The Computational Structure of Phonological and Phonetic Knowledge

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Download the slides!

Overview

- I provide a novel way for understanding the relationship between the phonetic properties of sound patterns with the phonological properties.

- Specifically, I relate both high-level and low-level characterizations using a computational approach.
  - This provides a bridge for formally connecting the types of abstract and concrete analyses that researchers argue over.
  - My accounts show how to unify disparate approaches.

- In general I show that it is possible to posit more abstract, discrete, representations of phonological knowledge as long as one is specific about the way the computations work.

What is the Nature of Phonological Knowledge?

- Phonological Knowledge:
  - Rules/Constraints
  - Representations

- What is the nature of this knowledge?
  - Some argue that it is Categorical.
  - Others argue that is is Gradient.

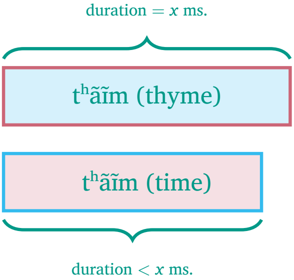
Alternatively

How directly does phonetic substance play a role in phonological representation and reasoning?

Categorical: Jakobson et al. (1951), Chomsky and Halle (1968), McCarthy (2003), Bermúdez-Otero (2007), Reiss and Volenec (2020), Du and Durvasula (2024); **Gradient:** Coleman and Pierrehumbert (1997), Bybee (2001), Flemming (2001), Albright and Hayes (2006), Coetzee and Pater (2008), Ernestus (2011), Smolensky and Goldrick (2016), Lionnet (2017); among many others on both sides.

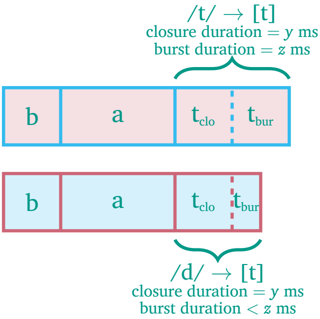
Some Empirical Phenomena Implicated in the Debate

Variation in Homophone Duration



Within the same category of speech more frequent homophones are shorter in duration

Incomplete Neutralization



Phonologically neutralized segments show systematic similarities to their underlying form along certain cues

A Deathblow to Formalism?

"...[incomplete neutralization] demonstrate[s] that the phonological structures employed by human speakers cannot provide the digital foundation for a formal system of language that is required by generative phonology as well as by all formal theories of language."

Port and Leary (2005) - *Against Formal Phonology*

Another Issue for Discrete Phonology?

"One set of implications of these results relates to the nature of phonological forms. The models of language production mentioned so far assume that phonological representations are composed of an alphabet of discrete segments…As we saw earlier, such a move is problematic for the [homophone] data…"

Gahl (2008) - *Time and thyme are not homophones*

Translation is too Complex?

"Rather than positing inexplicit implementation rules or proliferating ad hoc features, we propose to base phonological representation on an explicit and direct description of articulatory movement in space and over time...incorporation of time (in particular) into the basic definition of phonetic units can simplify much of the complex translation that is required in an approach like that of implementation rules."

Browman and Goldstein (1986) - *Towards an Articulatory Phonology*

Focus of Today's Talk

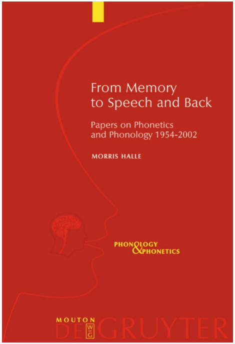
The big picture

- Is it possible to maintain categorical phonological knowledge while still explaining systematic continuous phonetic phenomena?
- Yes. The Blueprint Model of Production provides an explanation for how symbolic knowledge determines systematic fine-grained acoustic variation.
- Yes. Continuous gestural representations can be inferred directly from symbolic representations and vice versa.

Outline

Phonological and Phonetic Knowledge

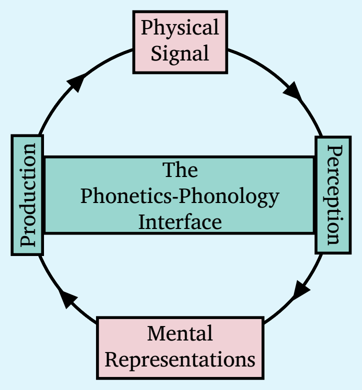
"...the overt aspects of language – the articulatory actions and the acoustic signal they produce – cannot be properly understood without reference to the covert aspect of language"



Halle (2003)

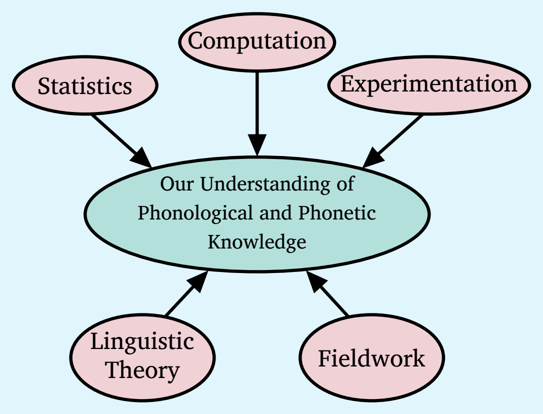
Phonological and Phonetic Knowledge

- The Phonetics-Phonology Interface is the translation mechanism between...
  - "the categories of the speaker's message to the utterance's articulatory continuum"
  - "the auditory continuum to the categories of the listener's recognition of the message's phonological content"



Kingston (2019)

A Multi-Faceted Approach

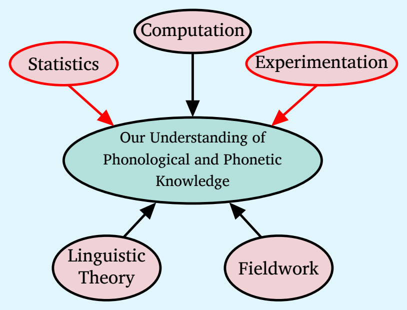


Durvasula and Nelson (2018), Nelson and Durvasula (2021), Taherkhani et al. (under revision), Taherkhani and Nelson (2024), Nelson (forthcoming), Nelson (2022), Nelson (in prep), Nelson and Heinz (2022), Nelson and Heinz (in press), Nelson and Baković (2024), Nelson (to appear)

Speech Perception as a Window into Phonological Representation

Durvasula, K. and Nelson, S. (2018). Lexical re-tuning targets features. *Proceedings of the 2017 Annual Meeting on Phonology*.

Nelson, S. and Durvasula, K. (2021). Lexically-guided perceptual learning does generalize to new phonetic contexts. *Journal of Phonetics*.

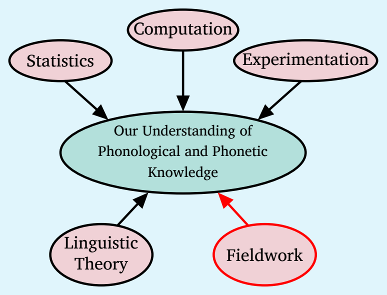


- I found that context-independent sub-segmental representations were implicated during the perception process, thus providing insight into representational knowledge.

Fieldwork as a Source of New Phenomena

Taherkhani, N. and Nelson, S. (2024). Southern Tati: Takestani Dialect. *Journal of the International Phonetic Association*.

