Morphology and
Finite State Transducers

L545
Spring 2017

Morphology

- Morphology is the study of the internal structure of words
  - morphemes: (roughly) minimal meaning-bearing unit in a language, smallest "building block" of words
- Morphological parsing is the task of breaking a word down into its component morphemes, i.e., assigning structure
  - *going* → *go* + *ing*
  - *running* → *run* + *ing*
    - Note: spelling rules are different from morphological rules
- Parsing can also provide us with an analysis
  - *going* → *go*:VERB + *ing*:GERUND

Kinds of morphology

- Inflectional morphology = grammatical morphemes that are required for words in certain syntactic situations
  - *I run*
  - *John runs*
    - -*s* is an inflectional morpheme marking 3rd person singular verb
- Derivational morphology = morphemes that are used to produce new words, providing new meanings and/or new parts of speech
  - *establish*
  - *establishment*
    - -*ment* is a derivational morpheme that turns verbs into nouns

Kinds of morphology (cont.)

- Cliticization: word stem + clitic
  - Clitic acts like a word syntactically, but is reduced in form
  - e.g., *'ve* or *'d*
- Non-Concatenative morphology
  - Unlike the other morphological patterns above, non-concatenative morphology doesn't build words up by concatenating them together
  - Root-and-pattern morphology:
    - Root of, e.g., 3 consonants – *lmd* (Hebrew) = 'to learn'
    - Template of CaCaC for active voice
      - Results in *lamad* for 'he studied'

More on morphology

- We will refer to the stem of a word (main part) and its affixes (additions), which include prefixes, suffixes, infixes, and circumfixes
- Most inflectional morphological endings (and some derivational) are productive – they apply to every word in a given class
  - -*ing* can attach to any verb (*running*, *hurting*)
  - *re*- can attach to virtually any verb (*rerun*, *rehurt*)
- Morphology is more complex in agglutinative languages like Turkish
  - Some of the work of syntax in English is in the morphology
  - Shows that we can't simply list all possible words

Overview

A. Morphological recognition with finite-state automata (FSAs)

B. Morphological parsing with finite-state transducers (FSTs)

C. Combining FSTs

D. More applications of FSTs

A. Morphological recognition with FSA

- Before we talk about assigning a full structure to a word, we can talk about recognizing legitimate words
- We have the technology to do this: finite-state automata (FSAs)

Overview of English verbal morphology

- 4 English regular verb forms: base, -*s*, -*ing*, -*ed*
  - walk/walks/walking/walked
  - merge/merges/merging/merged
  - try/tries/trying/tried
  - map/maps/mapping/mapped
- Generally productive forms
- English irregular verbs (~250):
  - eat/eats/eating/ate/eaten
  - catch/catches/catching/caught/caught
  - cut/cuts/cutting/cut/cut
  - etc.

Analyzing English verbs

- For the –*s* & –*ing* forms, both regular & irregular verbs use base forms
- Irregulars differ in how they treat the past and the past participle forms

- So, we categorize words by their regularity and then build an FSA
  - e.g., *walk* = vstem-reg
  - *ate* = verb-past-irreg

FSA for English verbal morphological analysis

- Q = {0, 1, 2, 3}; S= {0}; F ={1, 2, 3}
- ∑ = {verb-past-irreg, …}
- E = { (0, verb-past-irreg, 3), (0, vstem-reg, 1),
  (1, +past, 3), (1, +pastpart, 3),
  (0, vstem-reg, 2), (0, vstem-irreg, 2),
  (2, +prog, 3), (2, +sing, 3) }

NB: FSA for *morphotactics*, not spelling rules (requires a separate FSA): rules governing classes of morphemes

FSA Exercise: Isleta Morphology

- Consider the following data from Isleta, a dialect of Southern Tiwa, a Native American language spoken in New Mexico:

- [temiban] 'I went'
- [amiban] 'you went'
- [temiwe] 'I am going'
- [mimiay] 'he was going'
- [tewanban] 'I came'
- [tewanhi] 'I will come'

Practising Isleta

- List the morphemes corresponding to the following English translations:
  - 'I'
  - 'you'
  - 'he'
  - 'go'
  - 'come'
  - +past
  - +present_progressive
  - +past_progressive
  - +future
- What is the order of morphemes in Isleta?
- How would you say each of the following in Isleta?
  - 'He went'
  - 'I will go'
  - 'You were coming'

An FSA for Isleta Verbal Inflection

- Q = {0, 1, 2, 3}; S ={0}; F ={3}
- ∑ = {mi, te, a, wan, ban, we, ay, hi}
- E = { (0, mi, 1), (0, te, 1), (0, a, 1),

