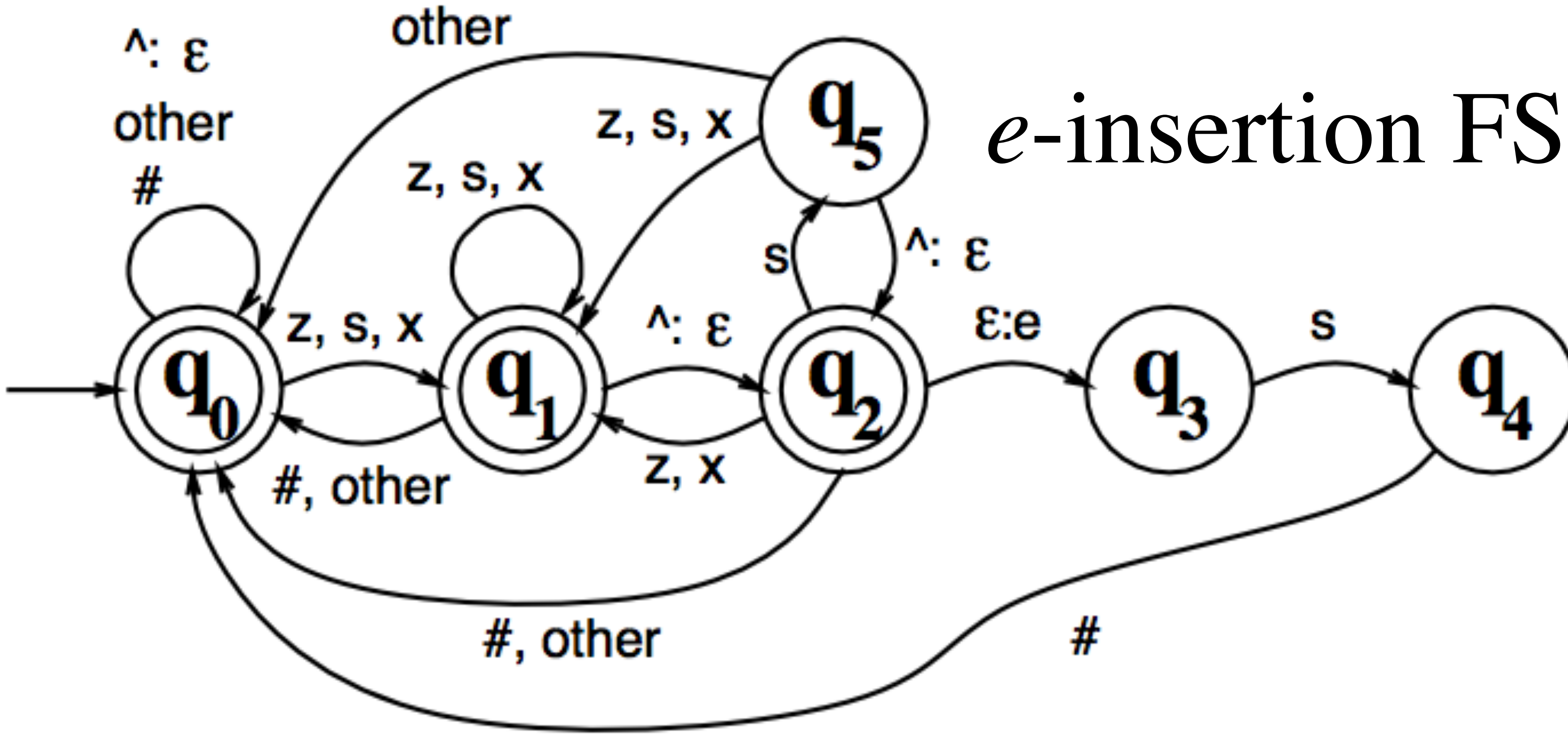
Compose the above lexicon FST with some inflection FST



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#*)

