CMPT-413

Computational Linguistics

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Formal Language Theory

- Σ is the alphabet, e.g. $\Sigma = \{a, b\}$

- Σ^* is the set of all strings with alphabet Σ
  The Library of Babel by Jorge Luis Borges (published in collections, e.g. *Ficciones*)

- A (formal) Language is a set of strings

Formal Language Theory

- For example, a **regular language** is a set of strings constructed as follows:
  - ϕ is a RL
  - $\forall x \in \Sigma \cup \epsilon, \{x\}$ is a RL
  - If L_1 and L_2 are RLs then the following are RLs,
    * $L_1 \cdot L_2 = \{xy \mid x \in L_1, y \in L_2\}$
    * $L_1 \cup L_2$
    * L_1^*

Formal Language Theory

- A (formal) Grammar is a finite description of a language using a specialized syntax
  e.g. REs are a grammar

- Each RE has an equivalent RL

Formal Language Theory

- Closure properties: intersection, difference, complementation, reversal
- Equivalence of other grammars and languages: context-free languages and context-free grammars.
- Decidability or recognition for languages: given a string, decide whether it is in a language or not.
- A hierarchy of grammars and languages: The Chomsky Hierarchy regular $\subset$ deterministic CF $\subset$ context-free $\subset$ tree-adjoining $\subset$ indexed $\subset$ context-sensitive $\subset$ recursively enumerable

Formal languages and Computational Linguistics

Formal Language theory	CL
Language	Data/corpus (finite)
Grammar	Grammar (inferred from data, produces infinite set of strings)
Automata	Recognition/Generation Algorithms

Grammar Development: Inflectional morphology

- Write an NFA for the following data such that each suffix type gets a single transition (e.g. adding an *-s* is the plural suffix):

  `cat cats` `dog dogs`
  `fox foxes` `mouse mice`

- Note that `foxes` is not an isolated case (irregular), e.g. `suffix`, `suffixes`

Grammar Development: Inflectional morphology

- Many regular cases (captured by a simple rule).
- Some exceptional cases like *mice* that are irregular, and have no simple generative rule
- But also some irregular cases that can be captured by rules like adding the *-es* suffix for plurals in the right context.
- A pervasive property of grammar development for NLs.

Grammar Development: Derivational morphology

- Write an NFA for the following data (ignore the parts of speech, also you can use substrings on the transitions, e.g. a transition can have `demon` on it):

```
demon/N demon+ize/V
demon+ize+ation/N demon+ize+able/A
demon+ize+er/N
formal/A formal+ity/N
formal+ness/N
```

Grammar Development: Derivational morphology

- Does your NFA accept the following additional strings (ignore the parts of speech). If not, what do you need to add to your previous NFA?

```
formal+ize/V formal+ize+ation/N
formal+ize+able/A formal+ize+er/N
demon+ize+able+ity/N
```

Finite-state transducers

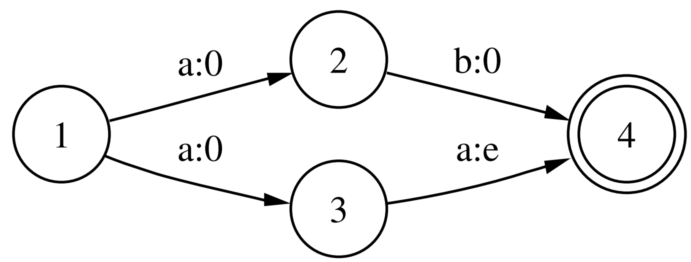
- `a:0` is notation for a map between two alphabets: Σ_1 and Σ_2
- FSTs accept pairs of strings. Language accepted by an FST: $L \subseteq (\Sigma_1^*, \Sigma_2^*)$
- FSAs equate to regular languages, and FSTs equate to **regular relations**
- Formal definition: analogous to the formal definition of FSAs

Finite-state transducers

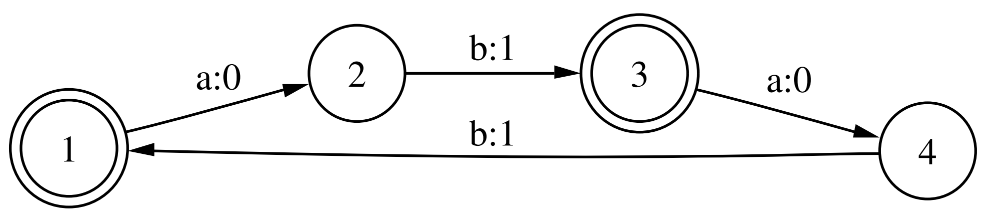
- Formal definition
  - Q: finite set of states, $q_0, q_1, \ldots, q_n$
  - Σ: a finite alphabet composed of input-output pairs $i : o$, where $i \in \Sigma_1$ and $o \in \Sigma_2$ and so $\Sigma \subseteq \Sigma_1 \times \Sigma_2$
  - q_0: Start state
  - F: set of final states
  - $\delta(q, i : o)$: the transition function
- Closure properties: union, inversion, composition

