# 6.863J Natural Language Processing
# Lecture 2: Automata, Two-level phonology, & PC-Kimmo
# (the Hamlet lecture)

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# The Menu Bar

- Administrivia

  web page: www.ai.mit.edu/courses/6.863/ now with Lecture 1, Lab1

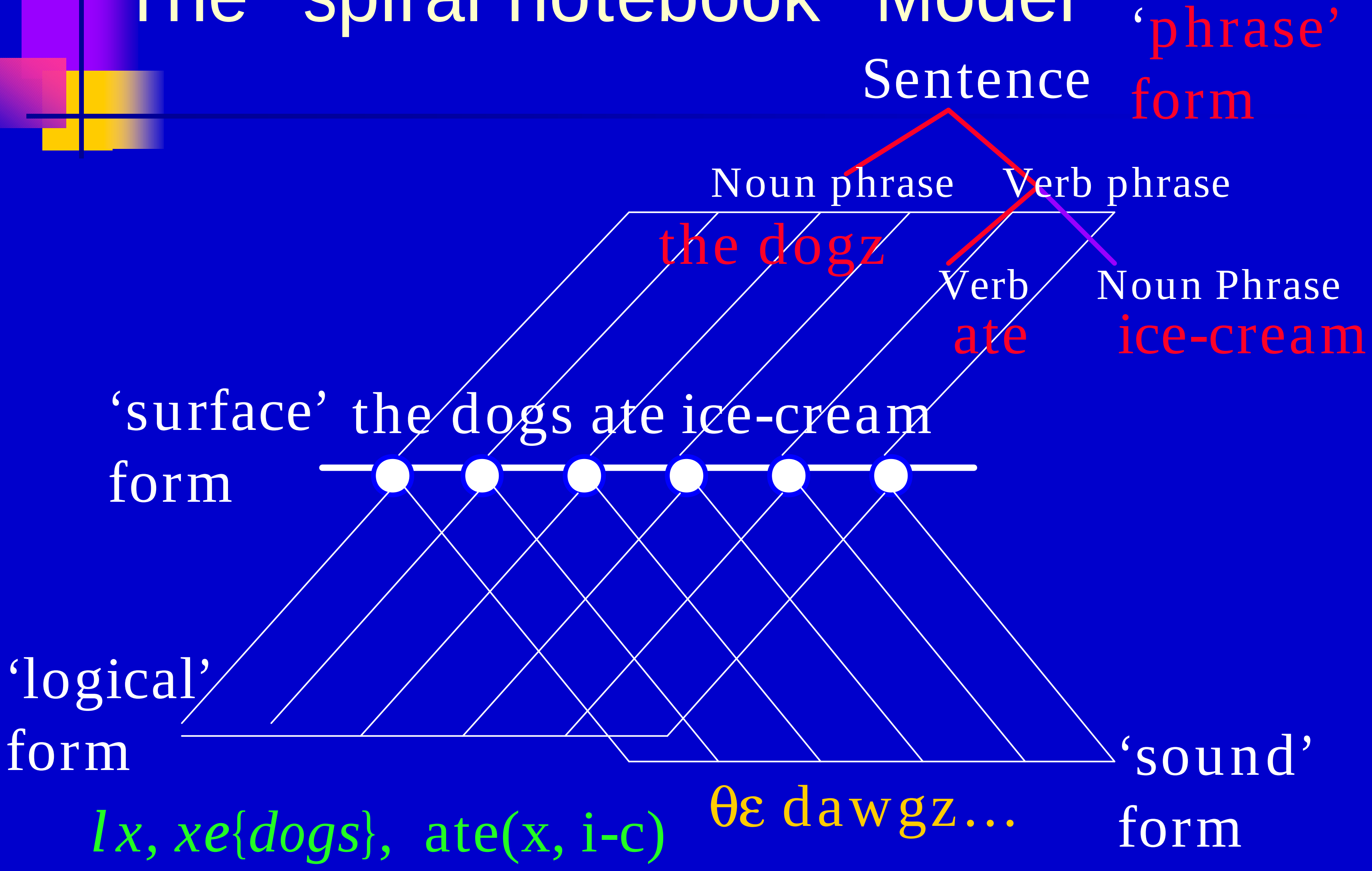
  Questionnaire posted (did you email it?)

  Lab1: split into Lab1a (this time) Lab1b (next time)
- *What* and *How:* word processing, or computational morphology
- What’s in a word: morphology
- Modeling morpho-phonology by finite-state devices
- Finite-state automata vs. finite state transducers
- Some examples from English
- PC-Kimmo & Laboratory 1:how-to

# Levels of language

- Phonetics/phonology/morphology: what words (or subwords) are we dealing with?
- Syntax: What phrases are we dealing with? Which words modify one another?
- Semantics: What's the literal meaning?
- Pragmatics: What should you conclude from the fact that I said something? How should you react?

# The “spiral notebook” Model



‘phrase’ form

Sentence

Noun phrase

Verb phrase

the dogz

Verb

ate

Noun Phrase

ice-cream

‘surface’ form

the dogs ate ice-cream

‘logical’ form

*l x*, *xe*{*dogs*}, ate(x, i-c)

θε dawgz…

‘sound’ form

# Start with words: they illustrate all the problems (and solutions) in NLP

- Parsing words

  Cats → CAT + N(oun) + PL(ural)
- Used in:
  - Traditional NLP applications
  - Finding word boundaries (e.g., Latin, Chinese)
  - Text to speech (*boathouse*)
  - Document retrieval (example next slide)
- In particular, the problems of *parsing*, *ambiguity,*and *computational efficiency* (as well as the problems of *how people do it*)

# Example from information retrieval

- Keywork retrieval: *marsupial* or *kangaroo* or *koala*
- Trying to form equivalence classes - ending not important
- Can try to do this without *extensive* knowledge, but then:

organization → organan Europe~~an~~ → Europe

generalization → generic noise → noisy

# Morphology

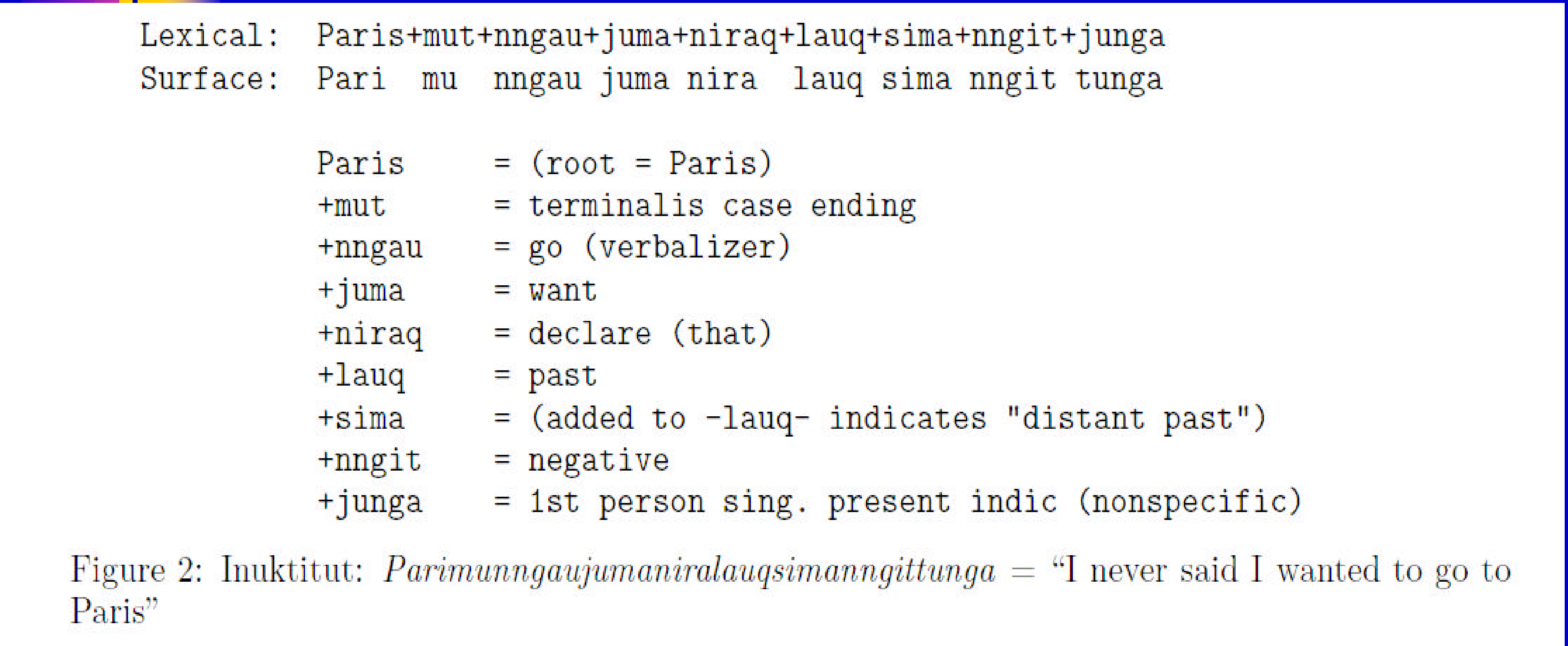
- Morphology is the study of how *words* are *built up* from smaller *meaningful* units called *morphemes*  (morph= shape; logos=word)
- Easy in English – what about other languages?

# What about other languages?

| Present indicative | Imperf | Imperf Indic. | Future | Preterite | Present Subjun | Cond | Imp. Subj. | Fu Su |
|---|---|---|---|---|---|---|---|---|
| *amo* | | *amaba* | *amaré* | *amé* | *ame* | *amaría* | *amara* | *ar* |
| *amas* | *ama* | *amabas* | *amarás* | *amaste* | *ames* | *amarías* | *amaras* | *ar* |
| | *ames* | | | | | | | |
| *ama* | | *amamba* | *amará* | *amó* | *ame* | *amaría* | *amara* | *ar* |
| *amamos* | | | | | | | | |
| *amáis* | *amad* | *amambais* | *amremos* | *amomos* | *amemos* | *amaríanos* | *amarais* | *ar* |
| | *amáis* | | | | | | | |
| *aman* | | *amamban* | *amarán* | *amaron* | *amen* | *amarían* | *amarain* | *ar* |

How to love in Spanish…incomplete…you can finish it after Valentine’s Day…

# What about other languages?



```
Lexical:  Paris+mut+nngau+juma+niraq+lauq+sima+nngit+junga
Surface:  Pari  mu  nngau juma nira  lauq sima nngit tunga
```

| | |
|---|---|
| Paris | = (root = Paris) |
| +mut | = terminalis case ending |
| +nngau | = go (verbalizer) |
| +juma | = want |
| +niraq | = declare (that) |
| +lauq | = past |
| +sima | = (added to -lauq- indicates "distant past") |
| +nngit | = negative |
| +junga | = 1st person sing. present indic (nonspecific) |

Figure 2: Inuktitut: *Parimunngaujumaniralauqsimanngittunga* = “I never said I wanted to go to Paris”

# What about other processes?

- Stem: core meaning unit (morpheme) of a word
- Affixes: bits and pieces that combine with the stem to modify its meaning and grammatical functions

Prefix: *un-* , *anti-*, etc.