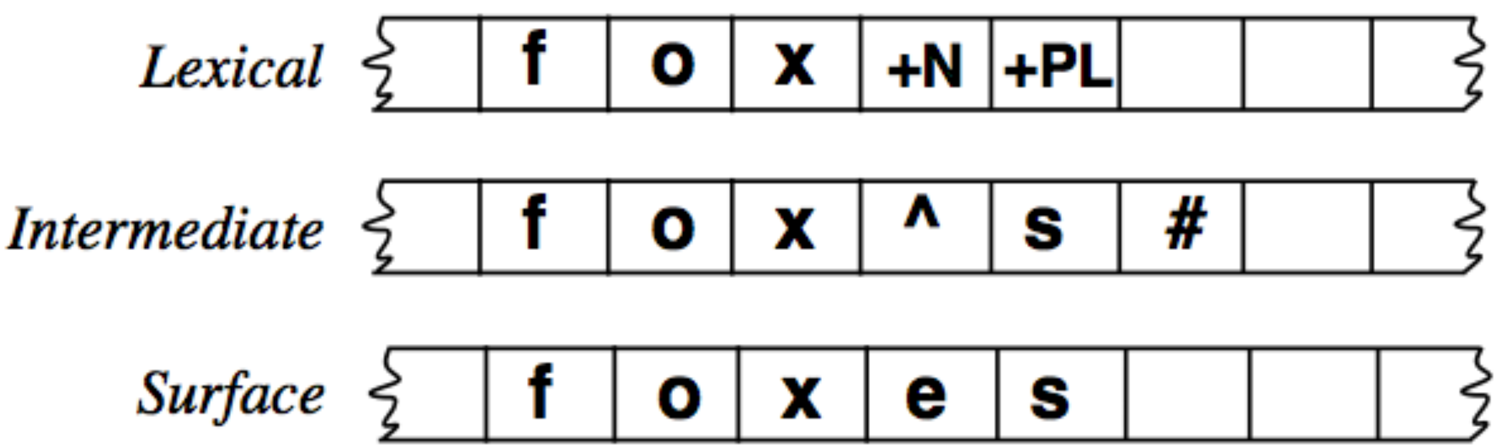
  (*fizz^s#*, *fizzs#*)

  (*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?



