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

Instructor: Robert C. Berwick

The Menu Bar

- Administrivia

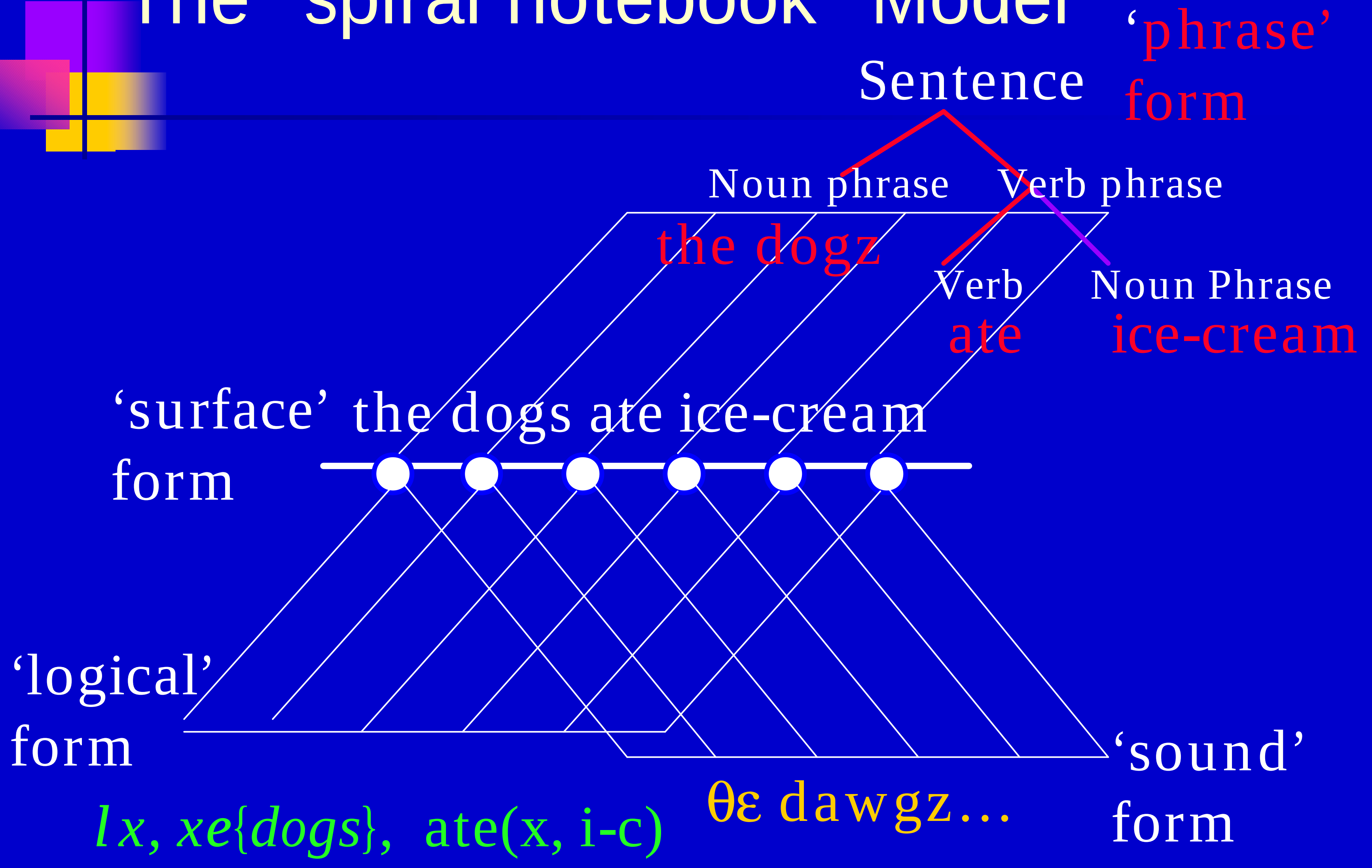
  Questionnaire posted (did you email it?)

  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 <u>transducers</u>
- 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



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

- Parsing words

  Cats $\rightarrow$ 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 $\rightarrow$ organ European~~an~~ $\rightarrow$ Europe

generalization $\rightarrow$ generic noise $\rightarrow$ 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* → ***h<u>um</u>ingi* (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?