Suffix: -*ity*, -*ation*, etc.

Infix:

Tagalog: *um*+*hinigi* → ***humingi*** **(borrow)**

Any infixes in ‘nonexotic’ language like English?

Here’s one: un-f******-believable

# OK, now how do we deal with this computationally?

- *What* knowledge do we need?
- *How* is that knowledge put to use?

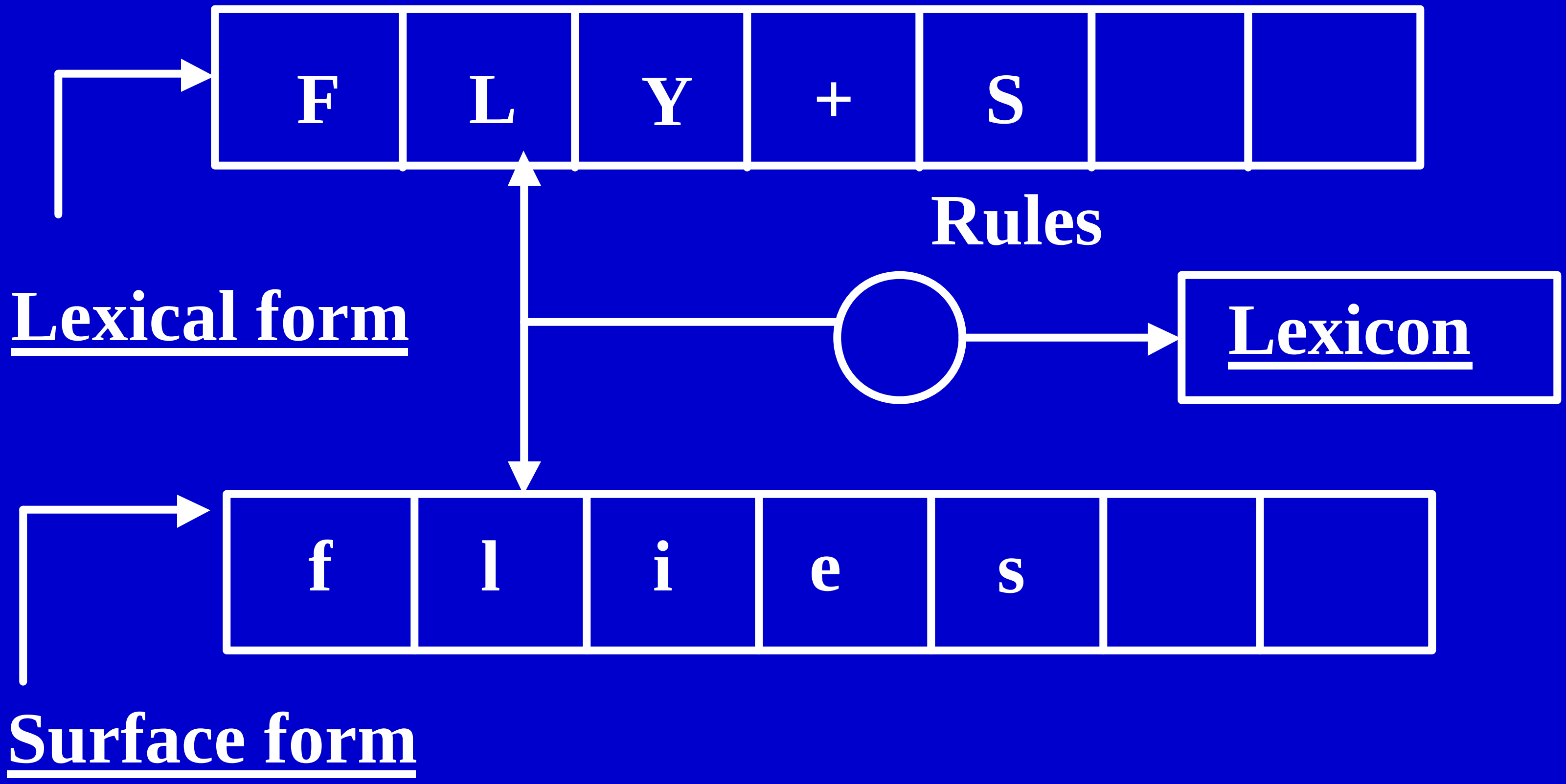
- *What:*

  *duckling; beer*  (implies what K...?)

  *chase* + *ed* → *chased*  (implies what K?)

  *breakable* + *un* →*unbreakable*  ('prefix')
- *How:* a bit trickier, but clearly we are at least doing this kind of mapping...

# Our goal: PC-Kimmo



| F | L | Y | + | S | | |
|---|---|---|---|---|---|---|

Rules

**Lexical form**

**Lexicon**

| f | l | i | e | s | | |
|---|---|---|---|---|---|---|

**Surface form**

# Two parts to the “what”

1. Which units can glue to which others (roots and affixes) (or stems and affixes), eg,
2. What ‘spelling changes’ (orthographic changes) occur – like dropping the *e* in ‘chase + ed’

OK, let’s tackle these one at a time, but first consider a (losing) alternative...

# KISS: A (very) large dictionary

1. Impractical: some languages associate a single meaning w/ a Sagan number of distinct surface forms (600 billion in Turkish)

   German: *Leben+s+versichergun+gesellschaft+s+angestellter*

   (life+CmpAug+insurance+CmpAug+company+CompAug +employee)

   Chinese compounding: about 3000 'words,' combine to yield tens of thousands

2. Speakers don't represent words as a list

   *Wug* test (Berko, 1958)

   *Juvenate* is rejected slower than *pertoire* (real prefix matters)

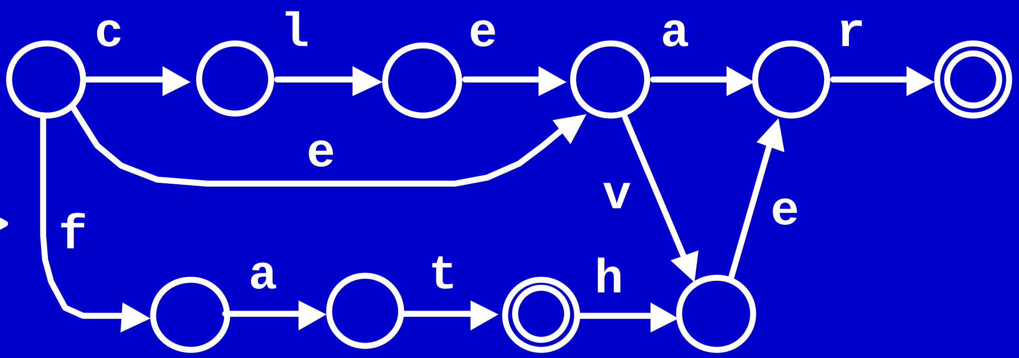
# Representing possible roots + affixes as a finite-state automaton

## Wordlist

clear
clever
ear
ever
fat
father

*compile*

## Network



**/usr/dict/words**

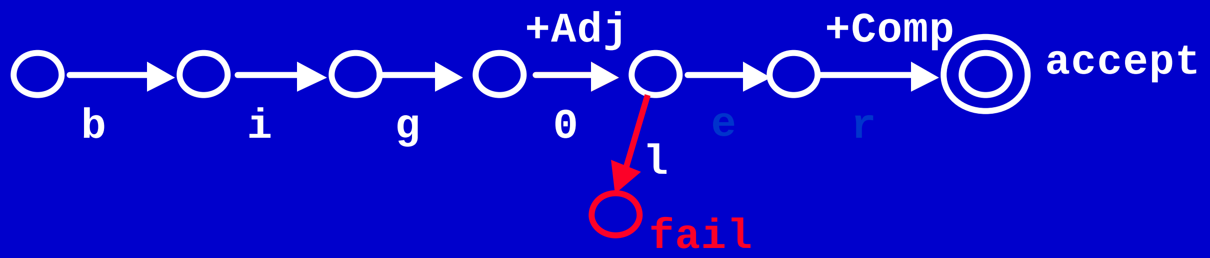
25K words
206K chars

2 sec

FSM

17728 states,
37100 arcs

# Now add in states to get possible combos, as well as features



This much is easy – a straightforward fsa

States = equivalence classes

# English morphology: what states do we need for the fsa?

- As an example, consider adjectives

  *Big, bigger, biggest*

  *Cool, cooler, coolest, coolly*

  *Red, redder, reddest*

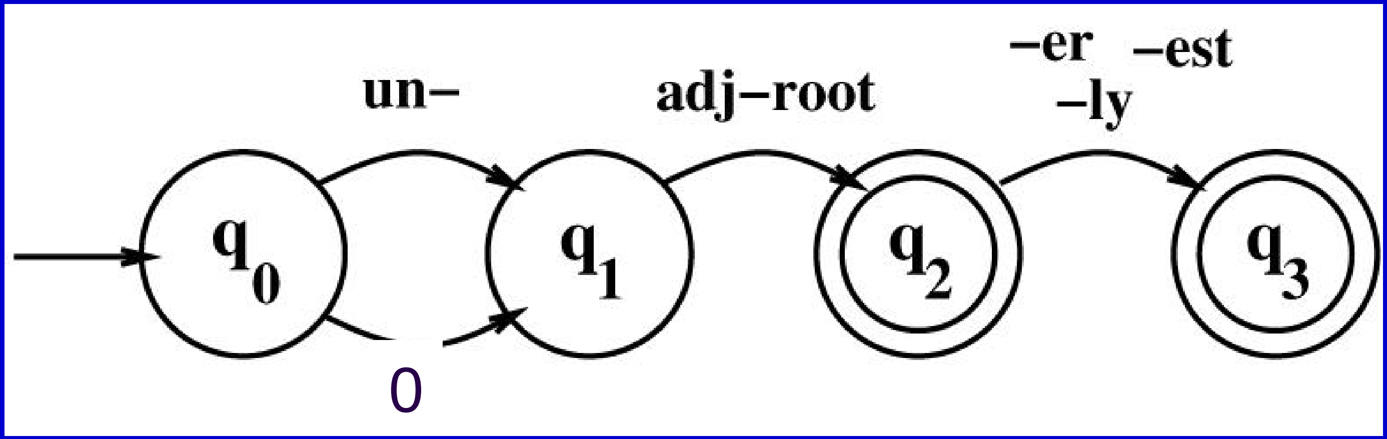
  *Clear, clearer, clearest, clearly, unclear, unclearly*

