# Gradient similarity in Lezgian laryngeal harmony: representation & computation

## Huteng Dai

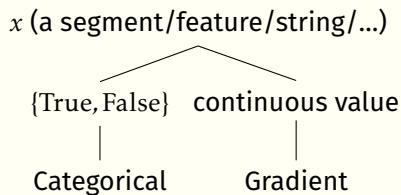Department of Linguistics and RuCCs, Rutgers University

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# Take-home message

Given a well-defined **representational structure** and **similarity metric**, gradient representation is not orthogonal to universal feature system and discrete symbolic computation.

Find the slides and code on `http://hutengdai.com`

# What's gradience?

- Gradience is still **abstraction**!
- The **abstract** property of gradience underlies various research programs: **similarity**, well-formedness, variability, etc.

$x$ (a segment/feature/string/…)

$\{True, False\}$   continuous value

Categorical          Gradient

# Similarity we live by

Similarity defines the natural classes that interact in **phonology,** which is directly connected to **phonetic** information.

| #   | Related research programs          | Selected works            |
| --- | ---------------------------------- | ------------------------- |
| 1.  | Output-driven Phonology            | Tesar (2014)              |
| 2.  | Base-Reduplicant Correspondence    | McCarthy & Prince (1995)  |
| 3.  | Paradigm Uniformity                | Benua (1997)              |
| 4.  | **Agreement by Correspondence**    | Rose & Walker (2004)      |
| 5.  | Dispersion Theory                  | Flemming (2013)           |
| 6.  | P-map                              | Steriade (2001)           |
| 7.  | Similarity avoidance principle     | Frisch et al. (2004)      |
| 8.  | Contrastive Hierarchy              | Dresher (2009)            |
| 9.  | Learning bias                      | Wilson (2006)             |
| 10. | Exemplar phonology                 | Bybee (2003)              |

# Similarity we live by

The linguistic inquiry of similarity is under the name of "contrast", "perceptibility", "perceptual distance/salience/distinctness".

| # | Related research programs | Selected works |
|---|---|---|
| 1. | Output-driven Phonology | Tesar (2014) |
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# Lesson from ABC

/kʰ/   /u/   /s/   /k/   /u/

Ident-IO ✓

[kʰ]   [u]   [s]   [k]   [u]
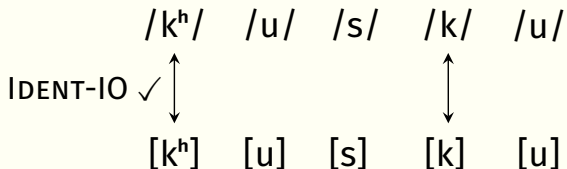
Bolivian Aymara (Rose & Walker, 2004)

Ident-IO[sg]

# Lesson from ABC

/kʰ/  /u/  /s/  /k/  /u/
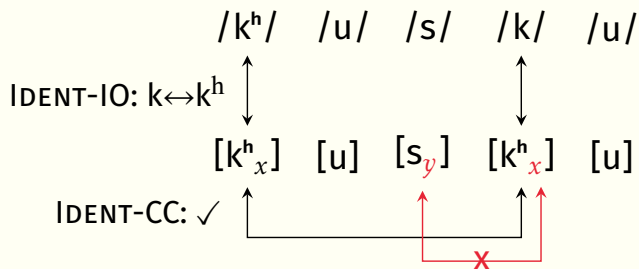
IDENT-IO ✓

[kʰ$_x$]  [u]  [s]  [k$_x$]  [u]

IDENT-CC: k↔kʰ
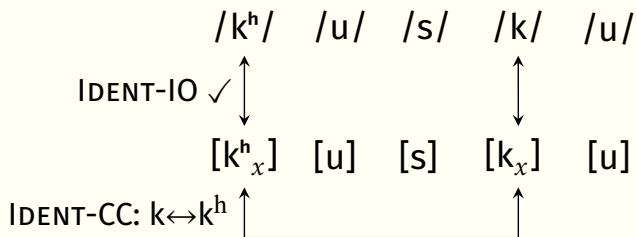
Bolivian Aymara (Rose & Walker, 2004)
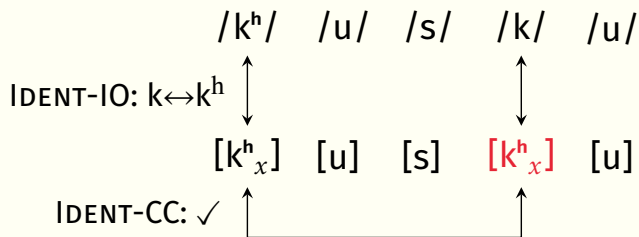
CORR(Tʰ↔T) > IDENT-IO[SG]

# Lesson from ABC



Bolivian Aymara (Rose & Walker, 2004)

IDENT-CC[SG], CORR(Tʰ↔T) > IDENT-IO[SG]

# Lesson from ABC



/kʰ/  /u/  /s/  /k/  /u/

IDENT-IO: k↔kʰ

[kʰₓ]  [u]  [sᵧ]  [kʰₓ]  [u]

IDENT-CC: ✓

✗

Bolivian Aymara (Rose & Walker, 2004)

IDENT-CC[SG], CORR(Tʰ↔T) > IDENT-IO[SG]

# Similarity and ABC

Similarity is encoded in the **correspondence (CORR) hierarchy**:

$$\text{CORR}[T \leftrightarrow T] \gg \text{CORR}[T \leftrightarrow D] \gg \text{CORR}[K \leftrightarrow T] \gg \text{CORR}[K \leftrightarrow D] \gg \dots$$

T'=Ejective, T=Voiceless, Tʰ=Aspirated, D=Voiced, D'=Implosive, T vs. K: the difference on PLACE.