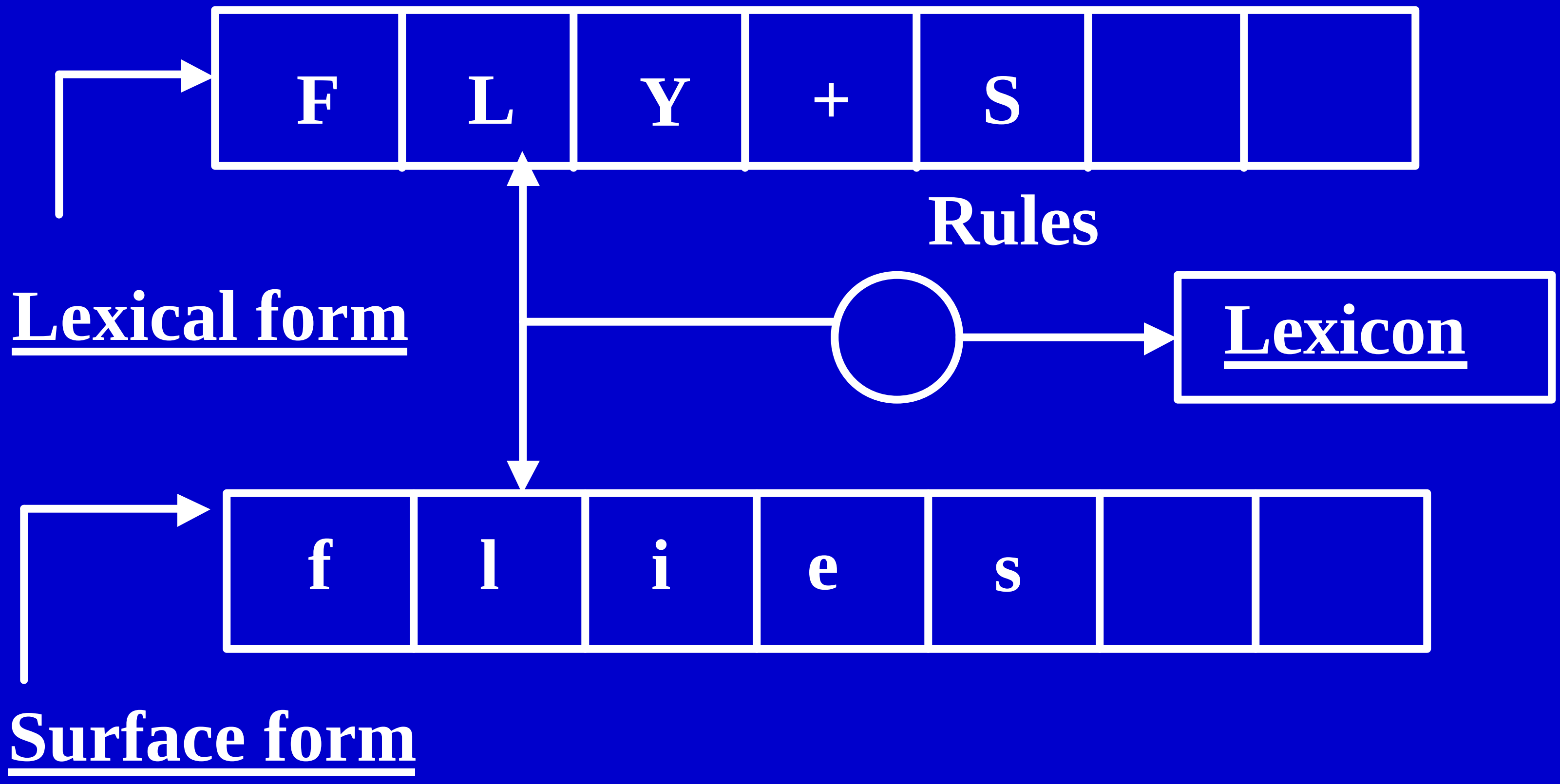
- *What:*

  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



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 <u>slower</u> than *pertoire* (real prefix matters)

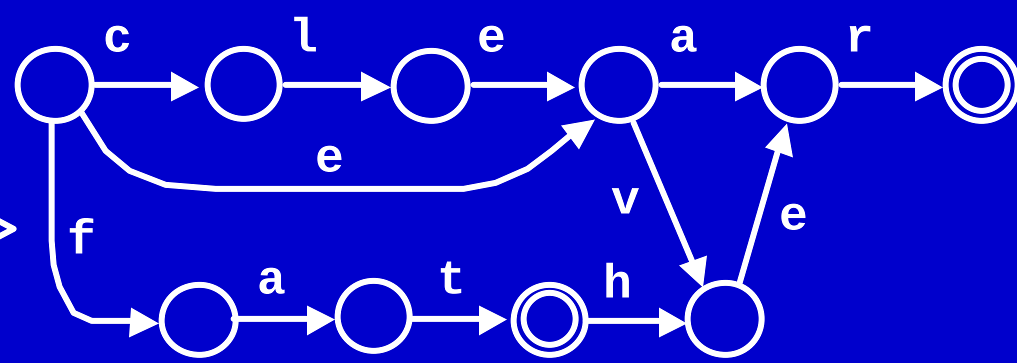
Representing possible roots + affixes as a finite-state automaton

Wordlist

clear
clever
ear
ever
fat
father

compile

Network



/usr/dict/words

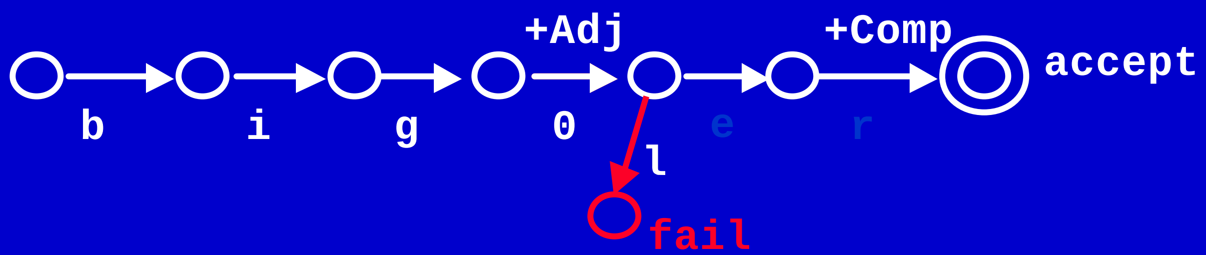
25K words
206K chars

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

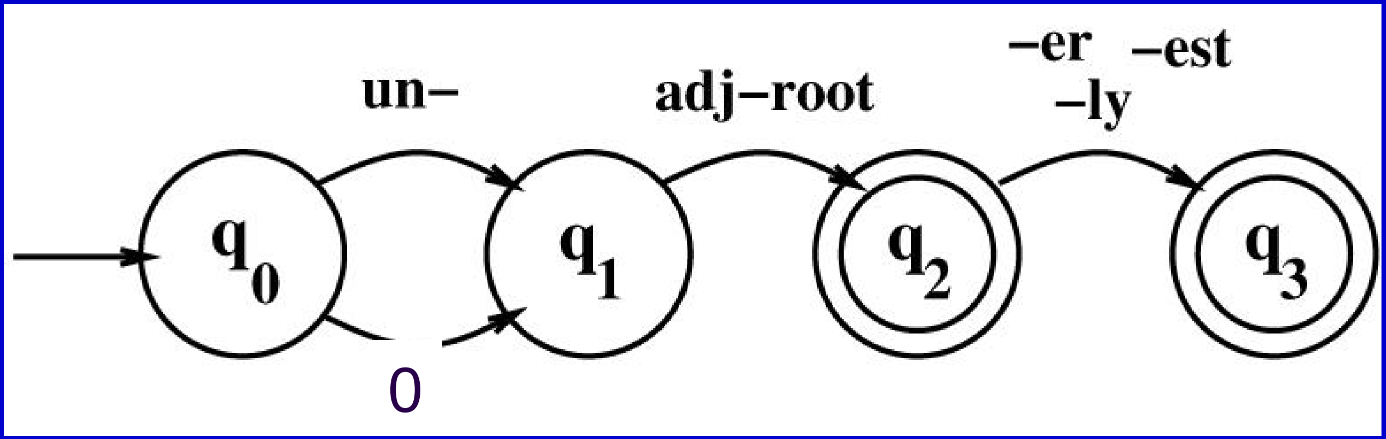
  Clear, clearer, clearest, clearly, unclear, unclearly