Taherkhani, N., Nelson, S., and Heinz, J. (under revision). A Contrastive Hierarchy for Vowels in Southern Tati: Takestani Dialect.



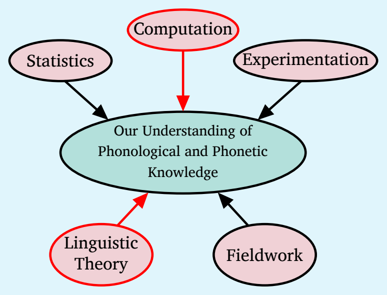
- I documented a typologically rare vowel inventory and showed its implications for the phonology of the language, thus expanding our understanding of what types of phonological and phonetic knowledge are possible.

Formalizing Theoretical Proposals

Nelson, S. (2022). A model theoretic perspective on phonological feature systems. *Proceedings of the Society for Computation in Linguistics*.

Nelson, S. (forthcoming). The logic and typology of derived environment effects. *Doing Computational Phonology*.

Nelson, S. and Baković, E. (2024). Underspecification without underspecified representations. *Proceedings of the Society for Computation in Linguistics*.



- Most recently, I showed how underspecification can be viewed as a property of computation rather than representation which has implications for theories of phonology as well as phonetic implementation and parsing.

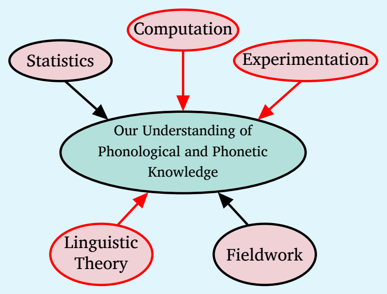
Computational Models of Production

Nelson, S. and Heinz, J. (2022). Incomplete neutralization and the blueprint model of production. *Proceedings of the 2021 Annual Meeting on Phonology*.

Nelson, S. and Heinz, J. (in press). The blueprint model of production. *Phonology*.

Nelson, S. (to appear). Optionality and the Phonetics-Phonology Interface. *Proceedings of WCCFL 42*.

Nelson, S. (in prep). Inferring linear order from non-linear gestural representations.



- The focus of today's talk!

The Blueprint Model of Production

Section Outline

1. Computation and Functions
2. Prior views of implementation
3. The Blueprint Model of Production
4. Simulating Empirical Data

Key Idea

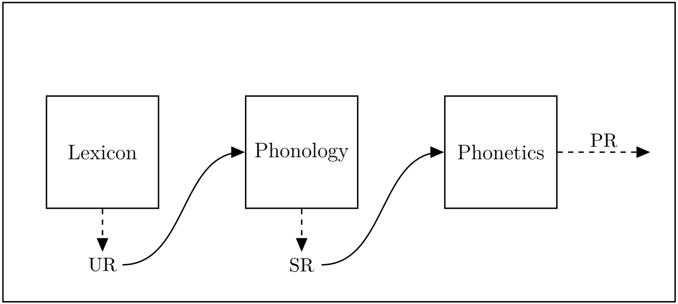
I propose a new model of the phonetics-phonology interface that shows how empirical phenomena like incomplete neutralization and variation in homophone duration are compatible with formal/discrete models of phonological knowledge.

Computation

- Typed functions, a generalization of the λ-calculus (a universal model of computation) can bring together two definitions of computation.
- $A :: B \rightarrow C$ describes a function A that maps B type things to C type things.
- An information processing device (A) takes some information (B) and processes it into something new (C).

Sipser (2013); Marr (1982); Pierce (2002); Church (1932, 1933)

Modular Feed-Forward Model



- The common view of the production process in generative linguistics is what is called the modular feed-forward model.

Pierrehumbert (2002); Bermúdez-Otero (2007); Kenstowicz (2010)

Thinking in Functions

- Phonology is a function that maps *UR*'s to *SR*'s ($P :: UR \rightarrow SR$)
- Phonetics is a function that maps *SR*'s to *PR*'s ($A_{\mathrm{MFF}} :: SR \rightarrow PR$)

Roark and Sproat (2007), Heinz (2018)

Modular Feed-Forward Model Redux

- Since phonology has the type $UR \to SR$ and phonetics has the type $SR \to PR$, the Modular Feed-Forward Model is a composed function $MFF :: UR \to PR$.
  - $A_{\text{MFF}}(P(UR)) = PR$

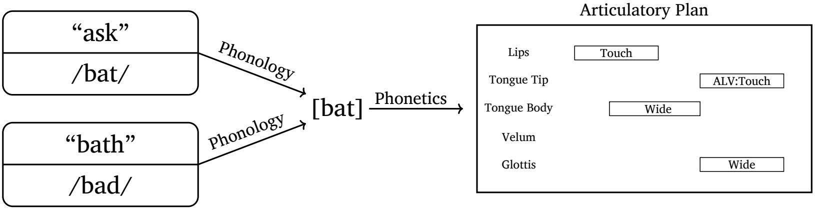
$$\begin{tikzcd} UR \arrow[r, "P"] \arrow[rr, bend left, "A_{\text{MFF}}"] & SR \arrow[r, "A"] & PR \end{tikzcd}$$

Questioning the Modular Feed-Forward Model

- Structuring the production process this way is what has lead researchers to question the validity of a traditional phonological grammar that maps discrete inputs to discrete outputs.

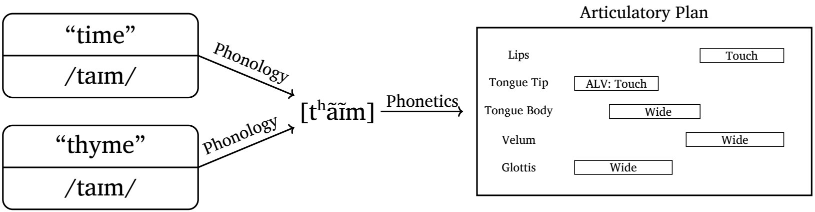
Problem 1 for the Modular Feed-forward Model

- Incomplete neutralization is a problem for the Modular Feed-Forward Model which predicts that two items with the same phonological surface form should have the same phonetic properties.



Problem 2 for the Modular Feed-Forward Model

- Variation in homophone duration is a problem for the Modular Feed-Forward Model which once again predicts that two items with the same phonological surface form should have the same phonetic properties.



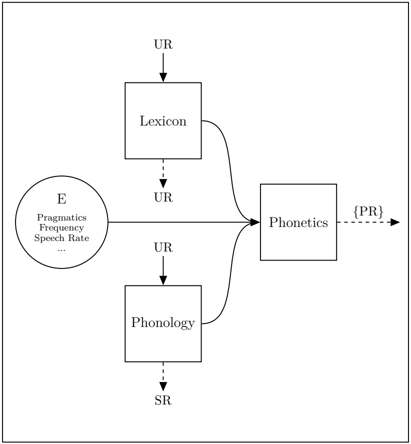
Taking a Step Back

- Our description of what a system does influences the way data is interpreted in relation to that system.
- By changing the structure of the system, it may provide a new interpretation of familiar data.