  *Happy, happier, happiest, happily*

  *Unhappy, unhappier, unhappiest, unhappily*

  *Real, unreal, silly*

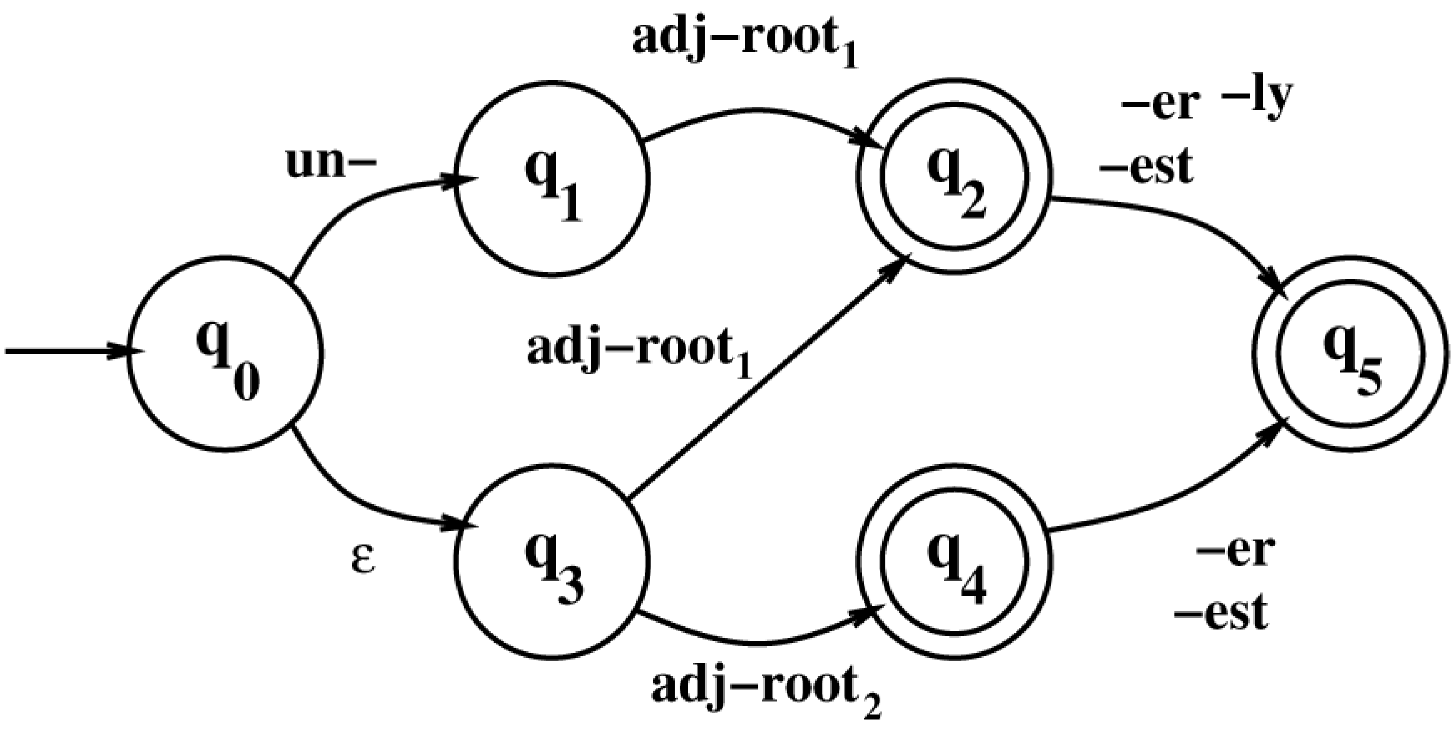
# Will this fsa work?



# Ans: no!

- Accepts all adjectives above, but
- Also accepts *unbig, readly, realest*
- Common problem: *<u>overgeneration</u>*
- Solution?

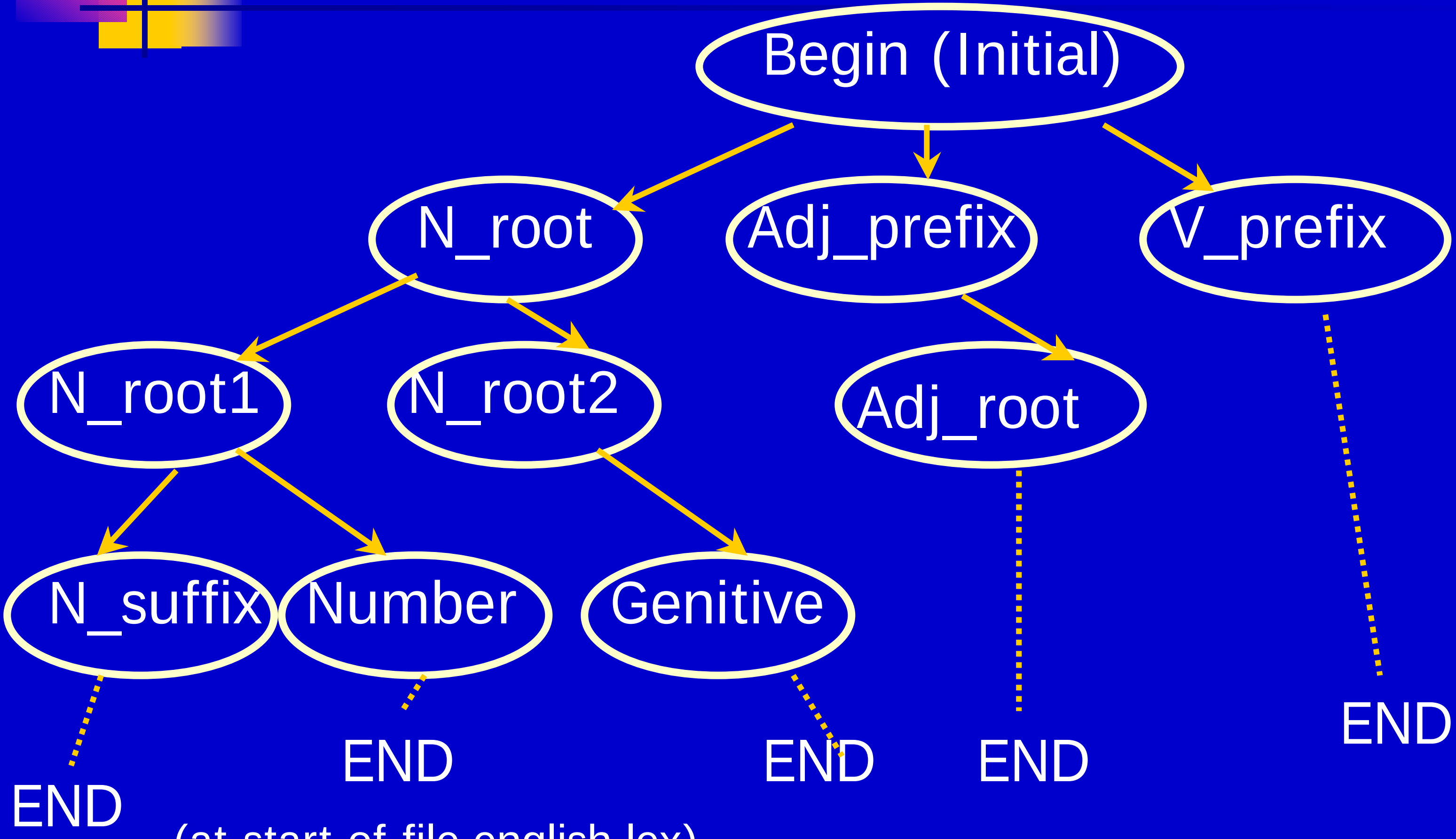
# Revised picture



# How does PC-Kimmo represent this?

Here’s what the pc-kimmo fsa looks like – the fsa states are called ‘alternation classes’ or ‘lexicons’

# PC-Kimmo states for affix combos (portion) = lexicon tree



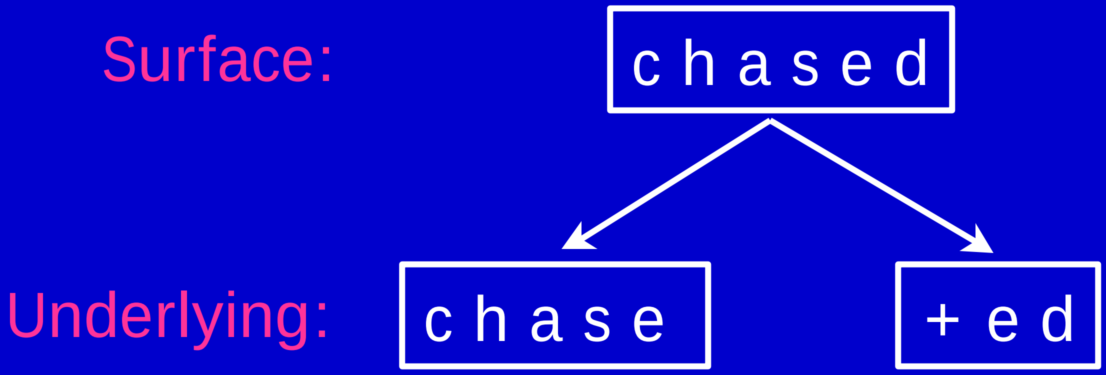
(at start of file english.lex)

# Next: what about the spelling changes?   That's harder!

- ✓ Which units can glue to which others (roots and affixes) (or stems and affixes)

2. What 'spelling changes' (orthographic changes) occur – like dropping the *e* in 'chase + ed'

# Mapping between surface form & underlying form



Surface: chased

Underlying: chase +ed

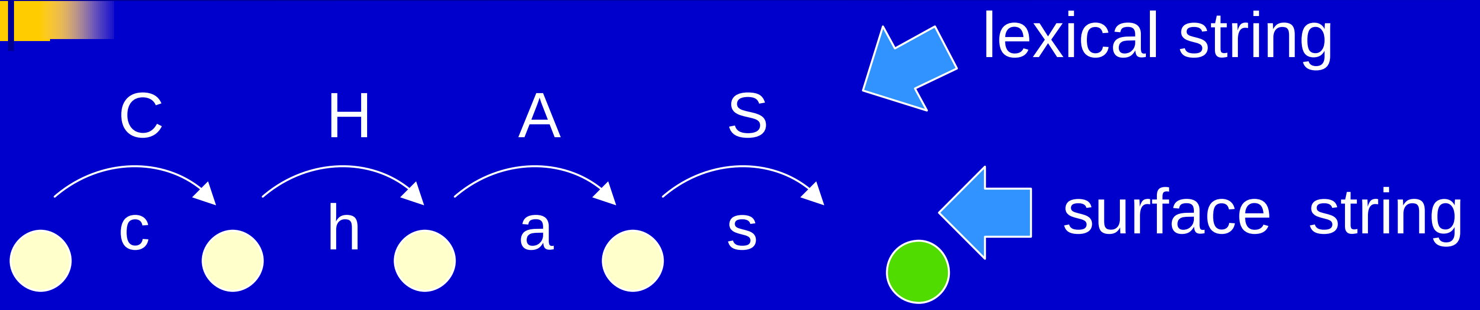
But clearly this can go either way – given the underlying form, we can *generate* the surface form – so we really have a *relation* betw. surface & underlying form, viz.:

# Conventional notation

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Lexical (underlying) form: | **c** | **h** | **a** | **s** | **e** | **+** | **e** | **d** |
| Surface form: | **c** | **h** | **a** | **s** | **0** | **0** | **e** | **d** |

The 0's "line up" the lexical & surface strings
This immediately suggests a finite-state automaton 'solution' : an extension known as a
*finite-state transducer*