  Happy, happier, happiest, happily

  Unhappy, unhappier, unhappiest, unhappily

  Real, unreal, silly

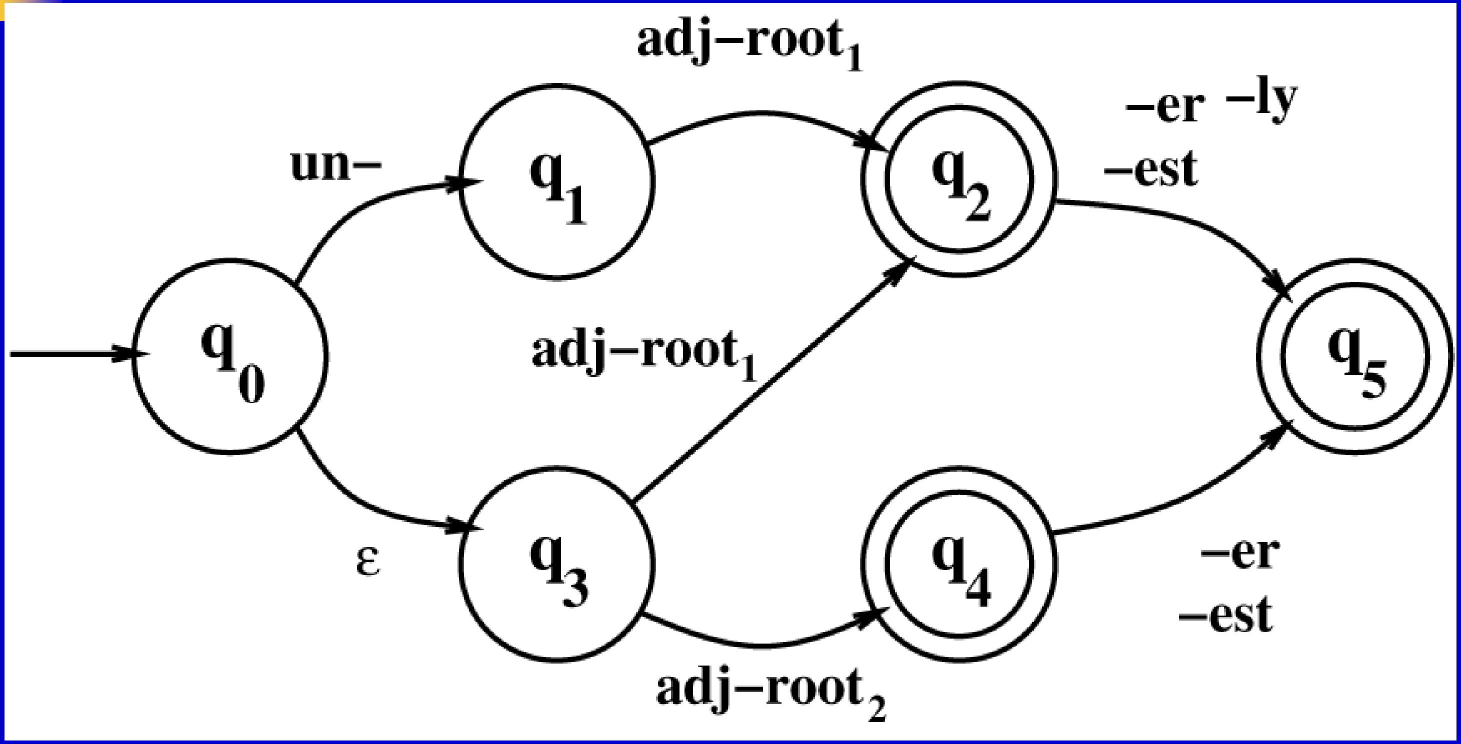
Will this fsa work?



Ans: no!