The Blueprint Model of Production

- Suppose two people use the same blueprint to build a picnic table
  1. Person A builds the table for indoor use
  2. Person B builds the table for outdoor use
- They use the same materials and same tools and end up with basically the same table.
- But Person B adds a clear coat of weatherproofing since the table will be kept outside.
- To the naked eye they're the same table! But there are subtle, fine-grained differences depending on how the table is to be used.

The Blueprint Model of Production



Nelson and Heinz (in press) - *Phonology*

The Blueprint Model of Production

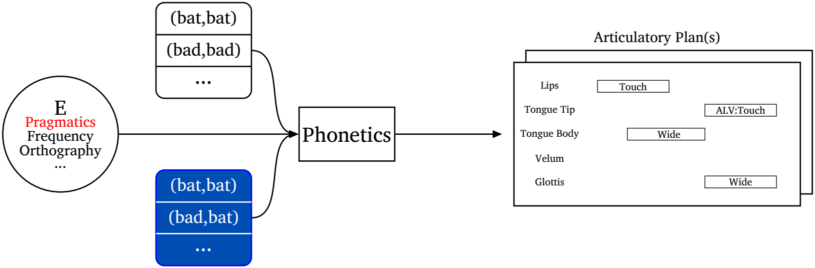
- The inputs to the phonetics function are the lexicon and phonology functions, as well as extra-grammatical information that influences production.
  - The lexicon is a function with type $L :: UR \rightarrow UR$.
  - Phonology is *still* a function with type $P :: UR \rightarrow SR$.
  - E is a cover type for extra-grammatical information.

- When a function takes a function as an input it is called a **higher-order function**.

- The phonetics function in the Blueprint Model of Production has type $A_{\text{BP}} :: L \rightarrow P \rightarrow E \rightarrow \{PR\}$.

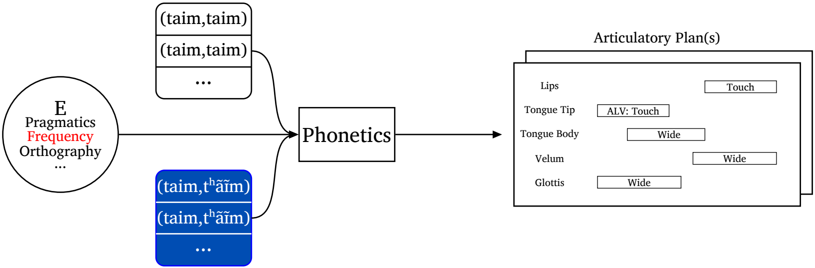
Problem 1 Is No Problem

- The Blueprint Model does not predict that two items with the same phonological surface form should necessarily have the same phonetic properties.



Problem 2 Is No Problem

- The Blueprint Model of production maintains a distinction between lexical items in the phonetics module.
- This distinction + extra-grammatical information makes variation unsurprising.



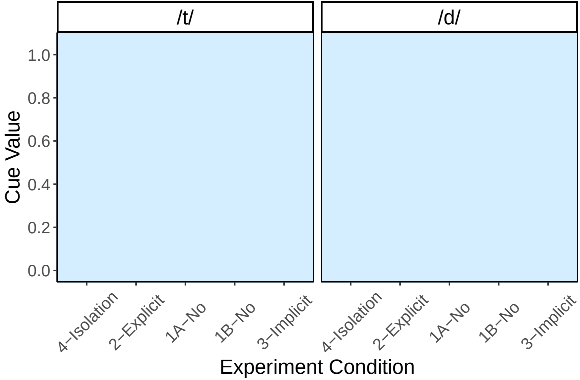
Simulating Empirical Phenomena

"Computational-level theories of capacities are not quantitative but qualitative models: They reveal the internal formal structure of a system, or the invariants that allow it to exercise a particular capacity across situations, conditions."

- Simulations show that the Blueprint Model of Production can produce systematic continuous phonetic effects with discrete phonological knowledge.

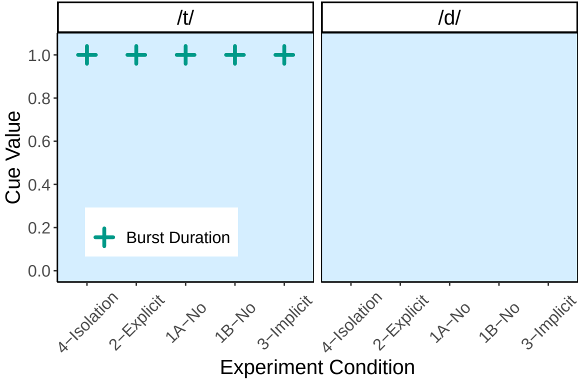
van Rooij and Baggio (2021); Simon (1990); Newell and Simon (1975)

Simulating Incomplete Neutralization with the Blueprint Model of Production



Port and Crawford (1989)

Simulating Incomplete Neutralization with the Blueprint Model of Production



Port and Crawford (1989)

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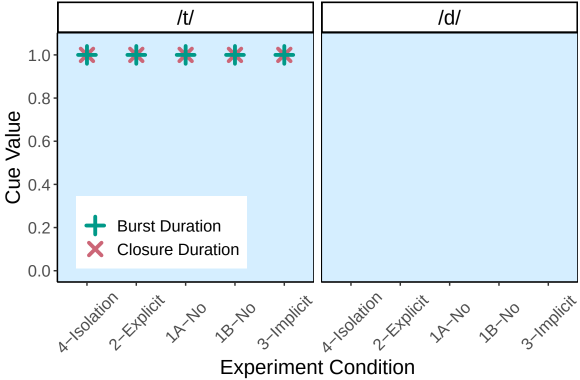

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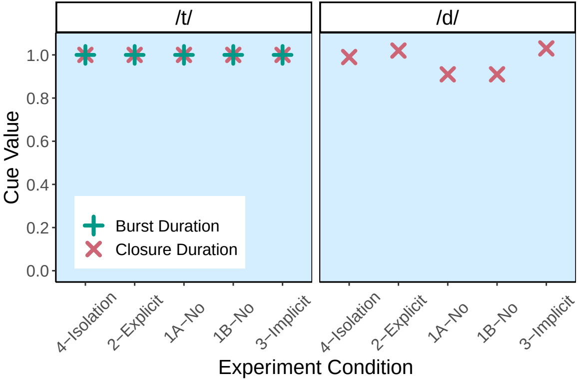
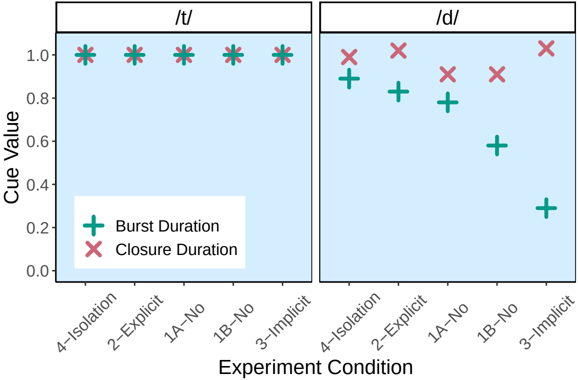


Port and Crawford (1989)

Simulating Incomplete Neutralization with the Blueprint Model of Production



Port and Crawford (1989)

Simulating Incomplete Neutralization with the Blueprint Model of Production

- The phonetics function has access to the underlying form, surface form, as well some intent to maintain the underlying form given pragmatic context (E).
- It is therefore possible to define a function that scales how much influence the UR and SR have on the phonetic form given the pragmatic context.