# Finite-state transducers: a *pairing* between lexical/surface strings



- Or more carefully

# Definition of finite-state automaton (fsa)

- A *(deterministic) finite-state automaton* (FSA) is a quintuple $(Q,\Sigma,\delta, q_0, F)$ where
  - *Q* is a *finite* set of states
  - $\Sigma$ is a finite set of terminal symbols, the alphabet
  - $q_0$ *Î* *Q* is the initial state
  - $F \subseteq Q$, the set of final states
  - $\delta$ is a function from $Q \times \Sigma \rightarrow Q$, the transition function

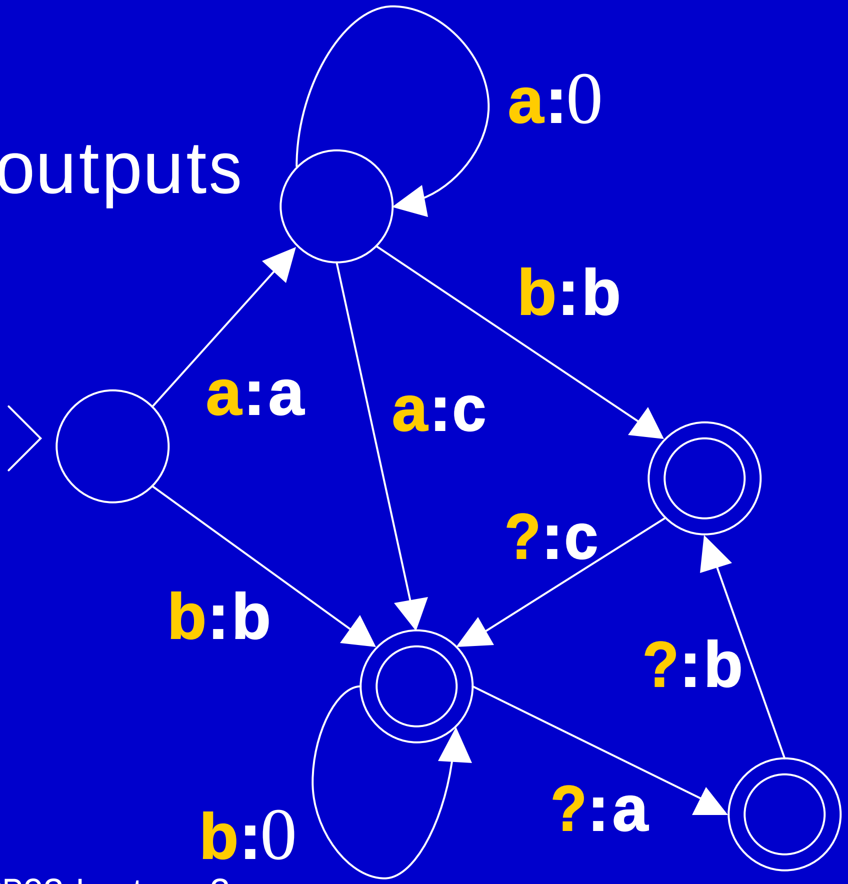
# Definition of finite-state transducer

- state set Q
- initial state $q_0$
- set of final states F
- input alphabet S (also define $\Sigma^*$, $\Sigma^+$)
- output alphabet D
- transition function $\delta : Q \times \Sigma \rightarrow 2^Q$
- output function $\sigma$: $Q \times \Sigma \times Q \rightarrow D^*$

# Regular relations on strings

- *Relation:* like a function, but multiple outputs ok
- *Regular:* finite-state
- *Transducer:* automaton w/ outputs

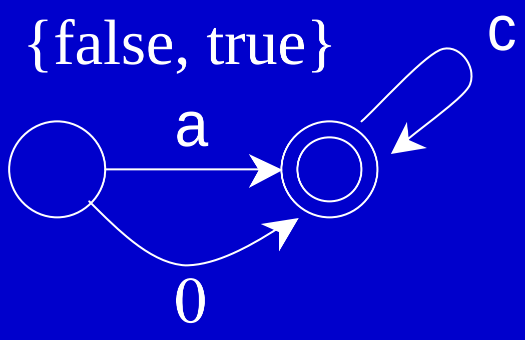
- b → {b} a → {}
- aaaaa → {ac, aca, acab, acabc}

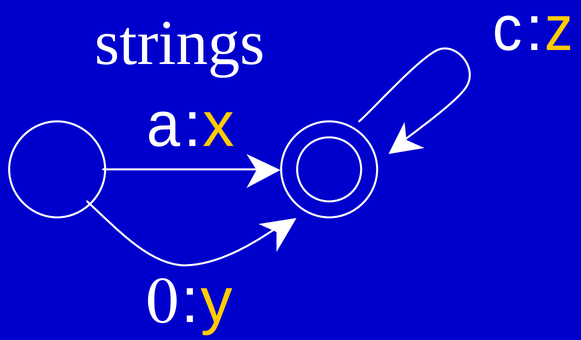


# The difference between (familiar) fsa's and fst's: functions from...

**Acceptors (FSAs)**

**Transducers (FSTs)**



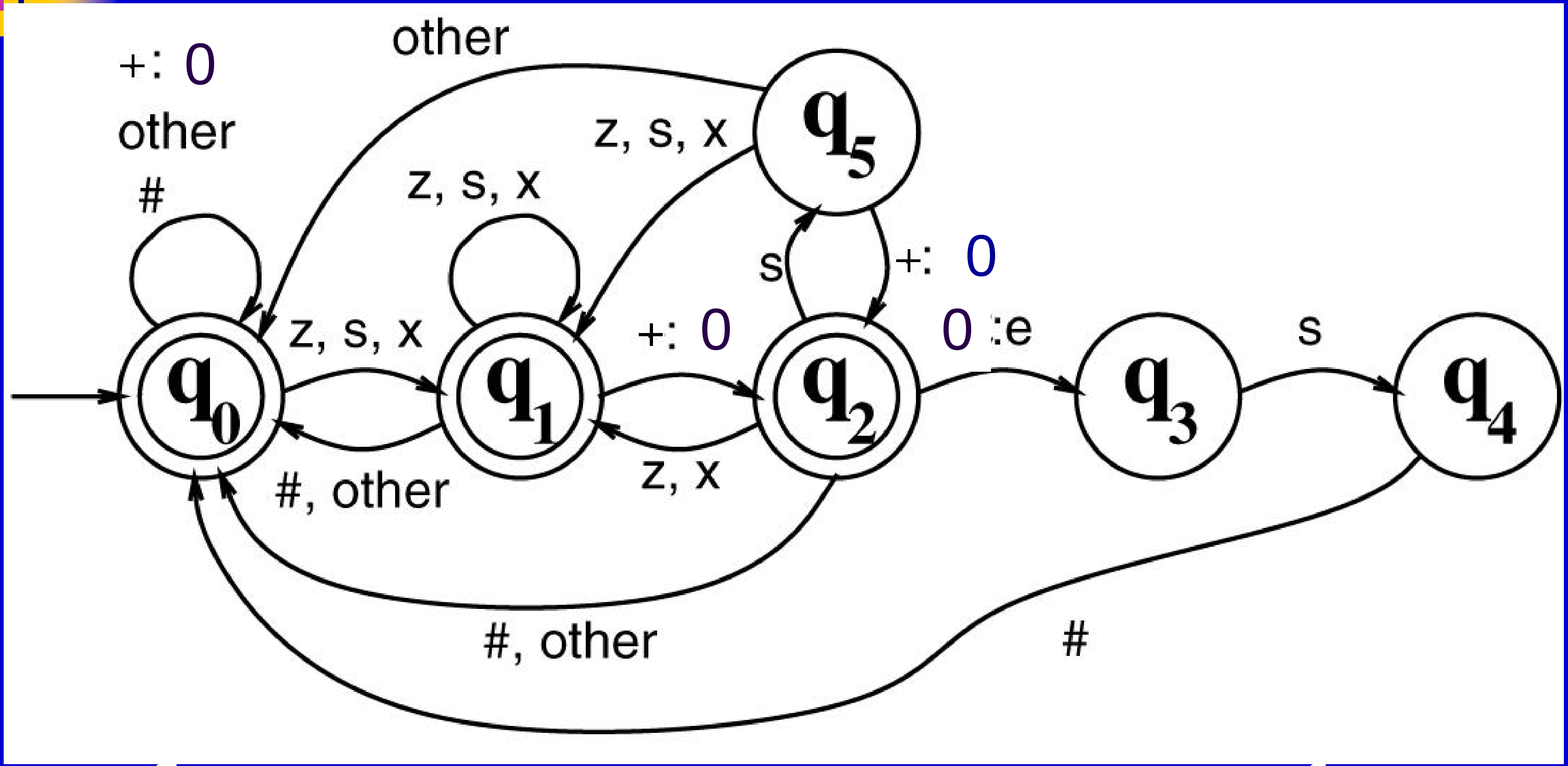


# Defining an fst for a spelling-change rule

- Suggests all we need to do is build an fst for a spelling-change rule that ‘matches’ lexical and surface strings
- Example: fox+s, foxes; buzz+s, buzzes
- Rule: Insert e before non initial x,s,z
- Instantiation as an fst (using PC-Kimmo notation)