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

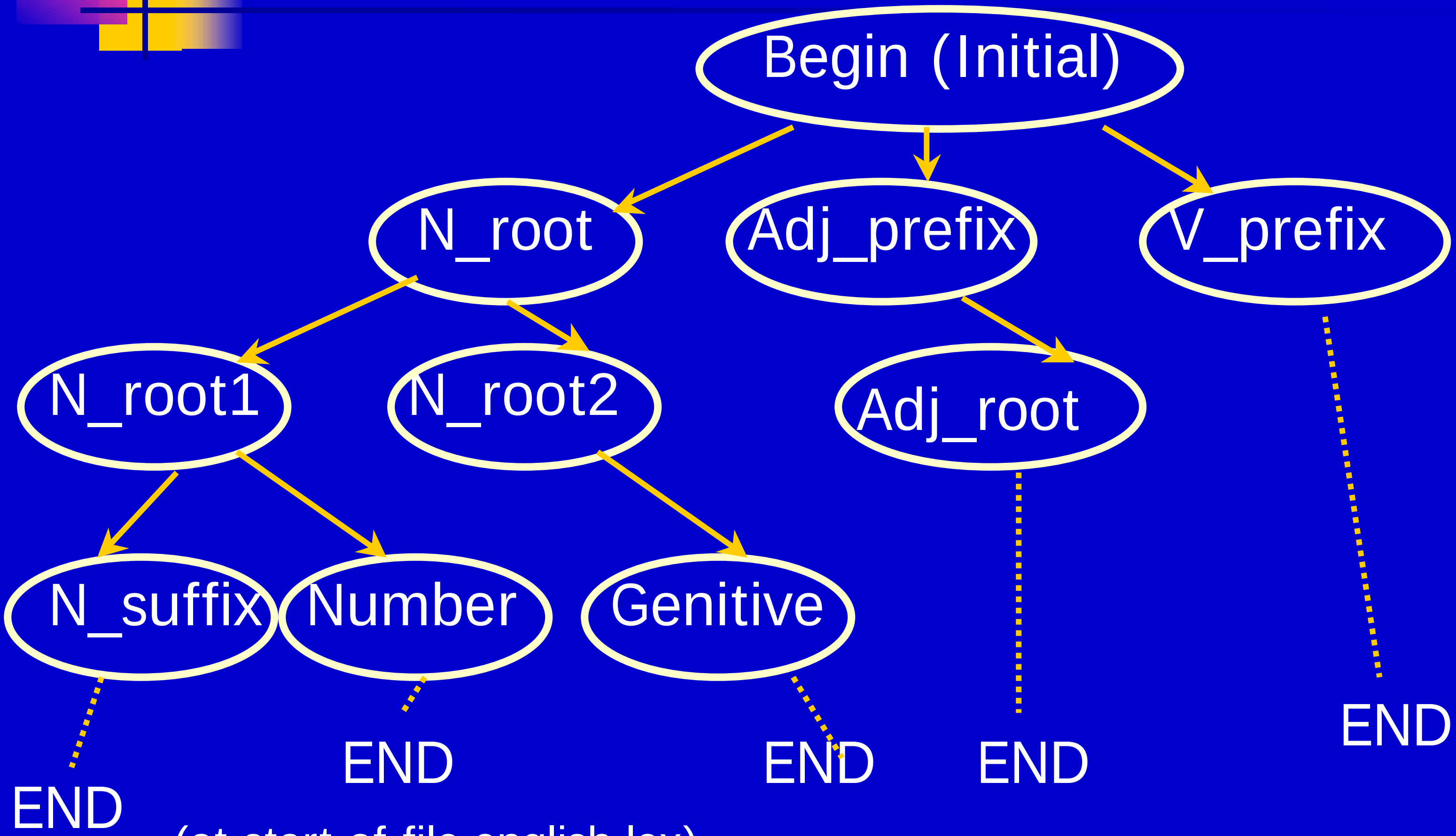
Revised picture



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



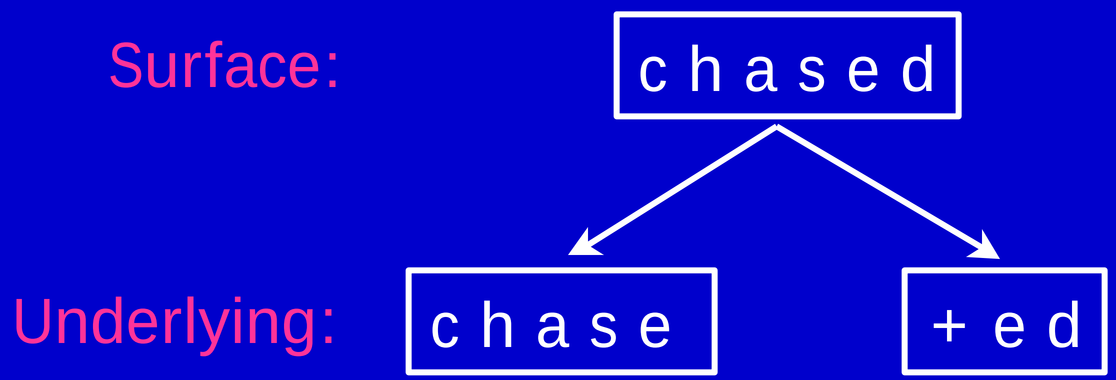
(at start of file english.lex)

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



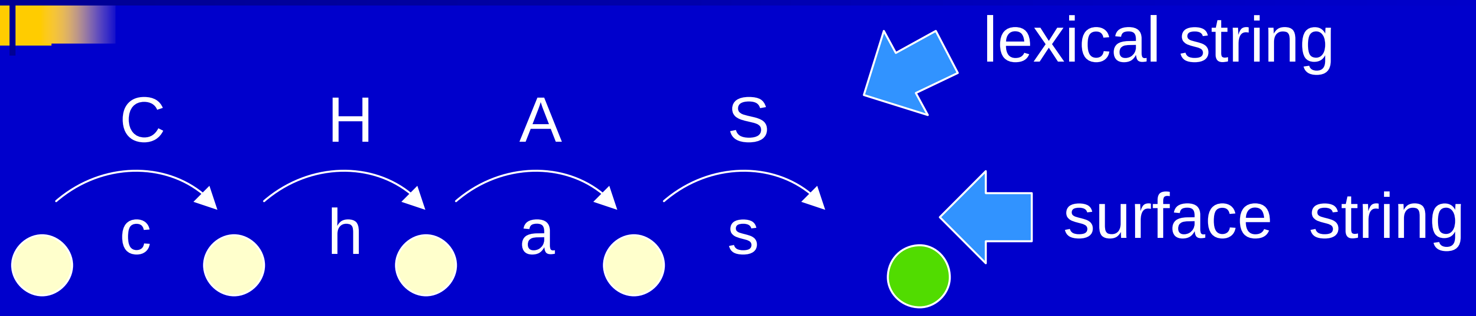
But clearly this can go either way – given the underlying form, we can *generate* the surface form – so we really have a *relation* betw. surface & underlying form, viz.:

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
  - Σ 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
  - δ is a function from $Q \times \Sigma \rightarrow Q$, the transition function

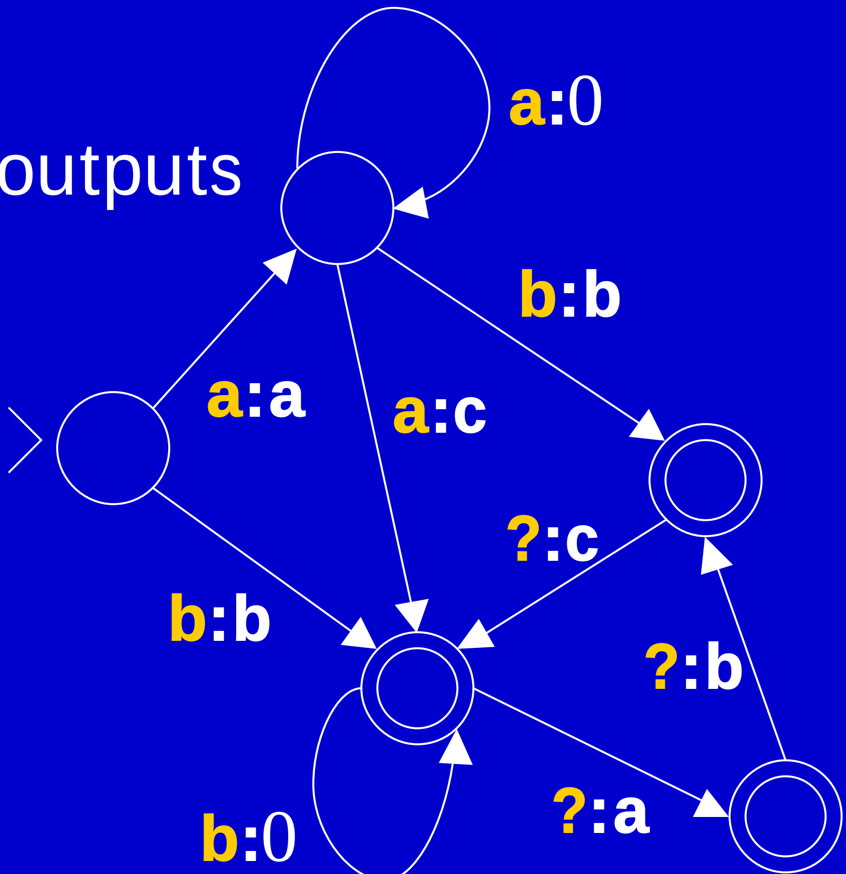
Definition of finite-state transducer

- state set Q
- initial state q_0
- set of final states F
- input alphabet S (also define Σ^*, Σ^+)
- 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