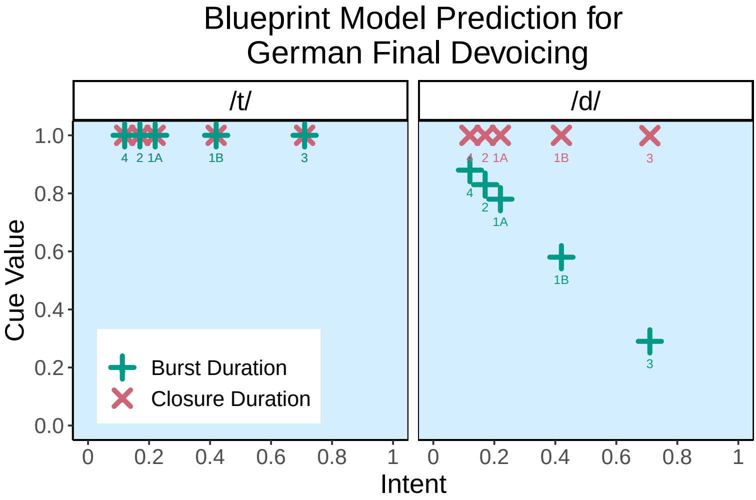
Simulating Incomplete Neutralization with the Blueprint Model of Production

$$c = \overbrace{c_{UR} \times i^{\alpha} + c_{SR}}^{c_{UR/SR} \text{ is 1 for t and 0 for d}} \times (1 - i)^{\alpha}$$

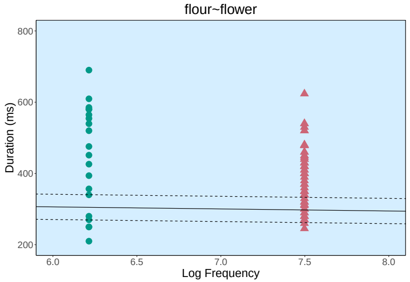
i values estimated based on pragmatic context

High α for cues that don't vary; Low α for those that do

Simulating Incomplete Neutralization with the Blueprint Model of Production



Simulations with the Blueprint Model of Production



- flour has mean duration of $\sim$ 446 ms
- flower has mean duration of $\sim$ 381 ms

$$PR_{duration} = duration_{target}(SR) + \delta(frequency(LI))$$

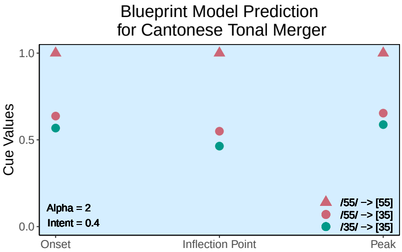
$$\hat{y} = \underbrace{\beta_0 + \beta_i \times [SR_i = SR(x)] + \beta_1 \times frequency(LI(x))}$$

varying intercepts based on surface phonological form

Single slope based on frequency of lexical item

Gahl (2008)

Simulations with the Blueprint Model of Production

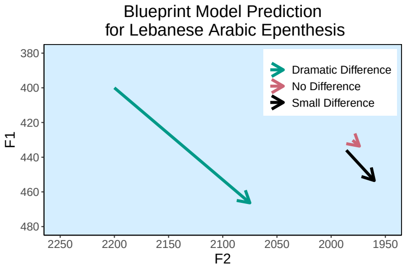


- /paŋ22 tsɔ35/ → [pɔ35]
  'to weigh (PERF)'
- /pɔŋ22 tɐk˺55/ → [pɔ35]
  'to weigh (POTENTIAL)'

"Thus, the extra-high f0 of the [derived mid-rising tone] can be interpreted as the retention of the tonal profile of an underlying [high] tone."

Yu (2007)

Simulations with the Blueprint Model of Production



- /libs/ → [libis] 'clothes'
- /libis/ → [libis] 'wore'

"...epenthesis introduces something less than an [i]: the vowel is backer and shorter, all properties that would make this vowel closer to [ɨ] or [ə] – and, arguably, to zero."

Gouskova and Hall (2009); Hall (2013)

Causal Inference and Auxiliary Assumptions

- Duhem-Quine Thesis:
  - When experimentally testing a scientific hypothesis, it is impossible to know if the reason the results don't match the theory is because the theory is wrong or if some unspoken auxiliary assumption is wrong.

- Empirical data on incomplete neutralization and variation in homophone duration are argued to be incompatible with a discrete and formal theory of phonology, but these claims have been made without consideration of the structure of the phonetics-phonology interface.

Quine (1951), Duhem (1954), Lakatos (1970)

Local Summary

Phonetic Production Data $\Rightarrow$ Non-categorical Phonology

Local Summary

~~Phonetic Production Data~~ $\Rightarrow$ ~~Non-categorical Phonology~~

Phonetic Production Data
+
MFF Model of Interface
$\Rightarrow$ Non-categorical Phonology

Local Summary

~~Phonetic Production Data~~ $\Rightarrow$ ~~Non-categorical Phonology~~

Phonetic Production Data
+
MFF Model of Interface
$\Rightarrow$ Non-categorical Phonology

Phonetic Production Data
+
BP Model of Interface
$\not\Rightarrow$ Non-categorical Phonology

Formally Relating Static Symbols and Dynamic Gestures

Section Outline

1. Model-Theoretic Phonology
2. Articulatory Phonology and gestural representations
3. Defining a bi-directional translation between segments and gestural representations
4. English past-tense alternation case study

Key Idea

I show how translating between symbolic representations of lexical items and gestural representations of lexical items is not complex which supports the phonetic properties being inferred from segmental representations rather than being directly stored in long-term memory.

Computational *Equivalency*

- Mathematical logic and model theory provide a tool for determining the expressivity of different types of phonological knowledge.
  - More powerful logic $\rightarrow$ more expressive pattern/more computational power needed

If one representation scheme can be interpreted in terms of another representation scheme with a certain type of logic, they make the same distinctions within the bounds of the expressivity of that logic.

