Learning tiers for long-distance phonotactics

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Introduction

- Languages have long-distance phonotactic patterns
- Children learn these patterns
- How could *anything* learn these patterns?

Introduction

- This talk presents a new learning algorithm for long-distance phonotactic dependencies
- Algorithm is provably correct with specific criteria for learning
- Theoretical result: phonological concepts of *tier* & *locality* are sufficient to induce a tier and grammar from positive data

Long-distance dependencies

- Latin: [l] and [r] alternate, ignoring intervening Cs and Vs (Jensen, 1974)

navalis	'naval'	militaris	'military'
episcopalis	'infinitalis'	floralis	'floral'
infinitalis	'negative'	sepulkralis	'funeareal'
solaris	'solar'	litoralis	'of the shore'
lunaris	'lunar'		

- Finnish: vowels in a word are either [+back] or [−back], ignoring Cs and /i,e/ (Ringen, 1975)

pöütä-nä	'table-ESS'
väkkärä-nä	'pinwheel-ESS'
ulko-ta	'outside-ABL'
pappi-na	'priest-ESS'

Trans.	[−B]	[+B]
i	ü	u
e	ö	o
	ä	a

Learning long-distance dependencies

- One solution: stipulate tier (Hayes and Wilson, 2008)
- Latin

navalis	'naval'	militaris	'military'
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- Strictly Local (SL) learning (García et al., 1990; Heinz, 2010): Contiguous chunks of a certain size
- SL grammar for liquids: $\{ll, rr\}$ are banned *on the stipulated tier*

Learning long-distance dependencies

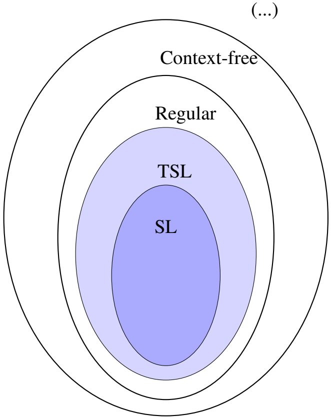
- Such a learner would have a lot of tiers to consider:
  Vowels (Turkish; Clements and Sezer, 1982)
  Vowels except /i,e/ (Finnish; Ringen, 1975)
  Liquids (Sundanese; Cohn, 1992)
  Liquids and non-coronals (Latin; Cser, 2010)
  Sibilants (Samala; Rose and Walker, 2004)
  Sibilants and round vowels, /r/, and some voiced
  obstruents (Koorete; McMullin and Hansson, 2014)
  ...
- An inventory of n phonemes has 2^n possible tiers
- Is it possible to *discover* a tier?

Learning a tier

- Goldsmith and Riggle (2012) offer solution based on mutual information
- They demonstrate an algorithm that works on Finnish data
- Some unanswered questions:
  - Does it work for any tier?
  - What kind of data does it need to see?

Tier-based SL

- *Tier-based Strictly Local (TSL)* formal languages (Heinz et al., 2011): generalization of SL with variable tier
- Hypothesized upper complexity bound for phonotactics (Heinz et al., 2011; Rogers et al., 2013; McMullin and Hansson, 2014)
- Evidence that such boundaries are psychologically real (Lai, 2013, 2014; McMullin and Hansson, 2014)



- I present a learner that *provably* learns TSL, given certain data

TSL grammars

- Given an inventory Σ, a TSL grammar is $G = (T, \overline{S})$ where:
  - $T \subseteq \Sigma$
  - $\overline{S}$ are *banned tier substrings* of elements of T
  - G checks strings if they include a member of $\overline{S}$, *ignoring any elements not on T*
- Example: $\Sigma = \{a, b, c\}$, $T = \{a, b\}$, $\overline{S} = \{aa, bb\}$
  - ✓ $aba, bab, bcacb, bcaccccbca, \ldots$
  - ✗ $aca, acccccca, cabccccbcc, \ldots$
- Latin: $\Sigma = \{l, r, C, V\}$, $T = \{l, r\}$, $\overline{S} = \{ll, rr\}$
- TSL learned like SL *if* we know T (Heinz et al., 2011)
- What if we don't?

The TSL Learning Algorithm

- Problem: Given an inventory Σ and a sufficient data set D of words, what is the TSL grammar for the language that generated D?
- This problem is *solvable* (Jardine and Heinz, in prep.)
- Partial solution given here to illustrate the main idea
- Goal: find nontier elements (freely distributed)
- Key: learn about tier piece-by-piece, building on knowledge

The TSL Learning Algorithm

- *Path*: $\langle \sigma_1, X, \sigma_2 \rangle$
  "σ_1 precedes σ_2 (at any distance), and
  X is the set of symbols which appear between them"

(1) $$\mathit{paths}(CVClVr) = \{ \begin{array}{l} \langle C, \{\}, V \rangle \\ \langle C, \{V\}, C \rangle \\ \quad \ldots \\ \langle C, \{V, C, l, \}, r \rangle \\ \quad \ldots \\ \langle V, \{C, l\}, V \rangle \\ \quad \ldots \\ \langle V, \{\}, r \rangle \end{array} \}$$

The TSL Learning Algorithm (simple version)