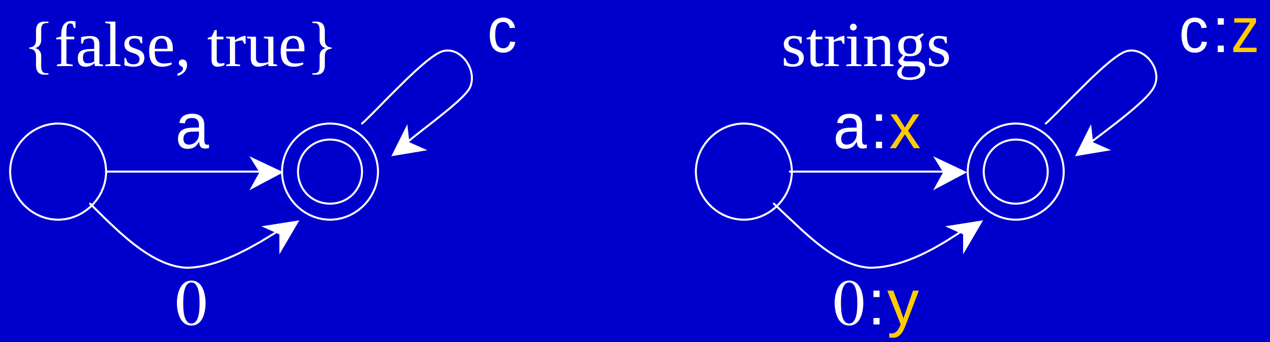
- *Relation:* like a function, but multiple outputs ok
- *Regular:* finite-state
- *Transducer:* automaton w/ outputs

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



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

Acceptors (FSAs) | **Transducers (FSTs)**

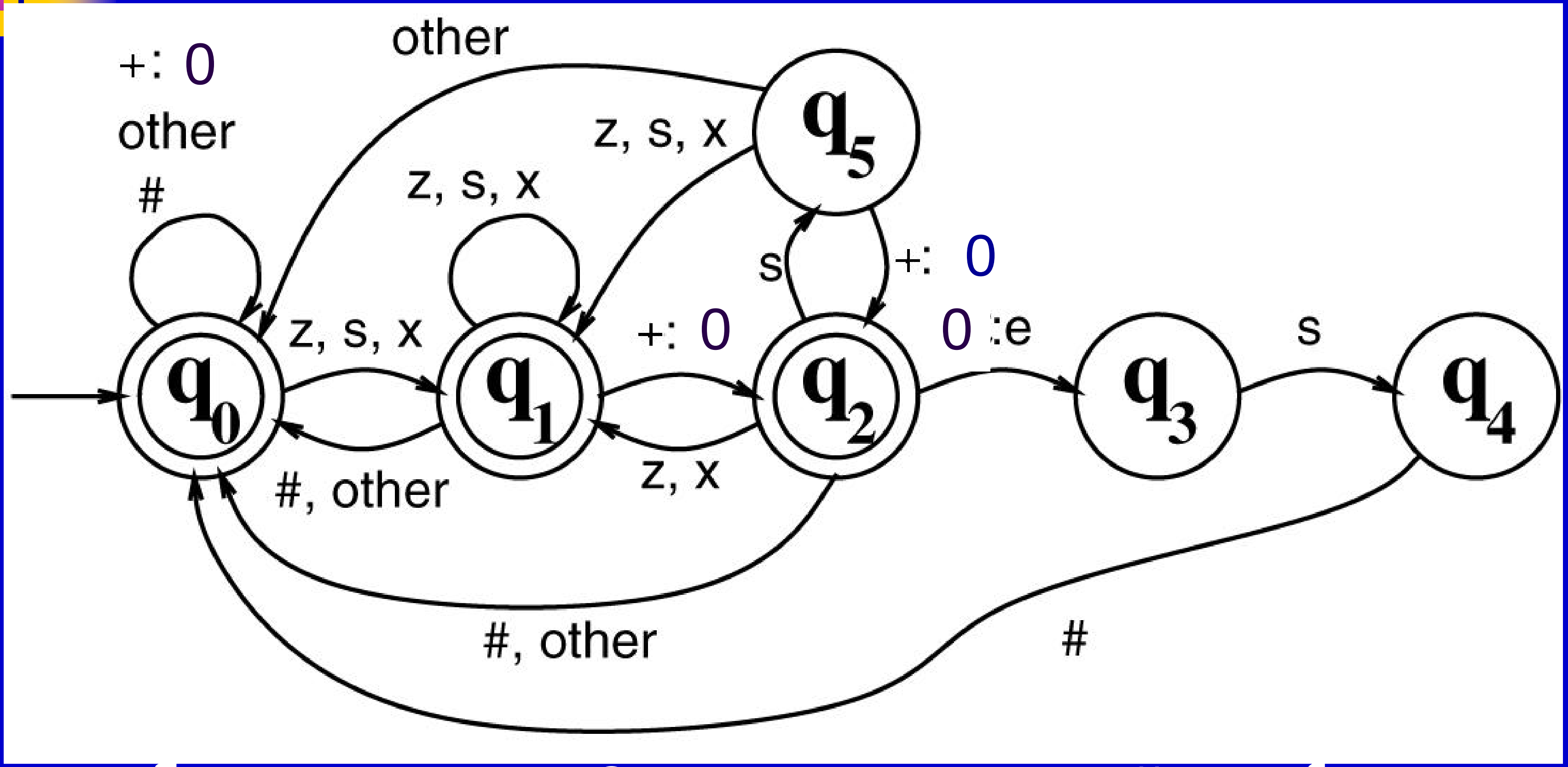


Defining an fst for a spelling-change rule

- 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: <u>Insert e before non initial x,s,z</u>
- Instantiation as an fst (using PC-Kimmo notation)