Rogers et al. (2010, 2013); Strother-Garcia (2019); Oakden (2020)

Model Theory - Phonological Transformations

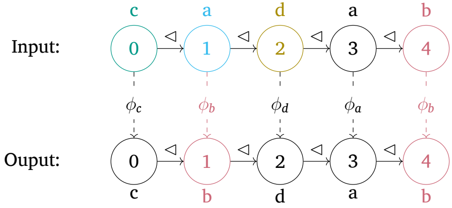
$$a \rightarrow b / c\_d$$

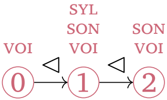
$$\phi_a(x) \stackrel{\text{def}}{=} a(x) \wedge \neg \exists y, z[y \lhd x \lhd z \wedge c(y) \wedge d(z)]$$

$$\phi_b(x) \stackrel{\text{def}}{=} b(x) \vee (a(x) \wedge \exists y, z[y \lhd x \lhd z \wedge c(y) \wedge d(z)])$$

$$\phi_c(x) \stackrel{\text{def}}{=} c(x)$$

$$\phi_d(x) \stackrel{\text{def}}{=} d(x)$$





$$\phi_{\texttt{voi}}(x) \stackrel{\text{def}}{=} d(x) \vee n(x) \vee a(x)$$

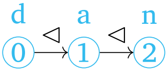
$$\phi_{\texttt{son}}(x) \stackrel{\text{def}}{=} n(x) \vee a(x)$$

$$\phi_{\texttt{syl}}(x) \stackrel{\text{def}}{=} a(x)$$

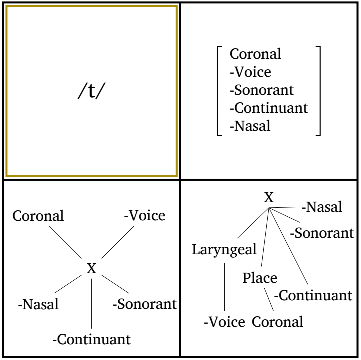
$$\phi_d(x) \stackrel{\text{def}}{=} \texttt{voi}(x) \wedge \neg\texttt{son}(x) \wedge \neg\texttt{syl}(x)$$

$$\phi_n(x) \stackrel{\text{def}}{=} \texttt{voi}(x) \wedge \texttt{son}(x) \wedge \neg\texttt{syl}(x)$$

$$\phi_a(x) \stackrel{\text{def}}{=} \texttt{voi}(x) \wedge \texttt{son}(x) \wedge \texttt{syl}(x)$$



Phonological Representations



- Representations are central to modern phonological theory.
- Many different discrete proposals throughout the years.
- Focus of this talk will be on segmental representations.

Gestural Representations

- Articulatory Phonology is a mono-stratal theory of phonology based around gestural representations.
- A **gesture** is "a characteristic pattern of movement of an articulator (or of an articulatory subsystem) through space, over time."
- Tract variables are given spatial coordinates that they must reach. The variables themselves are articulators like the lips, tongue tip, ...
  - Constriction Location: y-dimension; labeled with landmarks like "alveolar", "velar", ...
  - Constriction Degree: x-dimension; labeled with degrees like "closed", "critical", ...

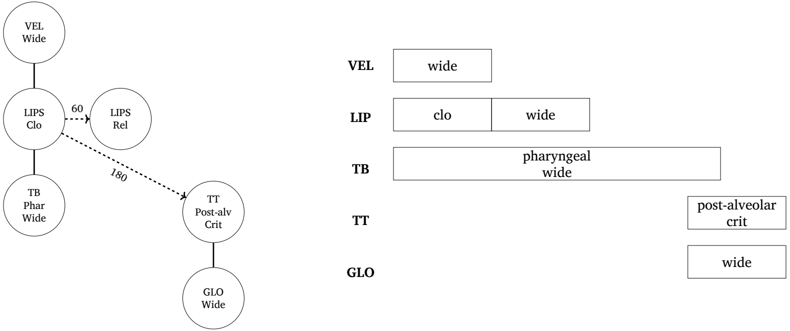
Browman and Goldstein (1986, 1995)

Coupling Graphs as Lexical Representations

"In this model, planning oscillators associated with the set of gestures in a given utterance are coupled in a pairwise, bidirectional manner specified in a coupling graph (or structure) that is part of **the lexical specification of a word***" (p. 38).*

Nam (2007)

Coupling Graphs as Lexical Representations



- Representations for *mash*
  - Coupling Graph (left)
  - Gestural score (right; automatically determined by left)

Nam (2007)

Coupling Graph Models

Relation	Label
$\diamond$	In-phase
$\lhd_{180}$	Anti-phase
$\lhd_{60}$	Abutting
$\lhd_{30}$	Eccentric

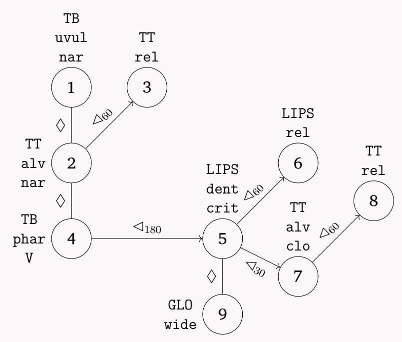
- 4 binary relations based on common phase relations in Articulatory Phonology

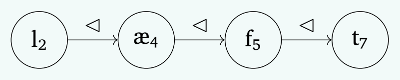
Coupling Graph Models

Relation	Label	Relation	Label
`LIPS`	Labial Articulator	`rel`	Constriction Degree: release
`TT`	Tongue Tip Articulator	`pro`	Constriction Location: protruded
`TB`	Tongue Body Articulator	`dent`	Constriction Location: dental
`VEL`	Velum Articulator	`alv`	Constriction Location: alveolar
`GLO`	Glottis Articulator	`palv`	Constriction Location: postalveolar
`clo`	Constriction Degree: closed	`pal`	Constriction Location: palatal
`crit`	Constriction Degree: critical	`vel`	Constriction Location: velar
`nar`	Constriction Degree: narrow	`uvul`	Constriction Location: uvular
`V`	Constriction Degree: vowel	`phar`	Constriction Location: pharyngeal
`wide`	Constriction Degree: wide		

- Unary labeling relations.

Models for *laughed*

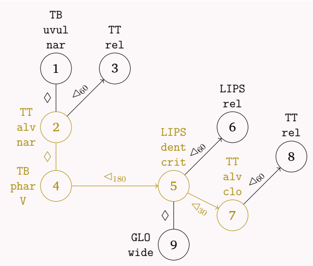




Translating between Structures

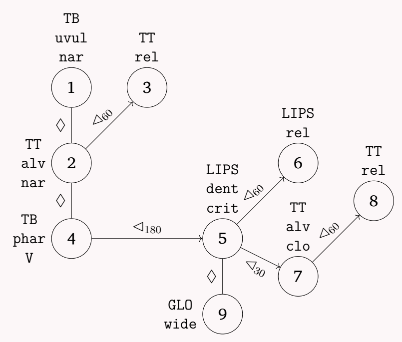
- Using the model-theoretic techniques previously described, I show how to relate these coupling graph representations with segmental strings and vice versa.

The key insight that allows for determining a string from a coupling graph is the notion of a "spine" which is made of what have been called "head gestures" (Gafos, 2002; Smith, 2018).