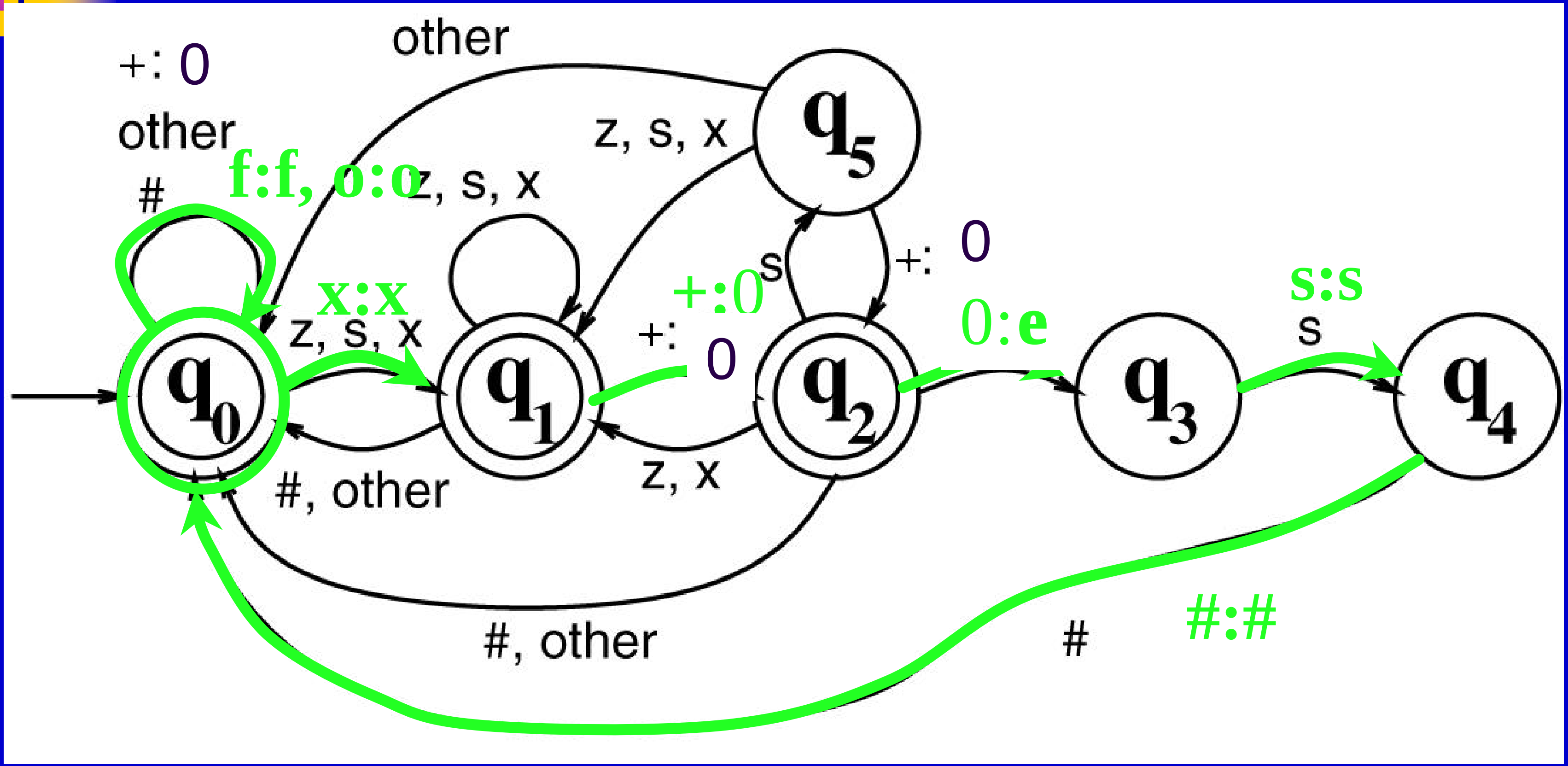
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| f | o | x | 0 | e | s | # | **surface** |
| **F** | **O** | **X** | **+** | **0** | **S** | **#** | **lexical** |

# Insert ‘e’ before non-initial z, s, x (“epenthesis”)



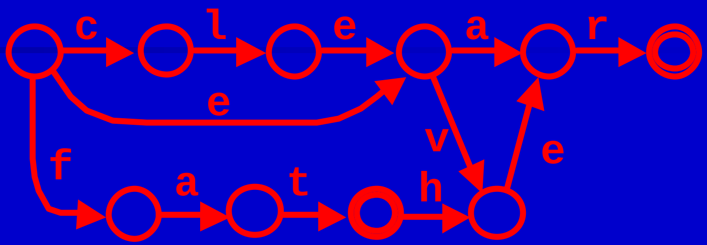
|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| f | o | x | 0 | e | s | # | **surface** |
| **F** | **O** | **X** | **+** | **0** | **S** | **#** | **lexical** |

# Successful pairing of foxes,fox+s

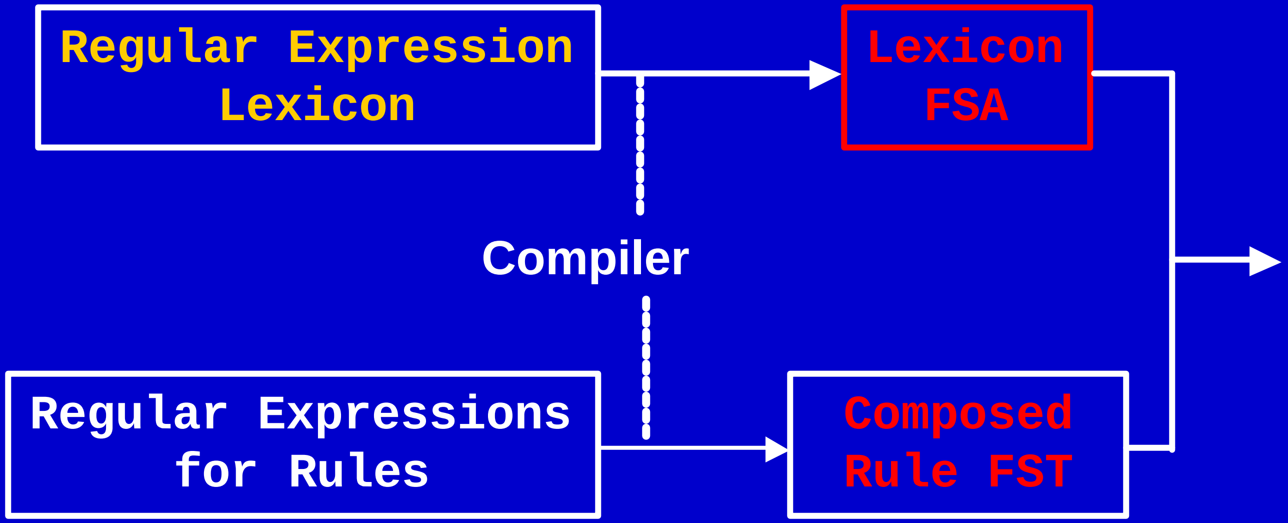


| | | | | | | | |
|---|---|---|---|---|---|---|---|
| f | o | x | 0 | e | s | # | **surface** |
| **F** | **O** | **X** | **+** | **0** | **S** | **#** | **lexical** |

# Now we *combine* the fst for the rules and the fsa for the lexicon by composition



**big | clear | clever | ear | fat | ...**



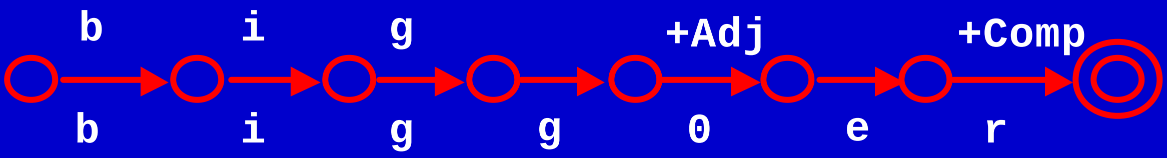
Regular Expression Lexicon

Lexicon FSA

Compiler

Regular Expressions for Rules

Composed Rule FST



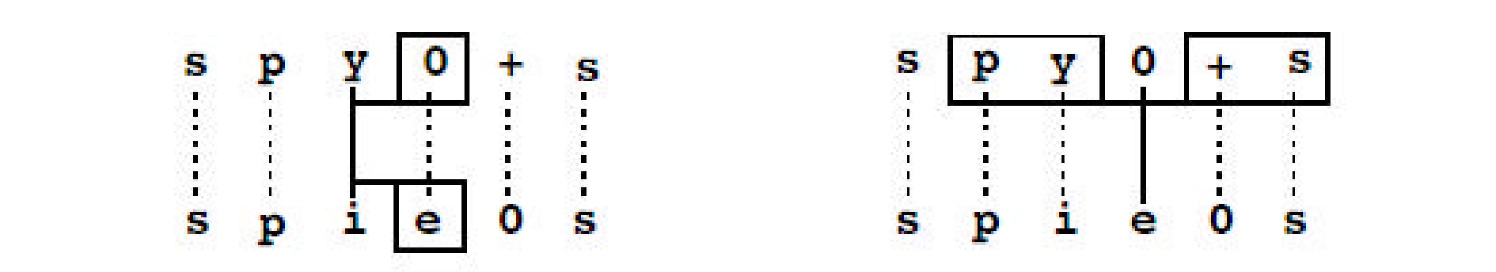
# So we're done, no?

- ✓ Which units can glue to which others (roots and affixes) (or stems and affixes)

- ✓ What 'spelling changes' (orthographic changes) occur – like dropping the *e* in 'chase + ed'

# So, we’re done, right?

- Not so fast...!!!!
- Sometimes, more than 1 spelling change rule applies. Example: spy+s, spies: y
- *y* goes to *i* before an inserted *e* (compare, “spying”
- *e* inserted at affix +s



# Simultaneous rules

- All we gotta do is write one fst for each of the spelling change rules we can think of, no?

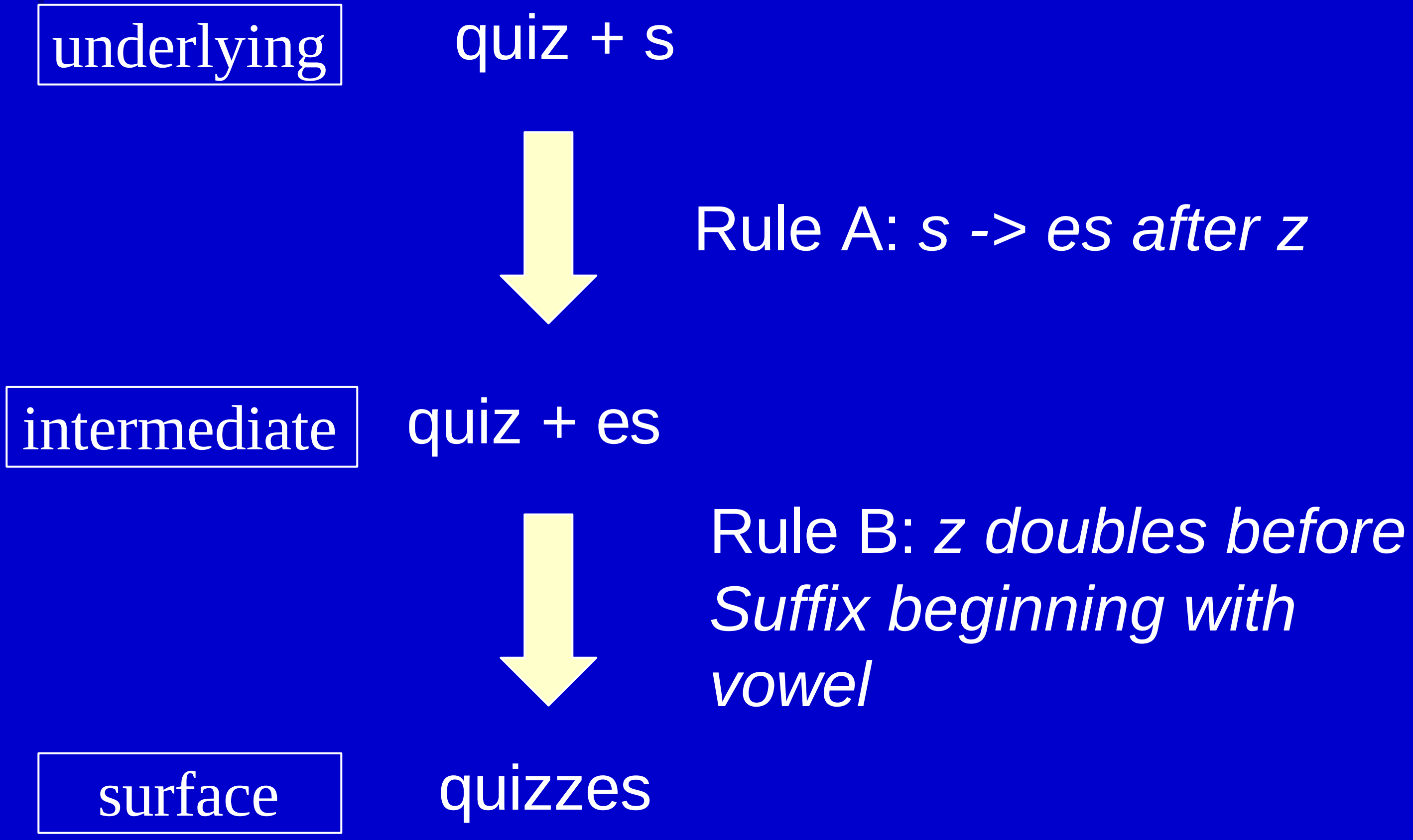
- Since fsa’s are *closed* under intersection, we can apply all the rules simultaneously... can we?