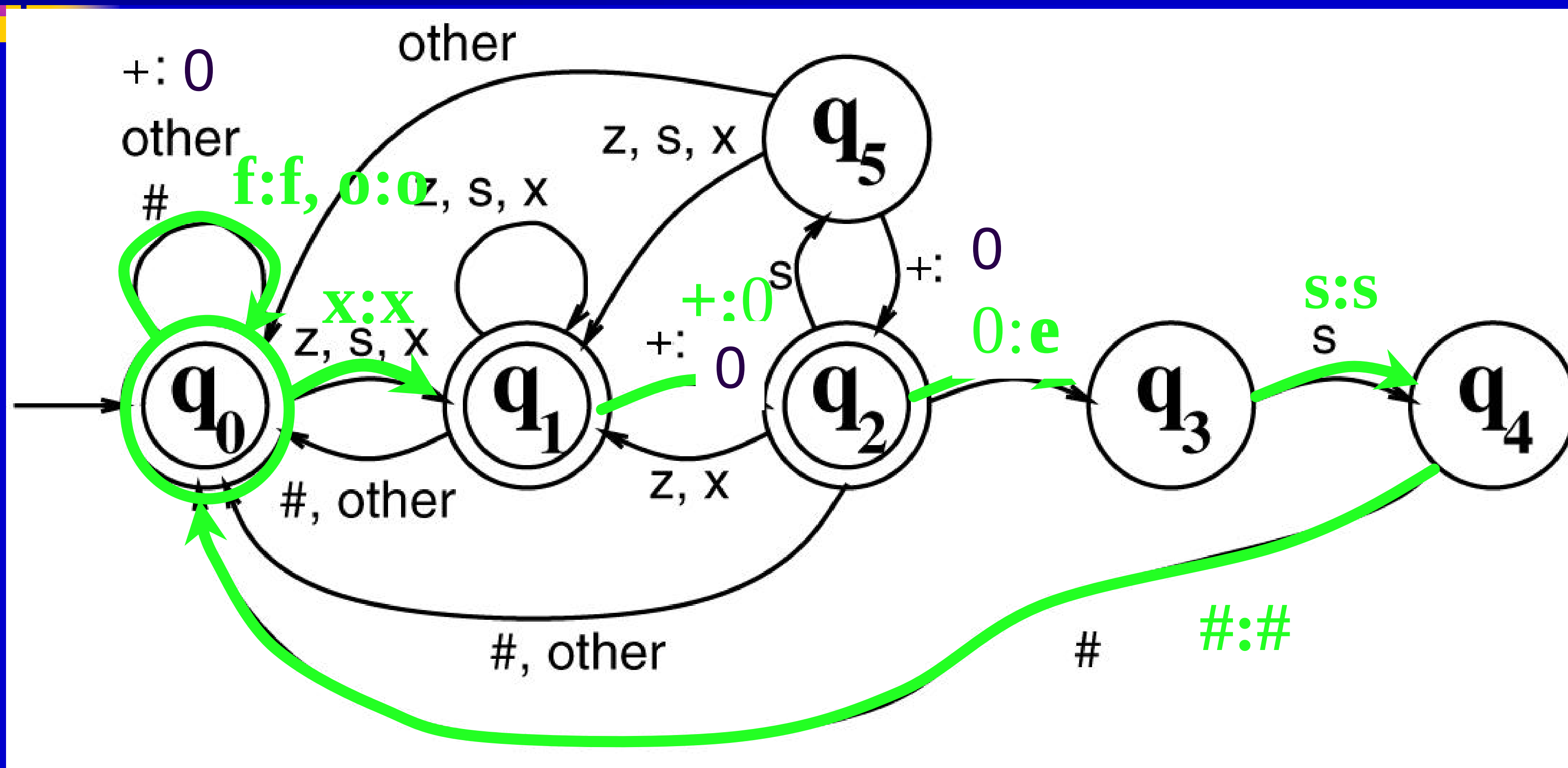
f	o	x	0	e	s	#	**surface**
F	**O**	**X**	**+**	**0**	**S**	**#**	**lexical**

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



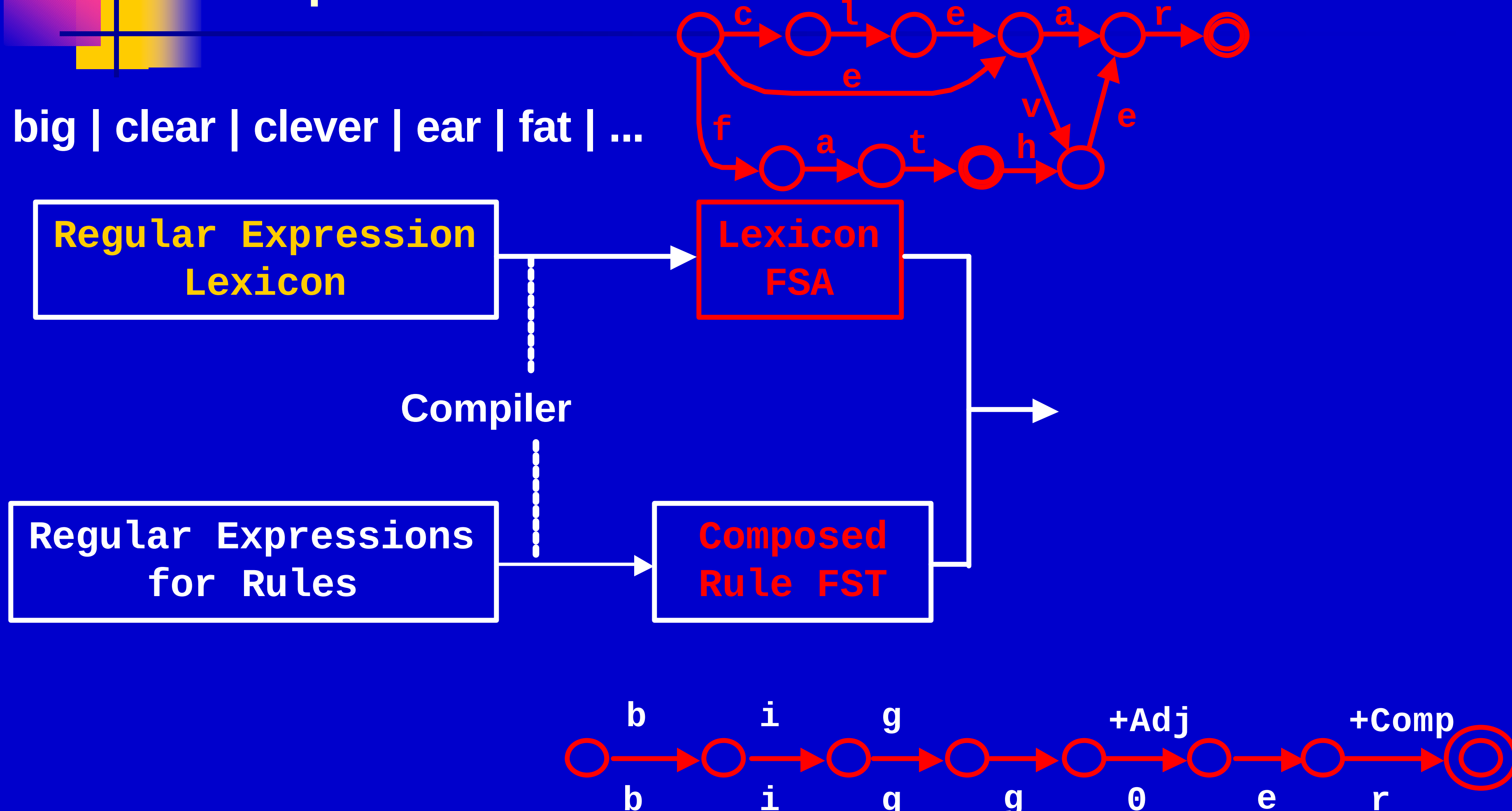
f	o	x	0	e	s	#	**surface**
F	**O**	**X**	**+**	**0**	**S**	**#**	**lexical**