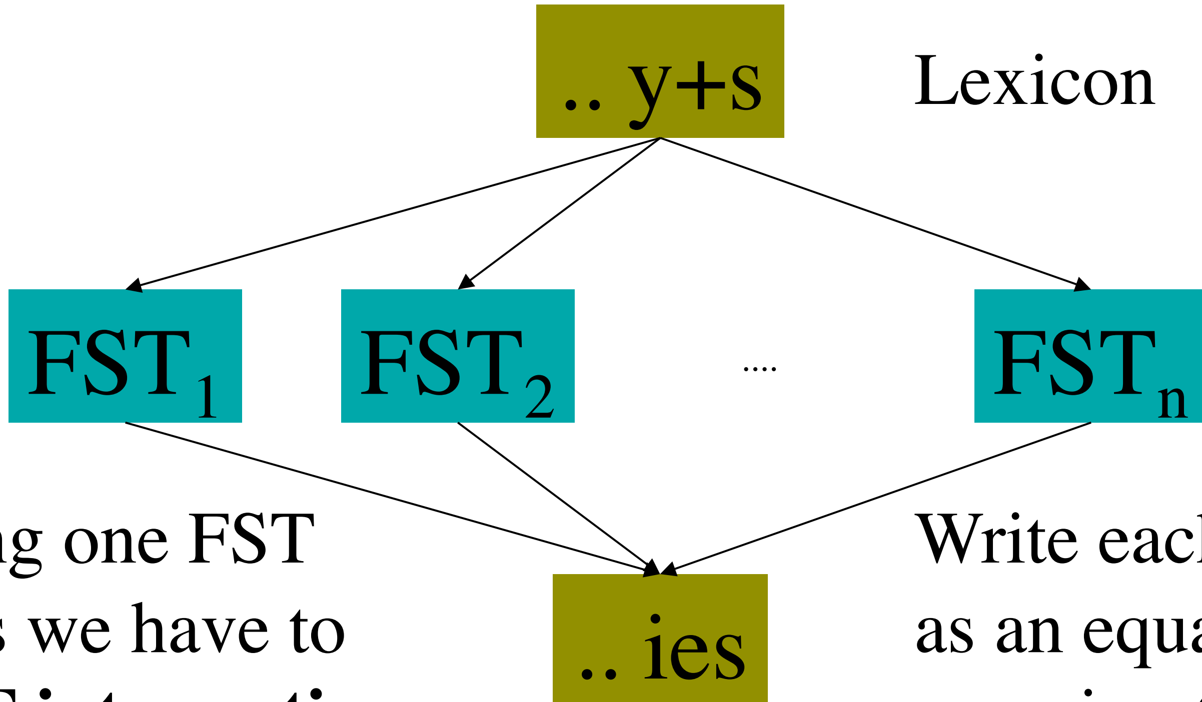
Method 1: Composition

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?*)

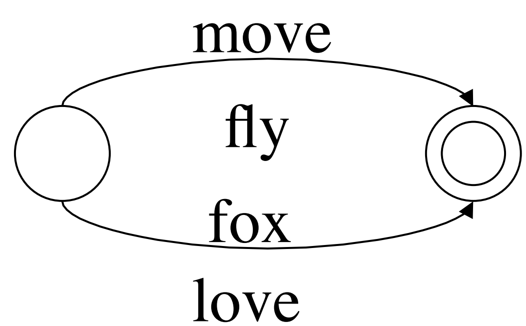
Write each FST as an equal length mapping (ε is taken to be a real symbol)

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

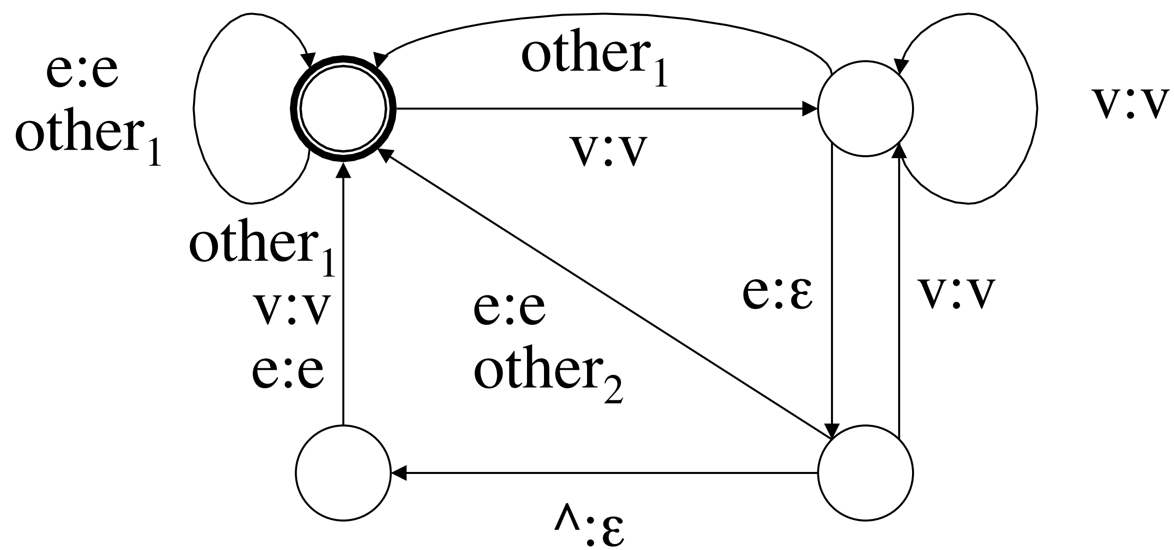
Length Preserving "two-level" FST for *e-deletion*

Stems/Lexicon



move ^ ed

movε ε ed



other$_1$ = Σ - {e,v}

other$_2$ = Σ - {e,v,^}

Should also work for leaving :: leave^ing

Motivation for using FSTs

- We have provided a formal device of FSTs that enables "finite-state" translations
- Translations of this kind are useful in many different contexts in computational linguistics (and beyond)
- But why use such a theoretically well-defined model -- why not use common programming language devices for translation?