- No!  Fst’s cannot, in general, be intersected... (but, they can, under certain conditions...)

# The classical problem

- Traditional phonological grammars consisted of a *cascade* of general rewrite rules, in the form: $x \rightarrow y/\varphi\_\_\gamma$
- If a symbol *x* is *rewritten* as a symbol *y*, then afterwards x is no longer available to other rules
- *Order* of rules is important
- Note this system is*Turing complete* – can simulate general steps of any computation.. So, gulp, how do we cram them into finite-state devices...?

# Example from English (“gemination”)



underlying quiz + s

Rule A: *s -> es after z*

intermediate quiz + es

Rule B: *z doubles before Suffix beginning with vowel*

surface quizzes

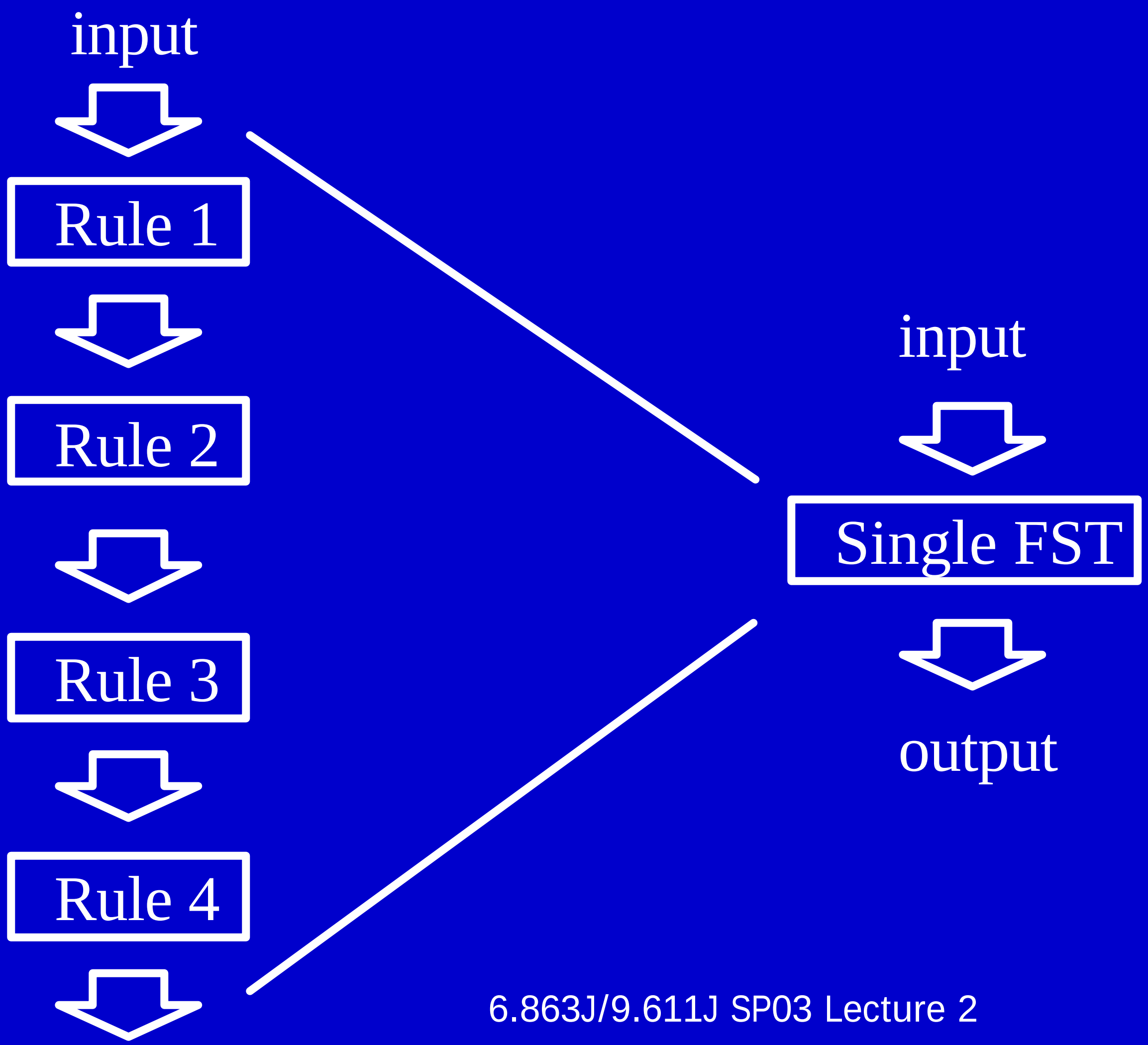
# What’s the difference?

- FSA isomorphic to *regular languages* (sets of strings)
- FST isomorphic to *regular relations,* or *sets of pairs of strings*
- Like FSAs, closed under union, *but unlike* FSAs, FSTs are *not* closed under complementation, intersection, or set difference

# But this is a problem…

- How do we know which order of rules?
- A transducer merely computes a static *regular relation,* and is therefore inherently reversible – so equally viable for analysis or synthesis
- The constraints are *declarative*
- Since the rules describe such *relations*, in general, more than one possible answer – which do we pick? (Inverting the order becomes hard)
- This blocked matters until C. Johnson recalled a theorem of Schuztenberger [1961] viz.,

# When is this possible?



input

Rule 1

Rule 2

Rule 3

Rule 4

input

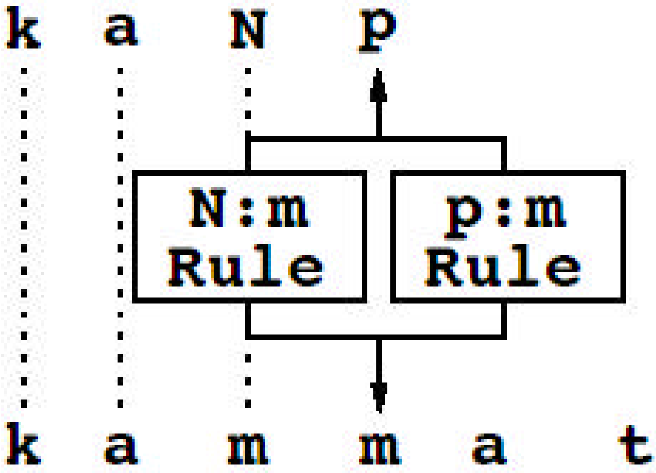
Single FST

output

# Schuztenberger’s condition on closure of fst’s

- The relations described by the individual transducers add up to a regular relation (I.e., a single transducer) when considered as a whole *if*
- The transducers act in lockstep: each character pair is seen simultaneously by all transducers, and they must all “agree” before the next character pair is considered
- No transducer can make a move on one string while keeping the other one in place unless all the other transducers do the same

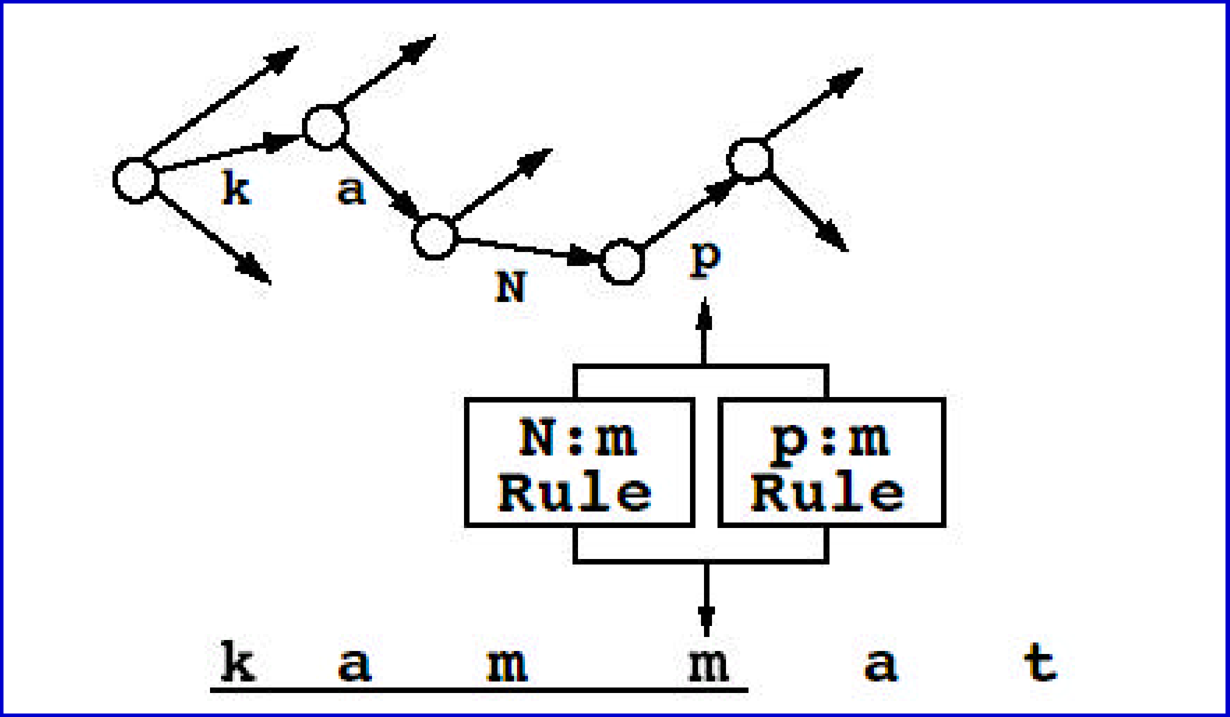
# Simultaneous read heads



# The condition

- For FSTs to act in lockstep, any 0 transitions must be synchronized – that is, the lexical/surface pairing must be *equal length*
- S. called this an *equal length relation*
- Under this condition, fst's *can* be intersected – PC-Kimmo program simulates this intersection, via simultaneous "read heads"

# Plus lexicon – lexical forms always constrained by the path we're following through the lexicon tree



# And that’s PC-Kimmo, folks… or “Two-level morphology”

- A lexicon tree (a fsa to represent the lexicon)
- A set of (declarative) lexical/underlying relations, represented as a set of fst’s that address *both* lexical and surface forms
- For English, roughly 5 rules does most of the work (you’ve seen 2 already) – 11 rules for a “full scale” system with 20,000 lexical entries (note that this typically achieves a 100-fold compression for English)