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



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

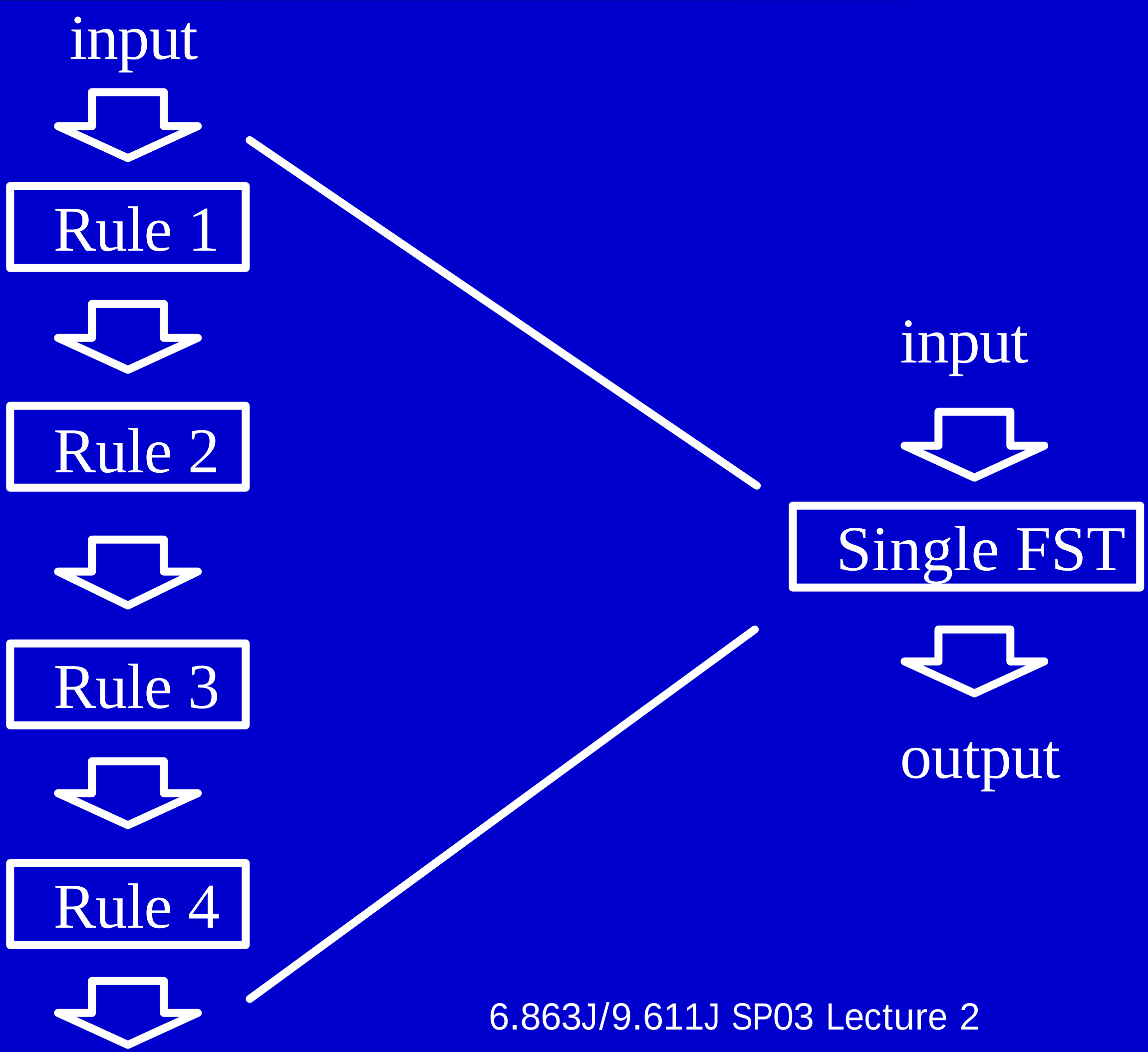
What's the difference?

- 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.,

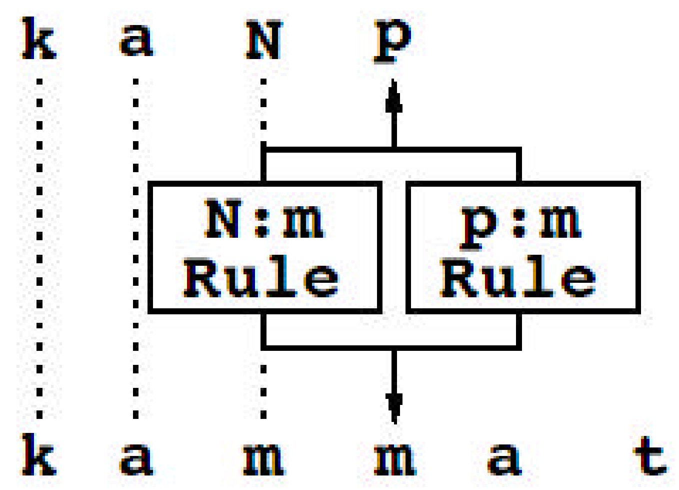
When is this possible?