REGEX v.s. FST

- The common method for string translations is the REGEX extension of regular expressions: allows match & replace
- For example, to perform ***e-insertion*** we would:

```
> infstem = 'fox+N+PL'
> inter = re.sub('\+N\+PL$', '^s#', infstem)
> inter == 'fox^s#'
> final = re.sub('([sxz])\^s\#', r'\1es', inter)
> final == 'foxes'
```

- Seems simple enough -- why bother with FSTs?
- REGEX algorithms are exponential-time, FSTs are linear time -- sometimes theory is useful in practice!
- Can we retain the useful notation of REGEX expressions?

Rewrite Rules

left context   right context

- Context dependent rewrite rules: $\alpha \rightarrow \beta \,/\, \lambda \_\_ \rho$
  - ($\lambda\ \alpha\ \rho \rightarrow \lambda\ \beta\ \rho$; that is α becomes β in context $\lambda \_\_ \rho$)
  - α, β, λ, ρ are regular expressions, α = input, β = output
  - e.g. $\alpha = (a|b)$ means input is either *a* or *b*, and $\beta = (a|b)$ means the output is ambiguous: should be either *a* or *b*
- How to apply rewrite rules:
  - Consider rewrite rule: a → b / ab __ ba
  - Apply rule on string *ababababa*
  - 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

Example: Finnish Harmony

Gloss	Nominative	Partitive
• sky	• taivas	• taivas+ta
• telephone	• puhelin	• puhelin+ta
• plain	• lakeus	• lakeut+ta
• reason	• syy	• syy+tä
• short	• lyhyt	• lyhyt+tä
• friendly	• ystävällinen	• ystävällinen+tä

i,*e* are neutral wrt harmony

talossansakaanko ‘not in his house either?’
kynässänsäkäänkö ‘not in his pen either?’

Long distance effects, but still possible to model as “finite-state” translation

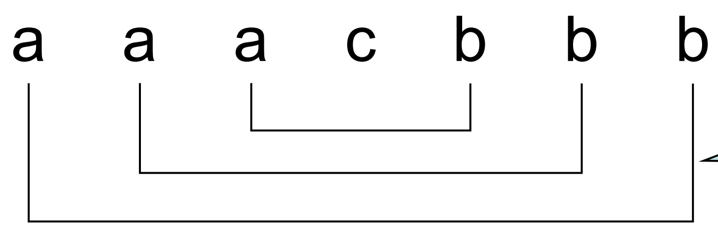
Rewrite Rules

a → ä / [ä,ö,y] C* ([i,e] C*)* ___

o → ö / [ä,ö,y] C* ([i,e] C*)* ___

Rewrite Rules

- Context dependent rewrite rules: $\alpha \rightarrow \beta \,/\, \lambda \_\_ \rho$
- Can express **context sensitive** rules or **regular** relations
- Computational constraints on rewrite rules:
  - Consider rewrite rule: c → acb / a __ b
  - Apply left to right iteratively on base-form *c*
  - Produces a sequence of strings:



Do we need such long-distance effects in morpho-phonological rules?

Rewrite Rules

- In a rewrite rule: $\alpha \rightarrow \beta \,/\, \lambda \,\_\_\, \rho$
- Rewrite rules are interpreted so that the **input** α does not match something introduced in the previous rule application
- 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)
- Impose a simple constraint on how rewrite rules are applied: output cannot be re-written

  e.g. $c \rightarrow a\underline{c}b \,/\, a \,\_\_\, b$

Rewrite Rules

- We cannot apply output of a rule as input to the rule itself iteratively:

  c → acb / a __ b

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

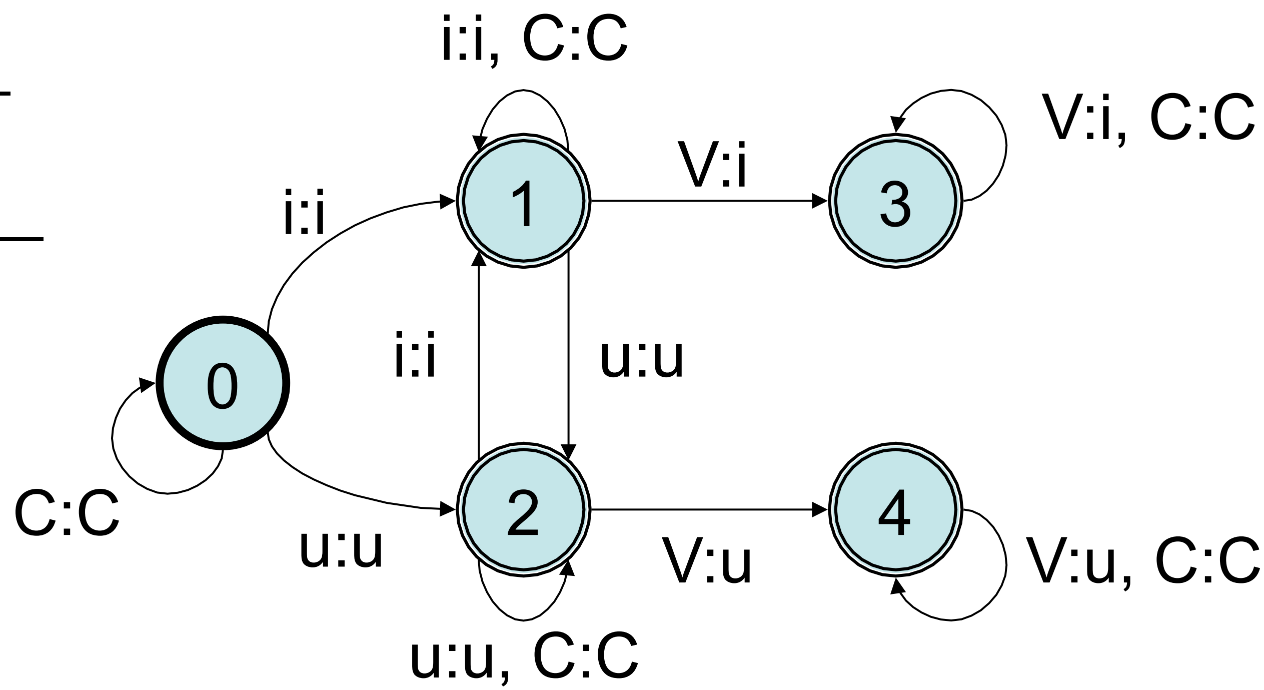
  Why? Because we rewrite the c in acb which was introduced in the previous rule application

  Matching the a__b as left/right context in acb is ok
- Kaplan and Kay constraints:
  - Constraint ensures rewrite rules are equivalent to regular relations
  - Naturally expresses the **local** nature of "finite-state" translation
  - Under these conditions, these rewrite rules are equivalent to FSTs

Rewrite Rules to FSTs

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

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



*kikukuku

√kikikikiki

In this example, V and C are actual symbols in the input

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

First try: does not work for iterative matching

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 $<_2$

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

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

- Change all *u* to *i* when delimited by $<_1$ >

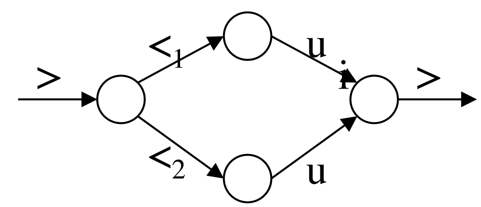
  $k > i > k > <_1 i > k > <_1 i > p > a > p > <_1 i >$

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

$<_1$ u

$<_2$ u

is a short-hand for multiple paths in an FST:



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

Rewrite rules to FSTs

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

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

- Delete >

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

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

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

$k \; i \; k \qquad i \; k \qquad i \; p \; a \; p$

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

- 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

Left to right iterative

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

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

Input: ababb

- Mark right contexts: $a > b\ a > b > b$
- Mark a and b before > with $<_1$ and $<_2$