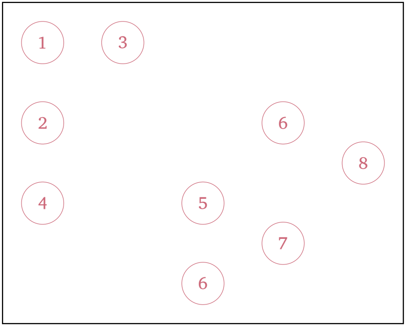


Translating from coupling graph to string

Input



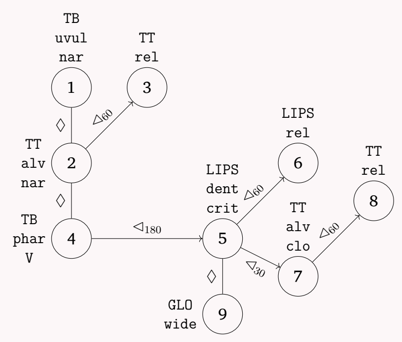
Workspace



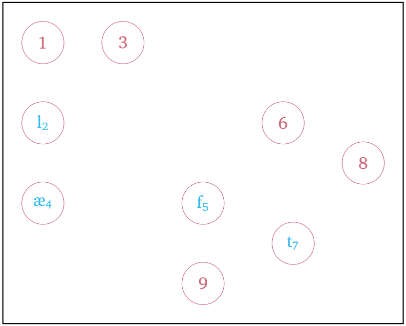
- $C := \{1\}$

Translating from coupling graph to string

Input



Workspace



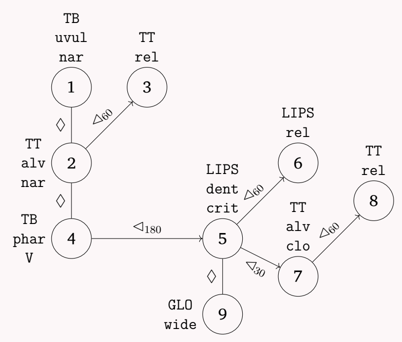
$$\varphi_{\mathrm{l}}(x) \overset{\mathrm{def}}{=} \mathtt{TT}(x) \wedge \mathtt{alv}(x) \wedge \mathtt{nar}(x) \wedge \exists y[x \Diamond y \wedge \mathtt{TB}(x) \wedge \mathtt{uvul}(x) \wedge \mathtt{nar}(x)]$$

$$\varphi_{\text{æ}}(x) \overset{\mathrm{def}}{=} \mathtt{TB}(x) \wedge \mathtt{phar}(x) \wedge \mathtt{V}(x)$$

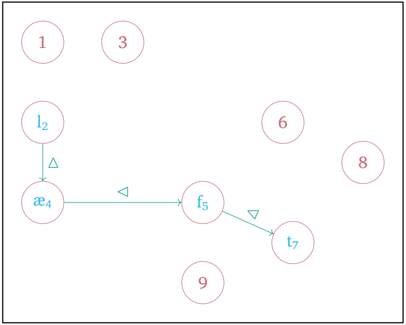
$$\varphi_{\mathrm{f}}(x) \overset{\mathrm{def}}{=} \mathtt{LIPS}(x) \wedge \mathtt{dent}(x) \wedge \exists y[x \Diamond y \wedge \mathtt{GLO}(y)]$$

$$\varphi_{\mathrm{t}}(x) \overset{\mathrm{def}}{=} \mathtt{TT}(x) \wedge \mathtt{alv}(x) \wedge \mathtt{clo}(x) \wedge \exists y[x \Diamond y \wedge \mathtt{GLO}(y)]$$

Input



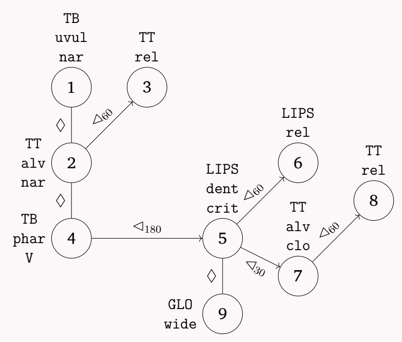
Workspace



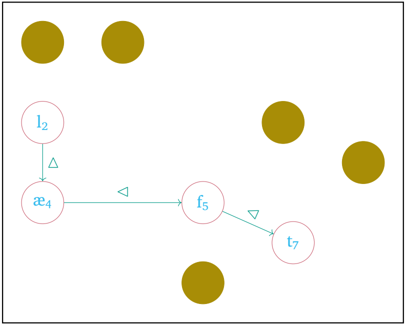
$$\varphi_{\lhd}(x,y) \overset{\text{def}}{=} (x \lhd_{180} y) \vee (x \lhd_{30} y) \vee (x \Diamond y \wedge \mathtt{V}(y) \wedge \neg \exists z[x \lhd_{180} z])$$

Translating from coupling graph to string

Input



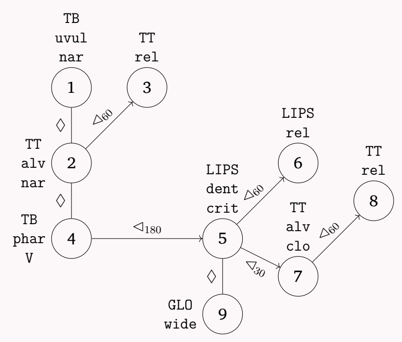
Workspace



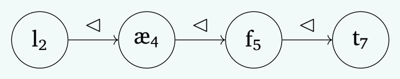
$$\varphi_{license}(x) \overset{\text{def}}{=} \neg\texttt{rel}(x) \land \neg\texttt{GLO}(x) \land \neg\texttt{VEL}(x) \neg \boxed{\texttt{SecArc}}\ (x)$$

Translating from coupling graph to string

Input



Output



Expansion

- Going from coupling graph to string removes information. What happens when we have to expand the representation and add more information by going from a string to a coupling graph?

Expansion

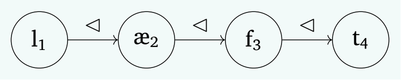
- Here, there is no issue. In fact, the TADA software which implements the Articulatory Phonology system has a program called GEST which turns strings into coupling graphs.

- GEST is written in Perl which is an imperative programing language which lists the steps that must be taken to solve the problem.

The logical transductions are equivalent to logical programs which provide declarative statements on the specs of the program. They tell us what properties must hold of any program solving the problem.

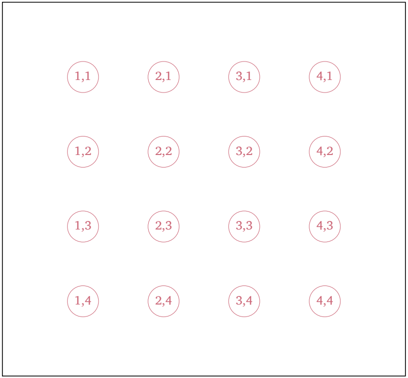
Translating from string to coupling graph