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

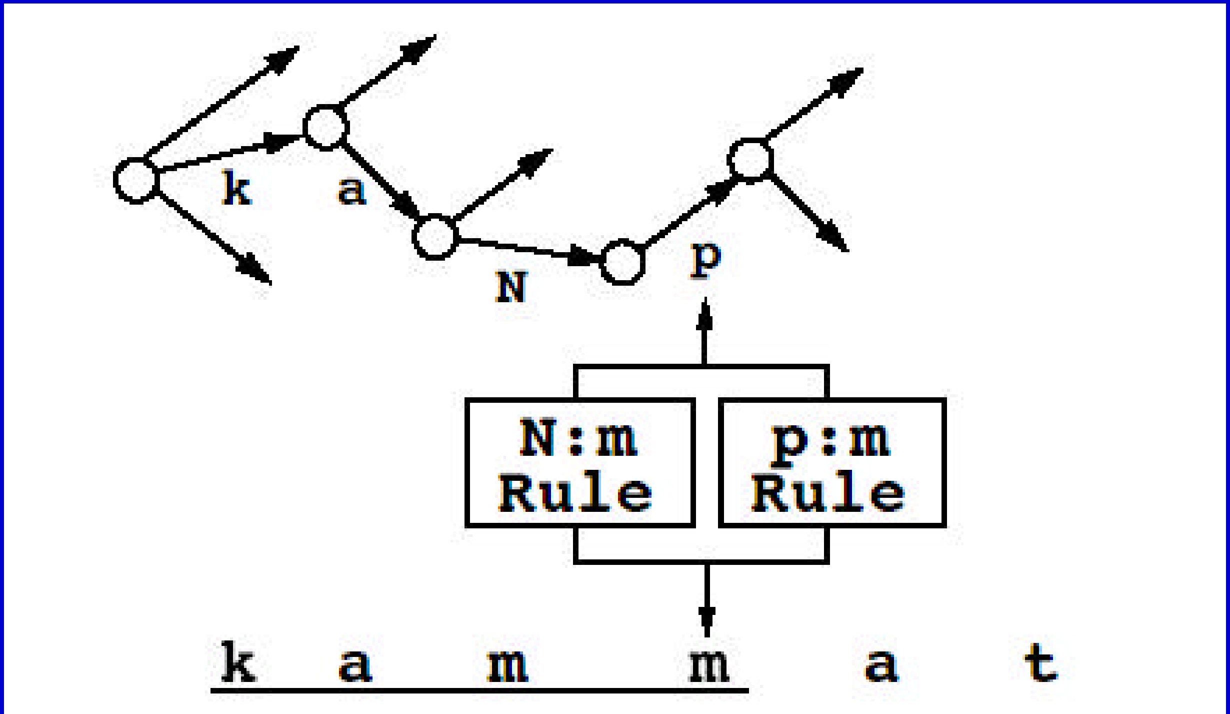
Simultaneous read heads



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

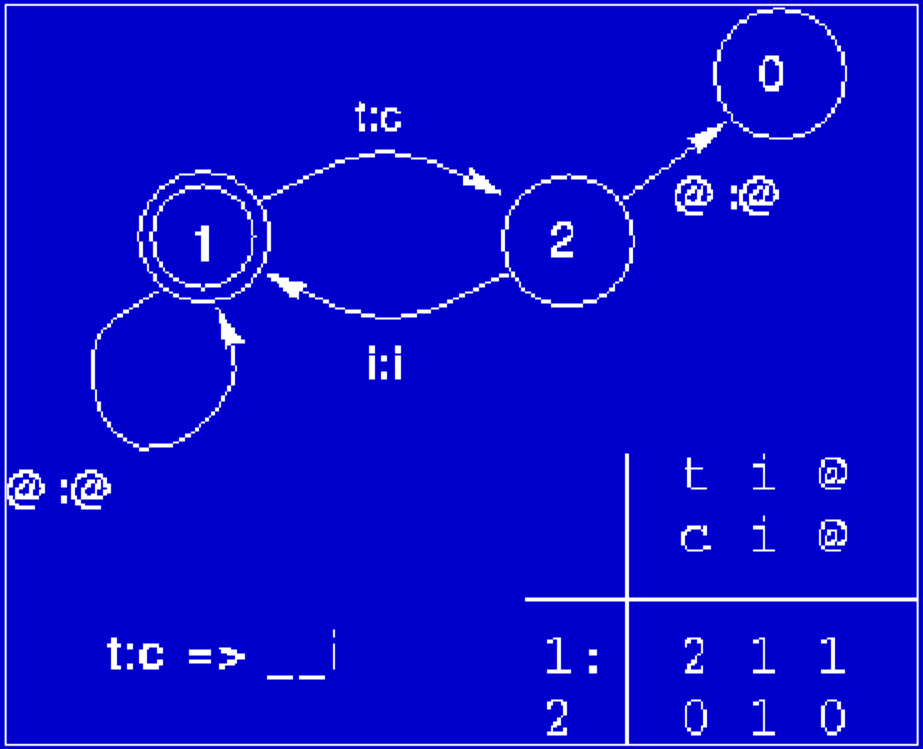
; LR: fox+0s kiss+0s church+0s spy+0s

; 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*



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

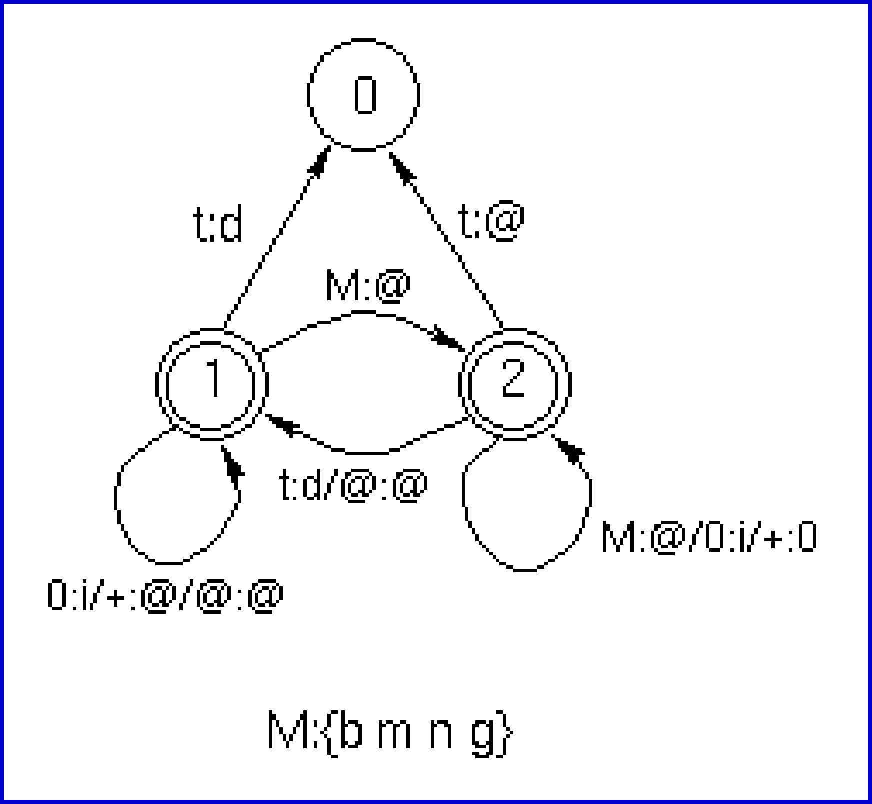
; LR: cat+s+'s fox+s+'s

; 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

Rule					
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