  (1, mi, 2), (1, wan, 2),

  (2, ban, 3), (2, we, 3), (2, ay, 3), (2, hi, 3) }

B. Morphological Parsing with FSTs

- Using a finite-state automata (FSA) to recognize a morphological realization of a word is useful
- But we also want to return an analysis of that word:
  - e.g. given *cats*, tell us that it's *cat* + N + PL
- A finite-state transducer (FST) do this:
  - Two-level morphology:
    - Lexical level: stem plus affixes
    - Surface level: actual spelling/realization of the word
  - So, for a word like *cats*, the analysis will (roughly) be:

    c:c a:a t:t ε:+N s:+PL

Finite-State Transducers

- While an FSA recognizes (accepts/rejects) an input expression, it doesn't produce any other output
  - An FST, on the other hand, produces an output expression → we define this in terms of relations
- FSA is a recognizer; an FST translates from one expression to another
  - Reads from one tape, and writes to another tape
  - Can also read from the output tape and write to the input tape
    - FSTs can be used for both analysis and generation (bidirectional)

Transducers and Relations

- Goal: translate from the Cyrillic alphabet to the Roman alphabet
- We can use a mapping table, such as:
  - A : A
  - Б : B
  - Г : G
  - Д : D
  - etc.
- We define R = {<A, A>, <Б, B>, <Г, G>, <Д, D>, ..}
  - We can thing of this as a relation R ⊆ Cyrillic X Roman

Relations and Functions

- The cartesian product A X B is the set of all ordered pairs (a, b), where a is from A and b is from B

  A = {1, 3, 9} B = {b, c, d}

  A X B = {(a, b) | a ∈ A and b ∈ B}

  = {1, 3, 9} X {b, c, d}

  = {(1, b), (1, c), (1, d), (3, b), (3, c), (3, d), ((9, b), (9, c), (9, d))}
- A relation R(A, B) is a subset of A X B

  R1(A, B) = {(1, b), (9, d)}
- A function from A to B is a binary relation where for each element a in A, there is exactly one ordered pair with first component a.
- The domain of a function f is the set of values that f maps, and the range of f is the set of values that f maps to

The Cyrillic Transducer

S ={0}; F = {0}

(0, A:A, 0)

(0, Б:B, 0)

(0, Г:G, 0)

(0, Д:D, 0)

….

- Transducers implement a mapping defined by a relation
- R = {<A, A>, <Б, B>, <Г, G>, <Д, D>, ..}
- These relations are called regular relations = sets of pairs of strings
- FSTs are equivalent to regular relations (akin to FSAs being equivalent to regular languages)

FSAs and FSTs

- FSTs, then, are almost identical to FSAs … Both have:
  - Q: finite set of states
  - S: set of start states
  - F: set of final states
  - E: set of edges (cf. transition function)
- Difference: alphabet for FST comprised of complex symbols (e.g., X:Y)
  - FSA: ∑ = a finite alphabet of symbols
  - FST: ∑ = a finite alphabet of complex symbols, or pairs
    - We can alternatively define an FST as using 4-tuples to define the set of edges E, instead of 3-tuples
    - Input & output each have their own alphabet
- NB: As a shorthand, if we have X:X, we often write this as X

FSTs for morphology

- For morphology, using FSTs allows us to:
  - set up pairs between the lexical level (stem+features) and the morphological level (stem+affixes)
    - c:c a:a t:t +N:^ +PL:s
  - set up pairs to go from the morphological level to the surface level (actual realization)
    - c:c a:a: t:t ^:ε s:s
    - g:g o:e o:e s:s e:e ^:ε s:ε
- Can combine both kinds of information into the same FST:
  - c:c a:a t:t +N:ε +PL:s
  - g:g o:o o:o s:s e:e +N:ε +SG:ε
  - g:g o:e o:e s:s e:e +N:ε +PL:ε

Isleta Verbal Inflection

- I will go
- Surface: temihi
- Lexical: te+PRO+1P+mi+hi +FUTURE

te	ε	ε	mi	hi	ε
te	+PRO	+1P	mi	hi	+FUT

- Note: the cells line up across tapes:
- If an input symbol gives rise to more/less output symbols, epsilons are added to the input/output tape in the appropriate positions.