- Problem: Given an inventory Σ and a sufficient data set D of words, what is the TSL grammar $(T, \overline{S})$ for the language that generated D?
- Solution:
  a. Calculate all paths for all words in D
  b. Start with $T = \Sigma$ as guess for tier
  c. Look at set of paths $\langle \sigma_1, X, \sigma_2 \rangle$ where σ_1, σ_2 on tier and X are non-tier elements (σ_1 and σ_2 are *tier adjacent*)
  d. Is there any member of T which is tier adjacent to every other member?
  e. If so, remove that member from T, and repeat from step (c)
  f. If not, return T, and $\overline{S}$ is any tier elements not tier-adjacent

The TSL Learning Algorithm (simple version)

- $\Sigma = \{C, V, l, r\}$
- T initialized to $\{C, V, l, r\}$
- Considering paths $\langle \sigma_1, \{\}, \sigma_2 \rangle$, are any symbols free?

$$T = \{C, V, r, l\}$$

navalis	militaris
episcopalis	floralis
infinitalis	sepulkralis
solaris	litoralis
lunaris	migrus
certe	

Data
(Latin; Jensen, 1974; Odden, 1994; Cawley, 2014)

The TSL Learning Algorithm (simple version)

- Yes! C is a free element:

$\langle \#, \{\}, C\rangle$	**n**avalis
$\langle C, \{\}, \#\rangle$	navali**s**
$\langle C, \{\}, C\rangle$	epi**sc**opalis
$\langle l, \{\}, C\rangle$	sepu**lk**ralis
$\langle C, \{\}, l\rangle$	**fl**oralis
$\langle r, \{\}, C\rangle$	ce**rt**e
$\langle C, \{\}, r\rangle$	mi**gr**us
$\langle V, \{\}, C\rangle$	n**av**alis
$\langle C, \{\}, V\rangle$	na**va**lis

- C is thus removed, and $T = \{V, r, l\}$

$$T = \{C, V, r, l\}$$

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Data

(Latin; Jensen, 1974; Odden, 1994; Cawley, 2014)

- Considering paths $\langle \sigma_1, \{\}, \sigma_2\rangle$, and $\langle \sigma_1, \{C\}, \sigma_2\rangle$ are any symbols free?

The TSL Learning Algorithm (simple version)

- Yes! V is a free element:

$\langle \#, \{\}, V \rangle$	**e**piscopalis
$\langle V, \{\}, \# \rangle$	cert**e**
$\langle l, \{\}, V \rangle$	nava**li**s
$\langle V, \{\}, l \rangle$	nav**al**is
$\langle V, \{\}, r \rangle$	c**er**te
$\langle r, \{\}, V \rangle$	mig**ru**s
$\langle V, \{\}, V \rangle$	none!
$\langle V, \{C\}, V \rangle$	n**ava**lis

- V is thus removed, and $T = \{r, l\}$

$T = \{V, r, l\}$

navalis	militaris
episcopalis	floralis
infinitalis	sepulkralis
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certe	

Data
(Latin; Jensen, 1974; Odden, 1994; Cawley, 2014)

- Considering paths $\langle \sigma_1, X, \sigma_2 \rangle$, where $X \subseteq \{C, V\}$, are any symbols free?

The TSL Learning Algorithm (simple version)

- No! We don't see paths:
  $\langle l, X, l\rangle$
  $\langle r, X, r\rangle$
  (where $X \subseteq \{C, V\}$)
- l and r are thus not removed
- ll and rr are added to $\bar{S}$
- Algorithm halts

$$T = \{r, l\}$$

navalis	militaris
episcopalis	floralis
infinitalis	sepulkralis
solaris	litoralis
lunaris	migrus
certe	

Data
(Latin; Jensen, 1974; Odden, 1994; Cawley, 2014)

The TSL Learning Algorithm (simple version)

- TLA correctly returns $T = \{r, l\}, \overline{S} = \{ll, rr\}$ on this small data set
- Idea: find free elements, using a decreasing T to aid search
- Result on natural language data: on harmonic forms from Goldsmith and Riggle (2012)'s Finnish corpus
  - over inventory {u, o, a, ü, ö, ä, i, e, J, T, S, N}
  - TLA learns
    $T = \{\text{u}, \text{o}, \text{a}, \text{ü}, \text{ö}, \text{ä}\}$
    $\overline{S} = \{\text{uü}, \text{uö}, \text{uä}, \text{oü}, \text{oä}, ..., \text{äa}\}$
- It can be *proven* that this algorithm will always be correct, given the right data

Discussion

- Full version of algorithm accounts for ‘free blockers’ — members of tier which do not play role in generalizaton
  - E.g., *g*, *m* in Latin (*legalis* ‘legal’ **legaris*)
- Full version provably learns entire TSL class (Jardine and Heinz, in prep)
- However, it requires more data

Discussion

- Neither version of algorithm does well with raw natural language data
- Issue: local dependencies prevent removal from tier
- Ex. from Finnish: [d] not followed by other consonants
- Integrating features (as in test Finnish inventory) will likely help with raw data
- Another issue: what if we need more than one tier?
- Future work: do humans learn like this? (Finley, 2012; McMullin and Hansson, 2015)

Conclusion

- Introduced algorithm that finds a tier and long distance dependencies
- Key is incrementally learning the tier and generalizing on that knowledge
- Algorithm is guaranteed to learn a *class* of phonotactic constraint, given the right data
- Theoretical result: phonological concepts of tier and locality are sufficient for finding particular tier and particular long-distance dependencies
- While some limitations, brings us closer to theory of how grammars for long distance phonological phenomena can be reliably acquired from corpora (by humans?)

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