- The only remaining business is to tidy up the actual format PC-KIMMO uses for writing fst tables (which is quite bizarre)

# Spelling change rules

| Name | Description | Example |
|---|---|---|
| Consonant Doubling (gemination, G) | 1-letter consonant doubled before -*ing/ed* | beg/begging |
| E deletion (elision, EL), | Silent *e* dropped before -*ing*, -*ed* | make/making |
| E insertion (epenthesis, EP) | *e* added after -*s*, -*z*, -*ch*, -*sh* before -*s* | fox/foxes |
| Y replacement (Y) | -*y* changes to -*ie* before -*ed* | try/tries |
| I spelling (I) | *I* goes to *y* before vowel | lie/lying |

# How do we write these in PC-Kimmo?

# PC-Kimmo 2-level Rules

- Rules look very similar to phonological rewrite rules, but their semantics is entirely different
- 2-level rules are completely declarative. No derivation; no ordering

- Rules are in effect modal statements about how a form can, must, or must not be realized

# Form & Semantics of 2-level Rules

- Basic form is

  L:S OP lc ... rc:

- Lexical L pairs with surface S in (optional) left, right context lc, rc. OP is one of

  => Only but not always,

  <= Always but not only

  <=> Always and only

  /<= Never

- lc and rc are 2-level i.e. can address lexical and surface strings

# a:b => l_r

- If the symbol pair a:b appears, it must be in context l_r
- If the symbol pair a:b appears outside the context l_r, FAIL

**lar lar lbr ~~xay~~**
**lbr lar lbr ~~xby~~**

# Example: epenthesis

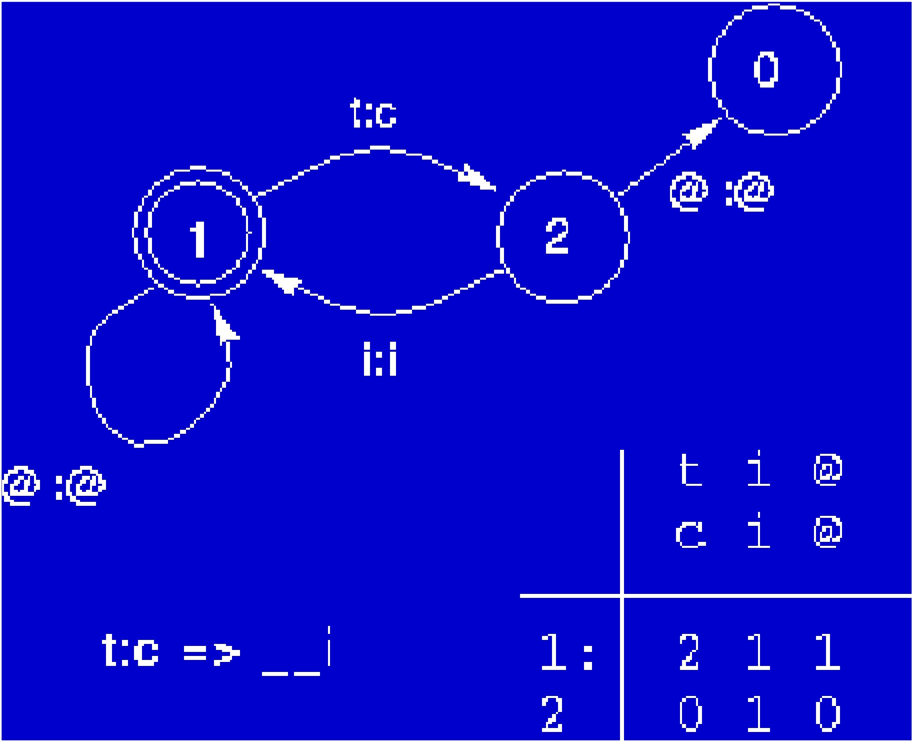
; LR: fox+0s  kiss+0s  church+0s  spy+0s

; SR: fox0es  kiss0es  church0es  spi0e

(note: we NEED the + to mark the end of the root ‘fox’ – we can’t just have fox0s paired with fox0es)

RULE "3 Epenthesis, 0:e => [Csib|ch|sh|y:i] +:0___s [+:0|#]" 7 9

# If a lexical *t* corresponds to a surface *c*, it precedes an *i*



t:c => __i

| | t | i | @ |
|---|---|---|---|
| | c | i | @ |
| 1: | 2 | 1 | 1 |
| 2 | 0 | 1 | 0 |

# a:b <= l_r

- If lexical a appears in context l_r, then it must be realized as surface b
- If lexical a appears in context l_r, if it is realized as anything other than surface b, FAIL

**lar ~~lar~~ lbr xay**
**lbr ~~lar~~ lbr xby**

# Y-I spelling

```
; y:i-spelling
; LR: spy+s  happy+ly  spot0+y+ness
; SR: spies  happi0ly  spott0i0ness

RULE "5 y:i-spelling, y:i <= :C__+:0 ~[i|']"  4 7
```

# a:b <=> l_r

- If the symbol pair a:b appears, it must be in context l_r
- If lexical a appears in context l_r, then it must be realized as surface b
- If the symbol pair a:b appears outside the context l_r, FAIL
- If lexical a appears in context l_r, if it is realized as anything other than surface b, FAIL

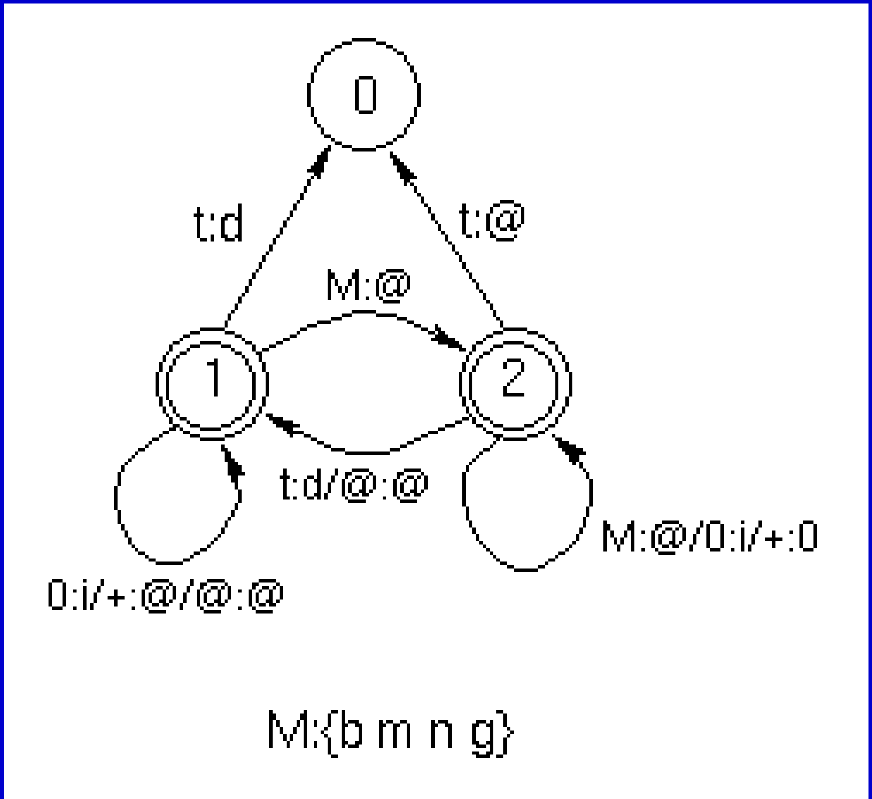
**lar ~~lar~~ lbr ~~xay~~**
**lbr ~~lar~~ lbr ~~xby~~**

# Possessives with ‘s’

```
; s-deletion
; LR: cat+s+'s  fox+s+'s
; SR: cat0s0'0  foxes0'0

RULE "7 s-deletion, s:0 <=> +:0 (0:e) s +:0 '___"
```

# Example: Japanese past tense

- *Voicing*: t:d <=> <b m n g>: (+:0) (0:i) ___



# a:b <= /l_r

- Lexical a is never realized as b in context l_r
- If lexical a is realized as b in the context l_r, FAIL

~~lar~~ lar lbr xay
~~lbr~~ lar lbr xby

# Gemination (consonant doubling)

```
; {C} = {b,d,f,g,l,m,n,p,r,s,t}
RULE "16 Gemination, 0:0 /<= `:0 C* V {C}___+:0 [V|y:]"  5 16
```

# 2-Level Rule Semantics: summary

| | | |
|---|---|---|
| a:b <=> l _ r; | lar ~~lar~~ lbr ~~xay~~ | lexical |
| | lbr ~~lar~~ lbr ~~xby~~ | surface |
| a:b <= l _ r; | lar ~~lar~~ lbr xay | |
| | lbr ~~lar~~ lbr xby | |
| a:b => l _ r; | lar lar lbr ~~xay~~ | |
| | lbr lar lbr ~~xby~~ | |
| a:b /<= l _ r; | ~~lar~~ lar lbr xay | |
| | ~~lbr~~ lar lbr xby | |

# Automata Notation (.rul file)

- What were those funny 2 numbers at the end of the ‘rewrite’ notation?
- They specify the rows and columns of the corresponding automaton
- I’ll show you one, but it’s like Halloween 6 – a nightmare you don’t want to remember
- We have a nicer way of writing them...
- OK, here goes...

# Shudder...

```
RULE "16 Gemination, 0:0 /<= `:0 C* V {C}___+:0 [V|y:]"  5 16
    `  V  y  b  d  f  g  l  m  n  p  r  s  t  +  @
     0  V  @  b  d  f  g  l  m  n  p  r  s  t  0  @
1:   2  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1
2:   2  4  2  2  2  2  2  2  2  2  2  2  2  2  1  2
3:   2  0  0  1  1  1  1  1  1  1  1  1  1  1  1  1
4:   2  1  1  5  5  5  5  5  5  5  5  5  5  5  1  1
5:   2  1  1  1  1  1  1  1  1  1  1  1  1  1  3  1
```

# Limits?

- Can PC-KIMMO do INFIXES?

  Infix:

  Tagalog: *um+hinigi* → ***h<u>um</u>ingi*** **(borrow)**

  Any infixes in 'nonexotic' language like English?