  $<_1 a > b <_1 a > <_1 b > b$

  $<_2 a \quad <_2 a \quad <_2 b$
- Match $<_1$ LHS > and convert to $<_1$ RHS >; delete >

  $<_1 b\ b <_1 b <_1 a\ b$

  $<_2 a \quad <_2 a <_2 b$
- Allow $<_1$ RHS when left context exists; delete $<_1$

  $<_1 b\ b <_1 b <_1 a\ b \quad = <_2 a\ b\ (b \mid <_2 a)\ (a \mid <_2 b)\ b$

  $<_2 a \quad <_2 a <_2 b$
- Allow $<_2$ LHS when left context does not exist; delete $<_2$

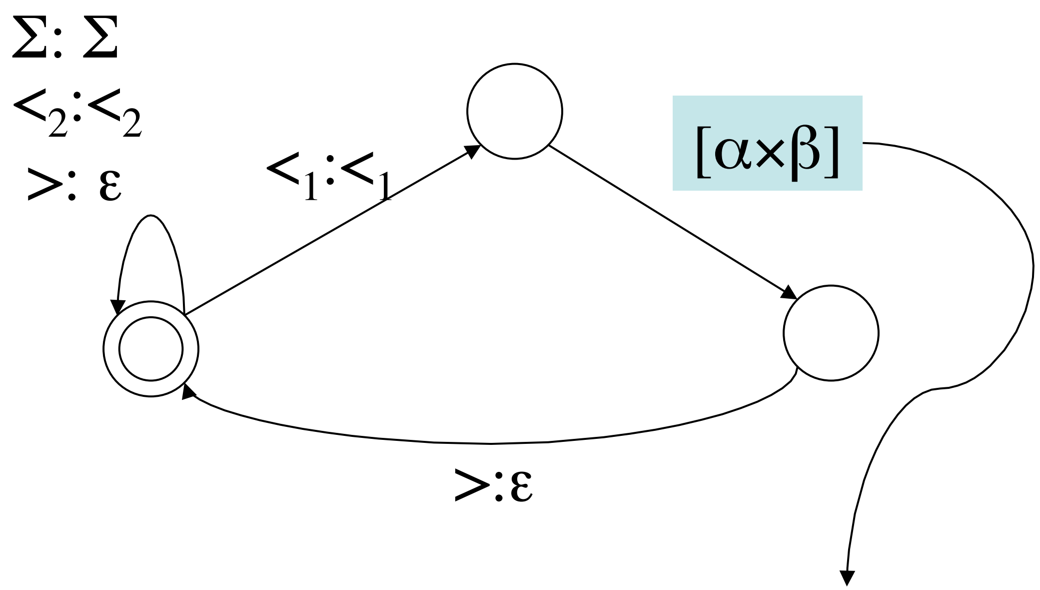
  a b b a b

Rewrite rules to FST

- For every rewrite rule: $\alpha \rightarrow \beta \,/\, \lambda \,\_\_\, \rho$:
- FST *r* that inserts > before every ρ
  $r = \varepsilon \rightarrow \,>\, / \,\Sigma^* \,\_\_\, \rho$
- FST *f* that inserts $<_1$ & $<_2$ before every α followed by >
  $f = \varepsilon \rightarrow (\{<_1\} \cup \{<_2\}) \,/\, (\Sigma \cup \{>\})^* \,\_\_\, \alpha_>$
  where $\alpha_>$ freely allows > anywhere in α
- FST *replace* that replaces α with β between $<_1$ and > and deletes >
  for *replace* we write a special cross product FST

Rewrite Rules to FST

FST for *replace*



Create a new FST by taking the cross product of the languages α and β (every string in α is mapped to every string in β)

Note that while matching α we need to ignore all the instances of $>$, $<_1$, $<_2$ we previously inserted