An FST for Isleta Verbal Inflection

- NB: teεε : te+PRO+1P is shorthand for 3 separate arcs …
- Q = {0, 1, 2, 3}; S ={0}; F ={3}
- E is characterized as:

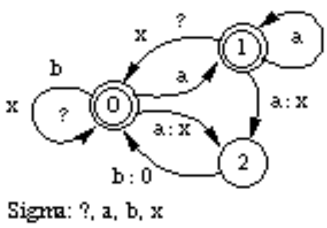
0-> miεε : mi+PRO+3P -> 1
teεε : te+PRO+1P
aεε : a+PRO+2P
1-> mi -> 2
wan
2-> baneε : ban+PAST -> 3
weεε : we+PRES+PROG
ayεε : ay+PAST+PROG
hiε : hi+FUT

A Lexical Transducer

- FSTs can be used in either direction: property of inversion
- l e a v e +VBZ : l e a v e s
  l e a v e +VB : l e a v e
  l e a v e +VBG : l e a v i n g
  l e a v e +VBD : l e f t
  l e a v e +NN : l e a v e
  l e a v e +NNS : l e a v e s
  l e a f +NNS : l e a v e s
  l e f t +JJ : l e f t
- Left-to-Right Input: leave+VBD (“upper language”)
  Output: left (“lower language”)
- Right-to-Left Input: leaves (lower language)
  Output: leave+NNS (upper language)
  leave+VBZ
  leaf+NNS

Transducer Example

- L1= [a-z]+
- Consider language L2 that results from replacing any instances of "ab" in L1 by "x".
- So, to define the mapping, we define a relation R ⊆ L1 X L2
  - e.g., <"abacab", "xacx”>
- Note: “xacx" in lower language is paired with 4 strings in upper language, "abacab", "abacx", "xacab", & "xacx"



NB: ? = [a-z]\{a,b,x}

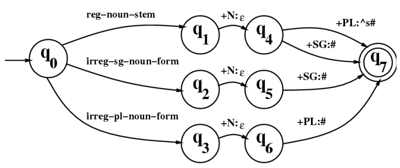
C. Combining FSTs: Spelling Rules

- So far, we have gone from a lexical level (e.g., cat+N+PL) to a surface level (e.g., cats) in two steps
  - Or vice versa
- We'd like to combine those two steps
  - The lexical level of "fox+N+PL" corresponds to "fox^s"
  - And "fox^s" corresponds to "foxes"
- Start: make the two stages clearer
  - Note that, in the following, we'll handle irregular plurals differently than before
  - We'll basically follow Jurafsky & Martin, although there are other ways to do this.

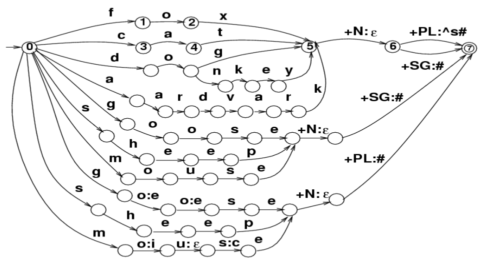
Lexicon FST (1st level)

- The lexicon FST converts a lexical form to an intermediate form
  - dog+N+PL → dog^s
  - fox+N+PL → fox^s
  - dog+V+SG → dog^s
  - mouse+N+PL →mice … because no spelling rules apply
- This will be of the form:
  - 0-> f ->1   3-> +N:^ ->4
  - 1-> o ->2   4-> +PL:s ->5
  - 2-> x ->3   4-> +SG:ε ->6
  - and so on …

English noun lexicon as a FST (Lex-FST)



J&M (1st ed.) Fig 3.9



Expanding the aliases

J&M (1st ed.) Fig 3.11

Rule FST (2nd level)

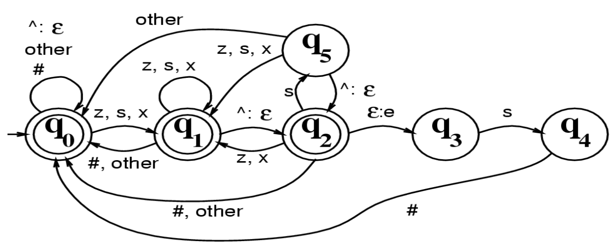
- The rule FST will convert the intermediate form into the surface form
  - dog^s → dogs (covers both N and V forms)
  - fox^s → foxes
  - mice → mice
- Assuming we include other arcs for every other character, this will be of the form:
  - 0-> f ->0   1-> ^:ε ->2
  - 0 -> o ->0   2-> ε:e ->3
  - 0 -> x -> 1   3-> s ->4
- But this FST is too impoverished …

Spelling rule example

- Issues:
  - For *foxes*, we need to account for *x* being in the middle of other words (e.g., *lexicon*)
  - Or, what do we do if we hit an *s* and an *e* has not been inserted?
- The point is that we need to account for all possibilities
  - In the FST on the next slide, compare how word-medial and word-final *x*'s are treated, for example