Here's one: *un-f******-believable*

# Summary: what have we learned so far?

- FSTs can model many morphophonological systems - esp. concatenative (linear) phonology
- You can compose and parallelize the FSTs
- Nulls cause nondeterminism - why can’t we get rid of nondeterminism like in FSAs
- What can this machine do?
- What can’t it do?
- How complex can it be? (computational complexity in official sense)
- How complex is it in practice?
- Example from Warlpiri

# Lab 1: PC-kimmo warmup

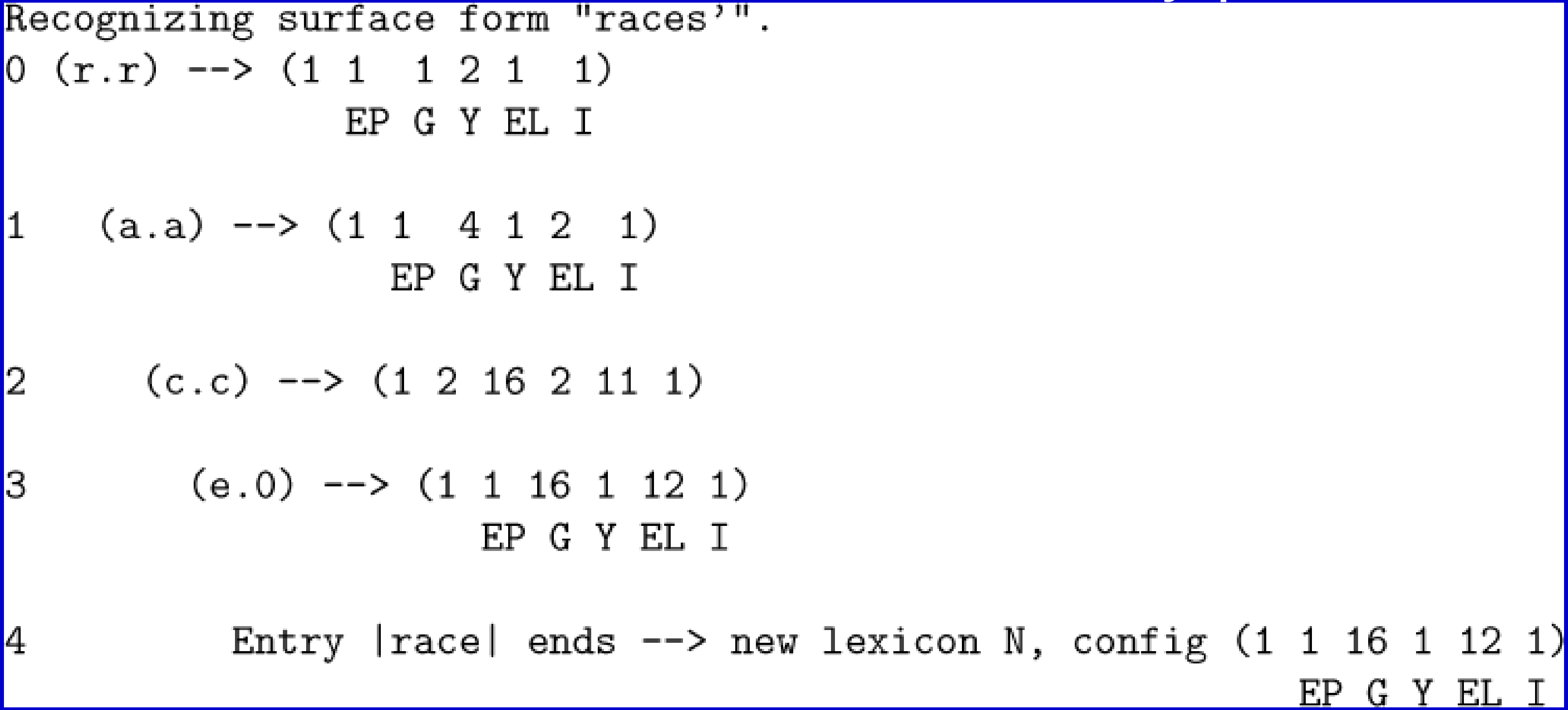
Login to Athena *SUN* workstation

```
Athena>attach 6.863
Athena> cd /mit/6.863/pckimmo-old
Athena>pckimmo
PC-Kimmo>take english
PC-Kimmo> recognize flies
          `fly+s fly+PL
    ...
PC-Kimmo>generate fly+s
          flies
PC-Kimmo>set tracing on
PC-Kimmo>quit
```

# An example – try it yourself

# Outfoxed? Off to the races...

- Trace of an example *races'*
- The machine has to dive down many paths...



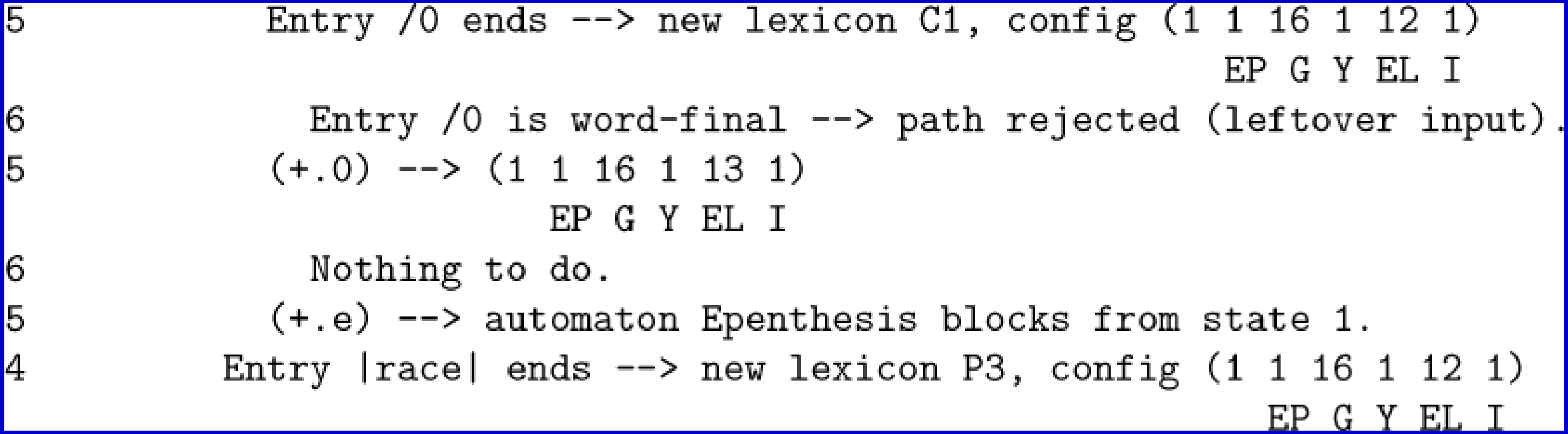
```
Recognizing surface form "races'".
0 (r.r) --> (1 1  1 2 1  1)
               EP G Y EL I

1   (a.a) --> (1 1  4 1 2  1)
                 EP G Y EL I

2     (c.c) --> (1 2 16 2 11 1)

3       (e.0) --> (1 1 16 1 12 1)
                     EP G Y EL I

4         Entry |race| ends --> new lexicon N, config (1 1 16 1 12 1)
                                                         EP G Y EL I
```

# More to go...

***Problem:* e** was paired with 0 (null)…!

(which is wrong - it’s guessing that the form is “racing” - has stuck in an *empty* (zero) *character* after *c* but before *e*) - *elision* automaton has 2 choices

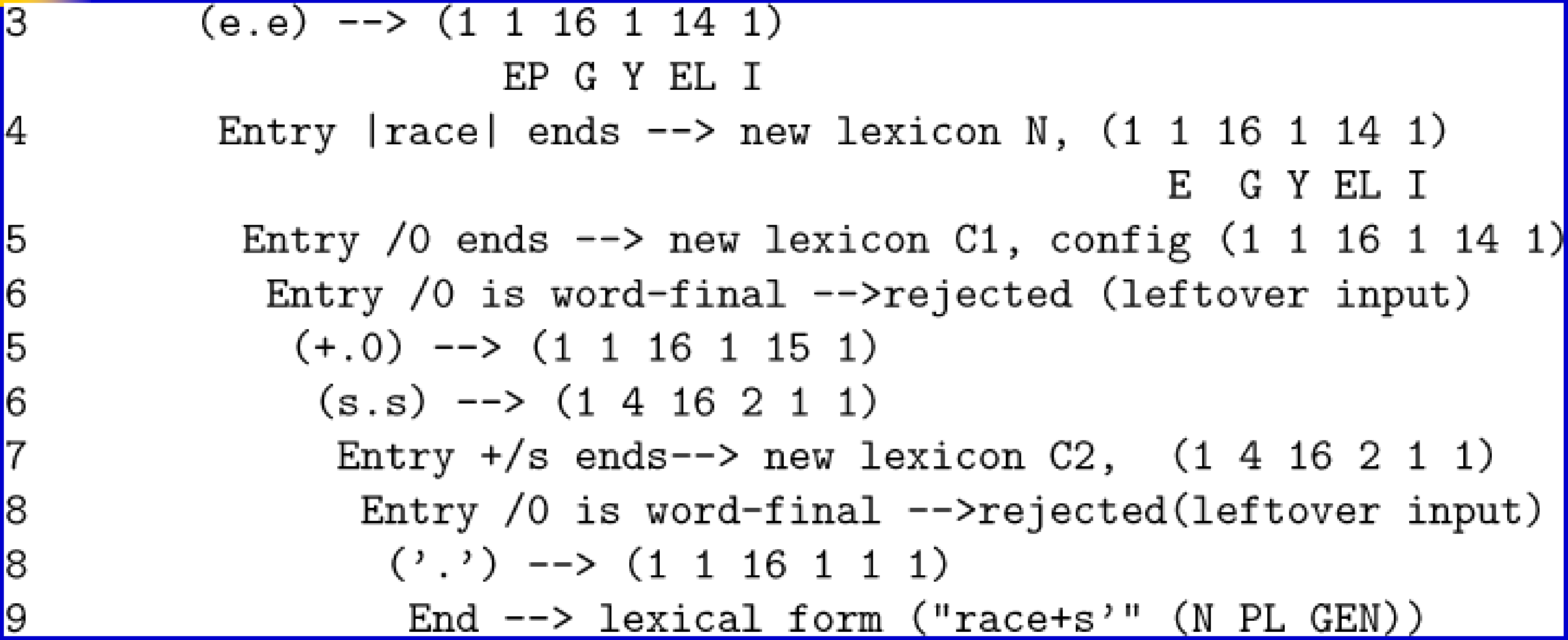
This is *nondeterminism* in action (or inaction)!



```
5           Entry /0 ends --> new lexicon C1, config (1 1 16 1 12 1)
                                                      EP G Y EL I
6             Entry /0 is word-final --> path rejected (leftover input).
5           (+.0) --> (1 1 16 1 13 1)
                              EP G Y EL I
6             Nothing to do.
5           (+.e) --> automaton Epenthesis blocks from state 1.
4         Entry |race| ends --> new lexicon P3, config (1 1 16 1 12 1)
                                                        EP G Y EL I
```

And still more maze of twisty passages, all alike...it’s going to try all the sublexicons w/ this bad guess..

# Winding paths...after 22 steps...



```
3        (e.e) --> (1 1 16 1 14 1)
                      EP G Y EL I
4         Entry |race| ends --> new lexicon N, (1 1 16 1 14 1)
                                                     E  G Y EL I
5          Entry /0 ends --> new lexicon C1, config (1 1 16 1 14 1)
6           Entry /0 is word-final -->rejected (leftover input)
5            (+.0) --> (1 1 16 1 15 1)
6             (s.s) --> (1 4 16 2 1 1)
7              Entry +/s ends--> new lexicon C2,  (1 4 16 2 1 1)
8               Entry /0 is word-final -->rejected(leftover input)
8                (’.’) --> (1 1 16 1 1 1)
9                 End --> lexical form ("race+s’" (N PL GEN))
```

# The End