Rewrite rules to FST

- FST λ_1 that only allows all $<_1 \beta$ preceded by λ and deletes $<_1$
  $\lambda_1 = <_1 \rightarrow \varepsilon$ / $\#\Sigma^*\lambda$ __ ε
  where # is a symbol marking start of the string and we ignore the $<_2$ symbols in the string
- FST λ_2 that only allows all $<_2 \beta$ **not** preceded by λ and deletes $<_2$
  $\lambda_2 = <_2 \rightarrow \varepsilon$ / #complement($\Sigma^*\lambda$) __ ε
- Final FST = $r \circ f \circ replace \circ \lambda_1 \circ \lambda_2$
- This is only for left-right iterative obligatory rewrite rules: similar construction for other types

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*)

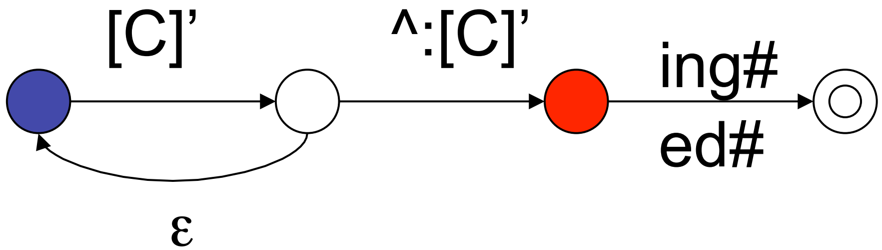
- Local ambiguity:

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

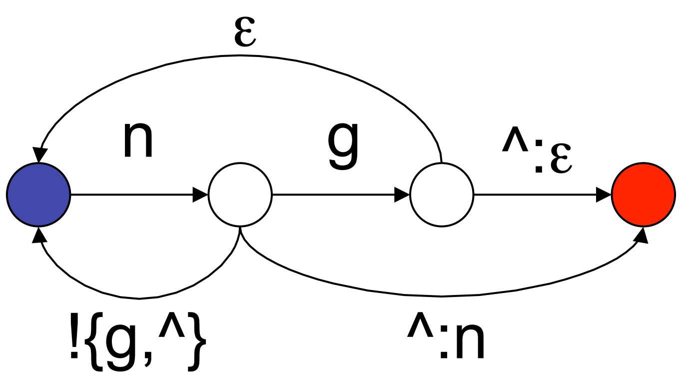
- Global ambiguity results in two valid answers, but local ambiguity returns only one.
- However, local ambiguity can also slow things down since two analyses are considered partway through the string.

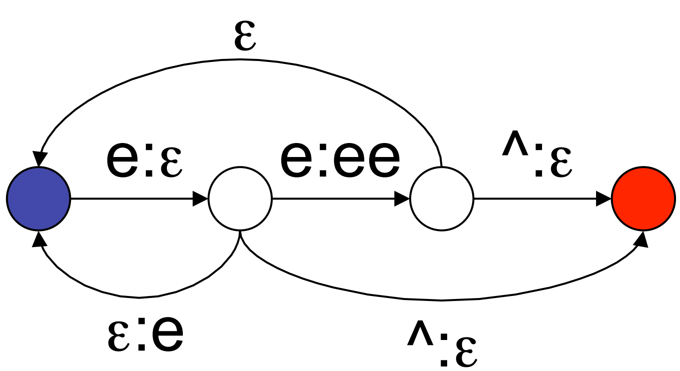
Summary

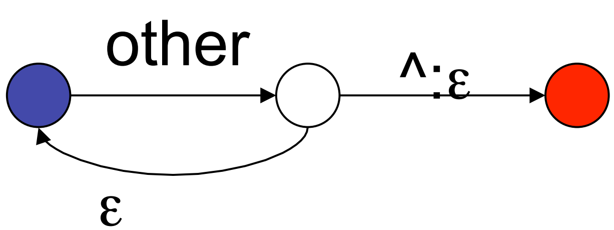
- FSTs can be applied to creating lexicons that are aware of morphology
- FSTs can be used for simple stemming
- FSTs can also be used for morphographemic changes in words (spelling rules), e.g. fox+N+PL becomes foxes
- Multiple FSTs can be composed to give a single FST (that can cover all spelling rules)
- 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}