E-insertion FST (J&M Fig 3.17, p. 64)

$$\varepsilon \rightarrow e / \left\langle \begin{matrix} x \\ s \\ z \end{matrix} \right\rangle \hat{} \_\_ s\#$$

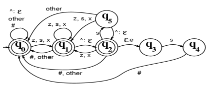


E-insertion FST

f	o	x	^	s	#	*Intermediate Tape*
f	o	x	e	s	#	*Surface Tape*

- Trace:
  - generating foxes# from fox^s#:
    q0-f->q0-o->q0-x->q1-^:ε->q2-ε:e->q3-s->q4-#->q0
  - generating foxs# from fox^s#:
    q0-f->q0-o->q0-x->q1-^:ε->q2-s->q5-#->FAIL
  - generating salt# from salt#:
    q0-s->q1-a->q0-l->q0-t>q0-#->q0
  - parsing assess#:
    q0-a->q0-s->q1-s->q1-^:ε->q2-ε:e->q3-s->q4-s->FAIL

    q0-a->q0-s->q1-s->q1-e->q0-s->q1-s->q1-#->q0



Combining Lexicon and Rule FSTs

- We would like to combine these two FSTs, so that we can go from the lexical level to the surface level.

- How do we integrate the intermediate level?
  - Cascade the FSTs: one after the other
  - Compose the FSTs: combine the rules at each state

Cascading FSTs

- The idea of cascading FSTs is simple:
  - Input1 → FST1 → Output1
  - Output1 → FST2 → Output2
- The output of the first FST is run as the input of the second

- Since both FSTs are reversible, the cascaded FSTs are still reversible/bi-directional.
  - As with one FST, it may not be a function in both directions

Composing FSTs

- We can compose each transition in one FST with a transition in another
  - FST1: p0-> a:b -> p1   p0-> d:e ->p1
  - FST2: q0-> b:c -> q1   q0-> e:f -> q0
- Composed FST:
  - (p0,q0)-> a:c ->(p1,q1)
  - (p0,q0)-> d:f ->(p1,q0)
- The new state names (e.g., (p0,q0)) ensures that two FSTs with different structures can still be composed
  - e.g., a:b and d:e originally went to the same state, but now we have to distinguish those states
  - Why doesn't e:f loop anymore?

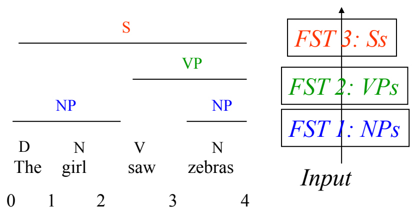
Composing FSTs for morphology

- With our lexical, intermediate, and surface levels, this means that we'll compose:
  - p2-> x ->p3   p4-> +PL:s ->p5
  - p3-> +N:^ ->p4   p4-> ε:ε ->p4 (implicit)
- and
  - q0-> x ->q1   q2-> ε:e ->q3
  - q1-> ^:ε ->q2   q3-> s ->q4
- into:
  - (p2,q0)-> x ->(p3,q1)
  - (p3,q1)-> +N:ε ->(p4,q2)
  - (p4,q2)-> ε:e ->(p4,q3)
  - (p4,q3)-> +PL:s ->(p4,q4)

D. More applications of FSTs

- Syntactic (partial) parsing using FSTs
  - Parsing – more than recognition; returns a structure
  - For syntactic recognition, FSA could be used
- How does syntax work?
  - S → NP VP   D → the
  - NP → (D) N   N → girl   N → zebras
  - VP → V NP   V → saw
- How do we go about encoding this?

Syntactic Parsing using FSTs



FST1
S={0}; final ={2}
E = {(0, N:NP, 2),
(0, D:ε, 1),
(1, N:NP, 2)}

D	N	V	N	
ε	NP	V	NP	*FST1*
ε	NP	ε	VP	*FST2*
ε	ε	ε	S	*FST3*

Noun Phrase (NP) parsing using FSTs

- If we make the task more narrow, we can have more success – e.g., only parse (base) NPs
  - The man on the floor likes the woman who is a trapeze artist
  - [The man]$_{NP}$ on [the floor]$_{NP}$ likes [the woman]$_{NP}$ who is [a trapeze artist]$_{NP}$
- Taking the NP chunker output as input, a PP chunker then can figure out base PPs:
  - [The man]$_{NP}$ [on [the floor]$_{NP}$]$_{PP}$ likes [the woman]$_{NP}$ who is [a trapeze artist]$_{NP}$