Input

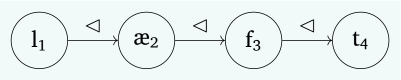


- $C := \{1, 2, 3, 4\}$

Workspace

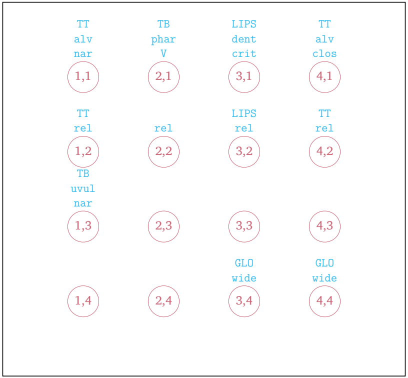


Input

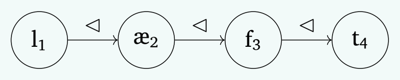


$$\varphi^1_{\texttt{LIPS}}(x) := \mathrm{f}(x)$$
$$\varphi^2_{\texttt{LIPS}}(x) := \varphi^1_{\texttt{LIPS}}(x)$$
$$\varphi^1_{\texttt{TT}}(x) := \mathrm{t}(x) \vee \mathrm{l}(x)$$
$$\varphi^2_{\texttt{TT}}(x) := \varphi^1_{\texttt{TT}}(x)$$
$$\varphi^1_{\texttt{TB}}(x) := \text{æ}(x)$$
$$\varphi^3_{\texttt{TB}}(x) := \mathrm{l}(x)$$
$$\varphi^4_{\texttt{GLO}}(x) := \mathrm{t}(x) \vee \mathrm{f}(x)$$
$$\varphi^1_{\texttt{dent}} := \mathrm{f}(x)$$
$$\varphi^1_{\texttt{alv}} := \mathrm{t}(x)$$
$$\varphi^1_{\texttt{phar}} := \text{æ}(x)$$
$$\varphi^3_{\texttt{uvul}} := \mathrm{l}(x)$$
$$\varphi^1_{\texttt{clo}} := \mathrm{t}(x)$$
$$\varphi^1_{\texttt{crit}} := \mathrm{f}(x)$$
$$\varphi^1_{\texttt{V}} := \text{æ}(x)$$
$$\varphi^1_{\texttt{nar}} := \mathrm{l}(x)$$
$$\varphi^3_{\texttt{nar}} := \mathrm{l}(x)$$
$$\varphi^4_{\texttt{wide}} := \mathrm{t}(x) \vee \mathrm{f}(x)$$

Workspace



Input



$$\varphi_{\Diamond}^{1,1}(x,y) := x \lhd y \wedge \text{æ}(y) \wedge \neg\text{æ}(x)$$

$$\varphi_{\Diamond}^{1,3}(x,y) := (x = y) \wedge \text{l}(x)$$

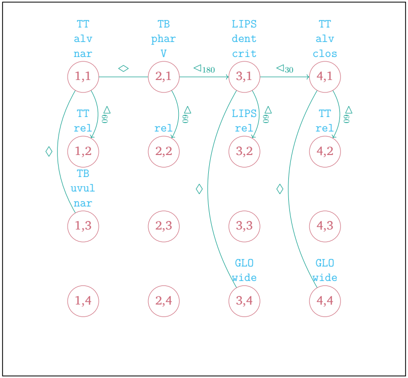
$$\varphi_{\Diamond}^{1,4}(x,y) := (x = y) \wedge \text{t}(x) \vee \text{f}(x)$$

$$\varphi_{\lhd_{180}}^{1,1}(x,y) := x \lhd y \wedge \text{æ}(x) \wedge \neg\text{æ}(y)$$

$$\varphi_{\lhd_{60}}^{1,2}(x,y) := (x = y)$$

$$\varphi_{\lhd_{30}}^{1,1}(x,y) := \neg\text{æ}(x) \wedge \neg\text{æ}(y) \wedge \exists z[z \lhd x \wedge \text{æ}(z)]$$

Workspace



Translating from string to coupling graph

Input

$$l_1 \xrightarrow{\lhd} æ_2 \xrightarrow{\lhd} f_3 \xrightarrow{\lhd} t_4$$

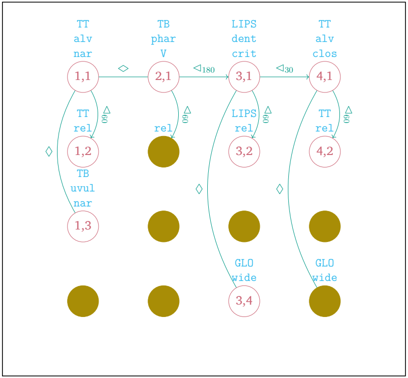
$\varphi^1_{license}(x) := \texttt{True}$

$\varphi^2_{license}(x) := \mathrm{f}(x) \vee \mathrm{t}(x) \vee \mathrm{l}(x)$

$\varphi^3_{license}(x) := \mathrm{l}(x)$

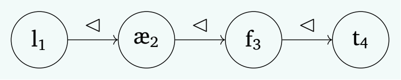
$\varphi^4_{license}(x) := \mathrm{t}(x) \vee \mathrm{f}(x) \wedge$
$\qquad \neg\exists y[y \lhd x \wedge \mathrm{f}(y) \vee \mathrm{t}(y)]$

Workspace

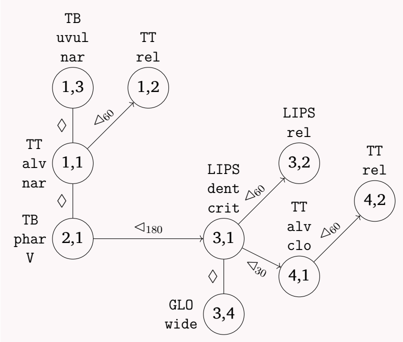


Translating from string to coupling graph

Input



Output



What now?

- First of all, we can understand phonetic effects through translation. These provide a lawful interpretation of how linear symbolic sequences relate to dynamic phonetic properties.

We can use further use these translations to also translate between constraints and transformations. These provide a way to embed these types of analyses directly into the language of Articulatory Phonology and vice versa.

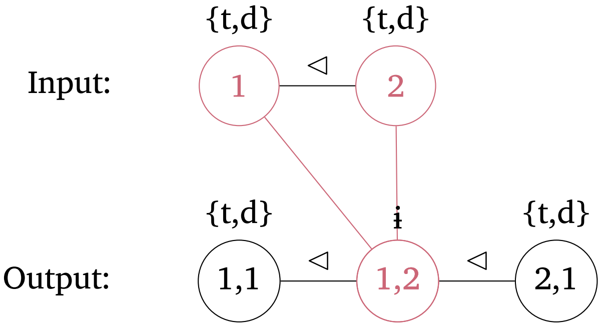
- I'll use the example of the English past-tense alternation (specifically determining when epenthesis occurs).

Theoretical Accounts of the Past Tense Alternations

- Rules
  - $\emptyset \rightarrow \text{ɨ} / \begin{bmatrix} -\texttt{son} \\ -\texttt{cont} \\ +\texttt{cor} \end{bmatrix} \_\_ \begin{bmatrix} -\texttt{son} \\ -\texttt{cont} \\ +\texttt{cor} \end{bmatrix}$
  - $[-\texttt{son}] \rightarrow [-\texttt{voi}] / [-\texttt{voi}]\_\_\#$
- Optimality Theory
  - NoGem, Agree(Voice) $\gg$ Dep(V) $\gg$ Ident(Voice)
- Coupling Graphs
  - Couple the TT closure gesture of the suffix coupling graph anti-phase to a stem-final vowel constriction gesture.
  - Couple the TT closure gesture of the suffix eccentric phase to a stem-final non-coronal obstruent constriction gesture.
  - Couple the TT closure gesture of the suffix eccentric phase to a stem-final coronal obstruent release gesture.

Rules and English Past Tense Epenthesis

$$\varphi^2_{\text{ɨ}}(x) \overset{\text{def}}{=} (\mathrm{t}(x) \vee \mathrm{d}(x)) \wedge \exists y[x \lhd y \wedge \mathrm{t}(y) \vee \mathrm{d}(y)]$$



- "if there is a sequence of two coronals, then on the output insert a [ɨ] between those coronals."

OT and English Past Tense Epenthesis

- The constraint ranking essentially gets us an `IF...THEN...ELSE` statement.