Dealing with `foxes`: Finite-state transducers

- FST for $(ab, \mathtt{00}), (aa, \mathtt{0})$

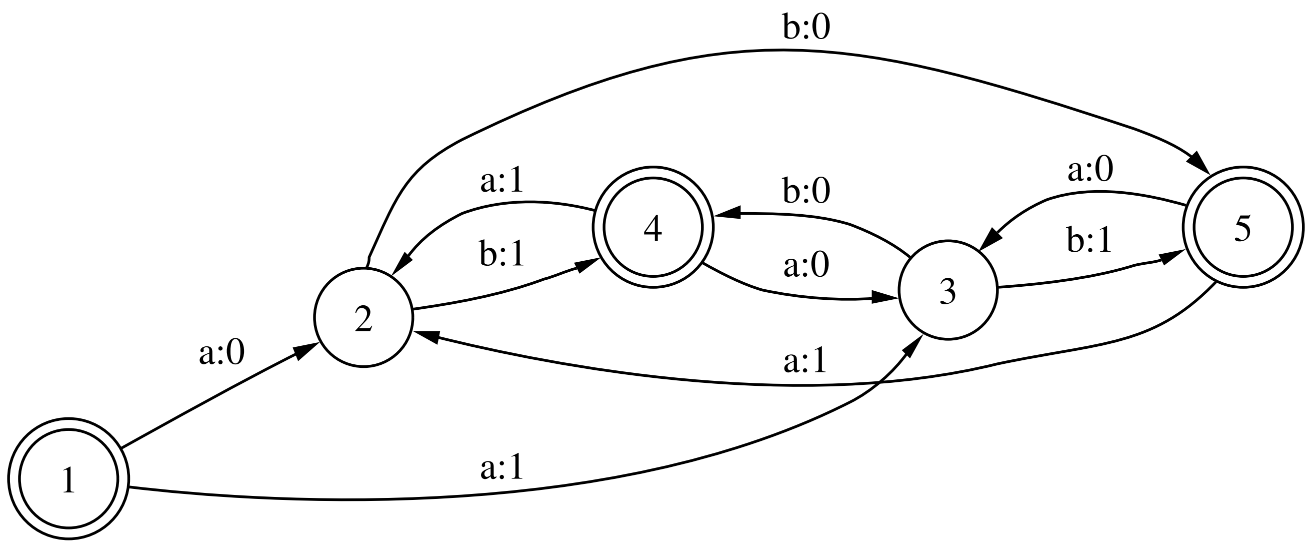


- FST for $(\epsilon, \epsilon), (ab, \mathtt{01}), (abab, \mathtt{0101}), \ldots$



Dealing with `foxes`: Finite-state transducers

- Draw FST for $(\epsilon,\epsilon),(ab,\texttt{00}),(ab,\texttt{01}),(ab,\texttt{10}),(ab,\texttt{11}),(abab,\texttt{0000}),\ldots$



Finite-state Transducers

- The mystery transducer: what does it do?

Morphological Parsing with Transducers

- Simpler to start by thinking of it as generation
- Start with `cat +N +PL` and then use a FST to produce `cats`
- Advantage: since we can add/delete material, we can handle `fox +N +PL` to get the correct form `foxes`
- As a first step, let us convert the `+N+PL` annotation into a suffix form `^s` but ignore the problematic `foxes` case.

Morphological Parsing with Transducers

- Draw a transducer for the following examples:

Input	Output	Input	Output
`cat+N+PL`	cat^s#	`cat+N+SG`	cat#
`dog+N+PL`	dog^s#	`dog+N+SG`	dog#
`fox+N+PL`	fox^s#	`fox+N+SG`	fox#
`mouse+N+PL`	mice#	`mouse+N+SG`	mouse#

Morphological Parsing with Transducers

- A transducer for the e-insertion rule
  if word ends in `x^s#` then output `xes`; similarly for `z^#` and `s^#`
  note the use of the intermediate output from the previous transducer
  define `other = [a-r,t-w,y]`

Input	Inter.	Output	Input	Inter.	Output
`cat+N+PL`	cat^s#	*cats*	`cat+N+SG`	cat#	*cat*
`fox+N+PL`	fox^s#	*foxes*	`fox+N+SG`	fox#	*fox*

Ambiguity when Parsing with FSTs

- Global ambiguity:
  foxes $\longrightarrow$ `fox+N+PL` OR `foxes+V+3SG`
  I saw two foxes yesterday
  That trickster foxes me every time

- Local ambiguity:
  assess has a prefix string which can be analyzed:
  `ass+N+PL` $\longrightarrow$ *asses*

- An FST will return the two answers in the first case, but only return one answer in the second case (even though it will consider a false analysis partway through the string)

Deterministic vs. Non-deterministic

- Deterministic transducers are called **subsequential** transducers (no backtracking when translating one string to another)

- Subsequential transducers with p outputs on reaching the final state are called p-subsequential transducers

- Deterministic transducers where all the states are final states are called **sequential** transducers.

Porter Stemmer

- Unlike our previous FSTs, the Porter Stemmer has no stems
  This makes the FST much smaller as a result – leading to a simple implementation (available widely on the web in many programming languages)

- *ational* $\longrightarrow$ *ate*
  ing $\longrightarrow \epsilon$ if stem contains vowel (e.g. motoring, motor)

Porter Stemmer

- Performs well enough most of the time, but suffers from problems that the FSTs we saw earlier do not have: *organization* $\rightarrow$ *organ*

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

  -Homer Simpson

- Still, it is used often for quick and dirty stemming in many NLP applications due to its simplicity and speed

FST Software in Research and Industry

- FSTs are used for many applications in NLP: morphology, stemming, segmentation

- FST software:

```
Van Noord fsa
    URL:http://odur.let.rug.nl/~Evannoord/Fsa/
AT&T fsm toolkit
    URL:http://www.research.att.com/sw/tools/fsm/
Xerox LinguistX
    URL:http://www.inxight.com/products/oem/linguistx/
Teragram
    URL:http://www.teragram.com/
```

- FSTs are also widely used in aligning sequences in genomics