If there is a sequence of two coronal plosives on the input (violating NOGEM), then changing the voicing valuation will not make a difference in harmony.The only way to salvage a candidate is by epenthesizing due to the ranking.

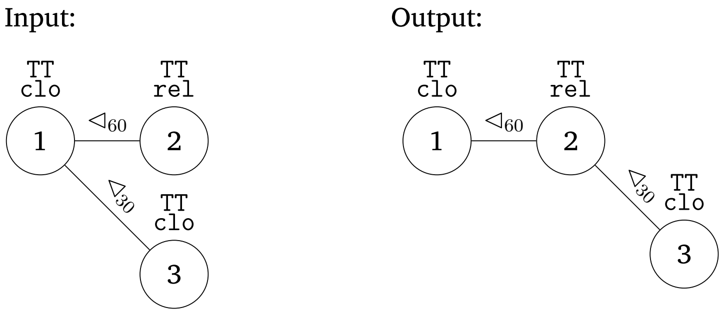
- $\varphi^2_{\text{ɨ}}(x) := \texttt{IF}\ \texttt{cor}(x) \wedge \texttt{cor}(\texttt{s}(\texttt{x}))\ \texttt{THEN}\ \texttt{true}\ \texttt{ELSE}\ \texttt{false}$

- In the FO language used previously, this is equivalent to the rule formula.

Bhaskar et al. (2020); Chandlee and Jardine (2021); Bhaskar et al. (2023)

Dynamic Grammar and English Past Tense Epenthesis

$$\varphi_{\triangleleft_{30}}(x,y) \stackrel{\text{def}}{=} \mathtt{TT}(y) \wedge \mathtt{clo}(y) \wedge \exists z[z \triangleleft_{30} y \wedge \mathtt{TT}(z) \wedge \mathtt{clo}(z) \wedge \exists w[z \diamond w] \wedge z \triangleleft_{60} x]$$



- If we abstract just a little bit, the extension of the Dynamic Grammar includes pairs where, if a given substructure exists in an input graph, then the output graph changes the coupling structure such that epenthesis occurs.

Dynamic Grammar and English Past Tense Epenthesis

$$\varphi_{\lhd}(x,y) \overset{\text{def}}{=} (x \lhd_{180} y) \vee (x \lhd_{30} y) \vee (x \diamond y \wedge \mathtt{V}(y) \wedge \neg\exists z[x \lhd_{180} z])$$

$$\varphi_{license}(x) \overset{\text{def}}{=} \neg\mathtt{rel}(x) \wedge \neg\mathtt{GLO}(x) \wedge \neg\mathtt{VEL}(x) \neg \boxed{\mathtt{SecArc}}\ (x)$$

$$\varphi_{\text{t,d}}(x) \overset{\text{def}}{=} \mathtt{TT}(x) \wedge \mathtt{clo}(x)$$

Input: Output:

- The substructure that drives epenthesis in the Dynamic Grammar is equivalent to the substructure driving epenthesis in the Rule Grammar.

Local Summary

- Given the results of this type of work, what are the consequences for the phonetics-phonology interface?
  1. Phonetic properties such as articulatory gestures do not need to be directly encoded in the long-term representation.
  2. Regardless of representational encoding, we need some type of structure to structure function.

Summary and Future Directions

Summary of Work

- I have provided a novel way for understanding the relationship between the phonetic properties of sound patterns with the phonological properties.

1. Function types/type theory to indicate the structure of the phonetics-phonology interface.
2. Model theory to indicate shared information in phonological and phonetic representations.

Summary of Work

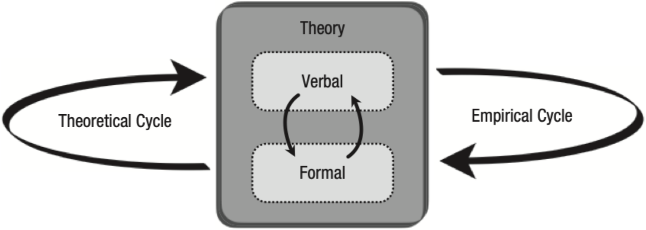
- Specifically, I related both high-level and low-level characterizations using a computational approach.
  - This provided a bridge for formally connecting the types of abstract and concrete analyses that researchers argue over.
  - My accounts showed how to unify disparate approaches.

1. Incomplete neutralization and variation in homophone duration are compatible with formal/discrete theories.
2. Rule/OT-based categorical transformations can be translated directly into the representational language of AP.

Summary of Work

- In general I showed that it is possible to posit more abstract, discrete, representations of phonological knowledge as long as one is specific about the way the computations work.

Next Steps



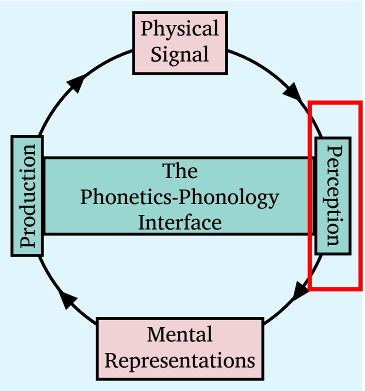
- The Blueprint Model is a response to an empirical cycle dominated by the Modular Feed-Forward Model.
- This is a step towards a new theoretical cycle which in turn can lead to a new empirical cycle.

van Rooij and Baggio (2021)

Next Steps

- Empirical Phenomena I Plan to Explore:
  - Deletion
  - Optionality
  - Boundary Effects
  - Absolute Neutralization
  - ...
- Determine computational complexity and exactly how to instantiate the various functions in the Blueprint Model of Production.
- Scale up the representational analyses to include prosodic and other suprasegmental representations.

Next Steps



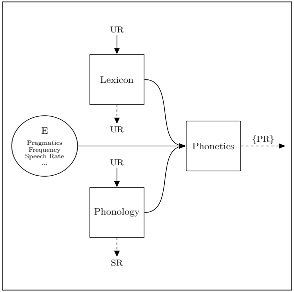
- Extend the general approach taken here to characterize a parallel Blueprint Model of Perception.

Next Steps

- Additional Domains to Explore in Relation to the Interface:
  - Sound Change
  - Loanword Adaptation
  - Sociolinguistic Variation
  - Formal Learning

- In each case, the structure of the interface puts constraints on the formal analysis and how we interpret empirical phenomena in these domains.

Thank You!


UR
Lexicon
UR
E
Pragmatics
Frequency
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Phonology
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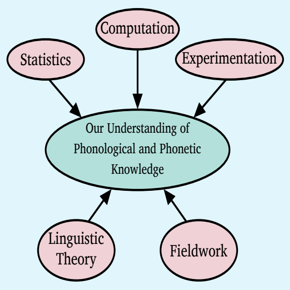
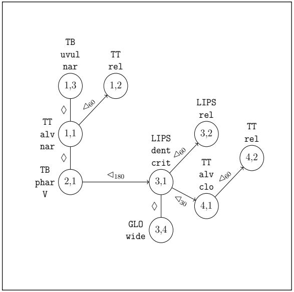

Computation
Statistics
Experimentation
Our Understanding of Phonological and Phonetic Knowledge
Linguistic Theory
Fieldwork


TB uvul nar
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LIPS rel
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TT alv clo
4,1
TT rel
4,2
GLO wide
3,4

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