(Rose & Walker, 2004)

# The probabilistic nature of similarity

❖ CORR hierarchy is grounded on **categorical** featural similarity metrics:

$$similarity(x, y) = \frac{\text{the number of shared features between } x \text{ and } y}{\text{the total number of shared and nonshared features}}$$

as in natural classes-based metrics (Frisch et al., 2004)

❖ A Bayesian perspective:

- ❖ Similarity is the **belief** that two segments $x$ and $y$ are **(non-)identical**;
- ❖ This belief is updated by the observed shared features.

(Tenenbaum & Griffiths, 2001; Jaynes, 2003)

# Structural assumption

- The distance from [+] to [−] is 1 step for any feature.
  - Any pairs of phonemes with the same amount of shared features have exactly the same similarity;
  - If T↔T' is sufficiently similar to be in agreement, then T↔Tʰ, T↔D, and T↔K must be in agreement as well.

# Lezgian laryngeal harmony

- *T'↔T is a categorical constraint in Lezgian ($N = 0$), and always triggers laryngeal harmony, while Tʰ↔T and T↔D are sufficiently **dissimilar** to escape the impetus to agree.

    - *Underrepresented co-occurrences* ($O/E < 1$)

        T↔T', T'↔T, T'↔D, T'↔Tʰ, D↔T', D↔Tʰ, Tʰ↔D, Tʰ↔T', ...

    - *Overrepresented co-occurrences* ($O/E \geq 1$)

| | | | | | |
|---|---|---|---|---|---|
| T'↔T' | [q'aft͡s'un] | 'get dirty' | T↔T | [qaqa] | 'ready' |
| Tʰ↔Tʰ | [t͡ʃʰipʰ] | 'fool' | D↔D | [midad] | 'grieve' |

(Ozburn & Kochetov, 2018)

# Lezgian laryngeal harmony

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  - *Underrepresented co-occurrences* ($O/E < 1$)

    <u>T↔T', T'↔T</u>, T'↔D, T'↔Tʰ, D↔T', D↔Tʰ, Tʰ↔D, Tʰ↔T', ...

  - *Overrepresented co-occurrences* ($O/E \geq 1$)

| T'↔T' | [q'aʦ'un] | 'get dirty' | T↔T | [qaqa] | 'ready' |
| Tʰ↔Tʰ | [tʃʰipʰ] | 'fool' | D↔D | [midad] | 'grieve' |
| Tʰ↔T | [kʰuʦun] | 'to flush' | T↔D | [eʦigun] | 'put' |

(Ozburn & Kochetov, 2018)

# Challenge to categorical similarity metrics

The calculated similarity neither aligns with the **co-occurrence** constraints, nor fits the distribution of **speech errors**.

(Rose & King, 2007)

| Inventory | minimally dissimilar pairs | Languages |
|---|---|---|
| T', T, T$^h$, D | *$\mathbf{T}\leftrightarrow\mathbf{T'}$, $\checkmark$T$\leftrightarrow$D, $\checkmark$T$^h\leftrightarrow$T ... | Lezgian, Ndebele |
| T', T, D | *$\mathbf{T}\leftrightarrow\mathbf{T'}$, $\checkmark$T$\leftrightarrow$D | Amharic, Chaha, Chontal |
| T', T, T$^h$ | *$\mathbf{T}\leftrightarrow\mathbf{T'}$, *T$\leftrightarrow$T$^h$ | Peruvian & Bolivian Aymara |
| T', T, D' | *$\mathbf{T}\leftrightarrow\mathbf{T'}$, $\checkmark$T'$\leftrightarrow$D' | Tzotzil, Tzutujil, Yucatec |
| T', T, D, D' | *$\mathbf{T}\leftrightarrow\mathbf{T'}$, *$\mathbf{D'}\leftrightarrow\mathbf{D}$, $\checkmark$T$\leftrightarrow$D ... | Hausa |
| T, D, D' | *$\mathbf{D'}\leftrightarrow\mathbf{D}$, $\checkmark$T$\leftrightarrow$D | Bumo Izon, Kalabari Ijo |

# Analysis: the special status of [ᴄɢ]

- Cross-linguistically, different features play different roles in similarity.

- Only the difference on [ᴄɢ] **always** triggers harmony

- Hypothesis: the distance from [+ᴄɢ] to [-ᴄɢ] is systematically shorter than in other Lᴀʀʏɴɢᴇᴀʟ features.

  (Gallagher & Coon, 2009; Kochetov & Ozburn, 2014)

# Acoustic cues

Cross-linguistically, the difference of VOT and preceding vowel duration on [ᴄɢ] is less distinctive than [ᴠᴏɪᴄᴇ] and [sɢ].

(Beguš, 2017; Gallagher, 2010a)
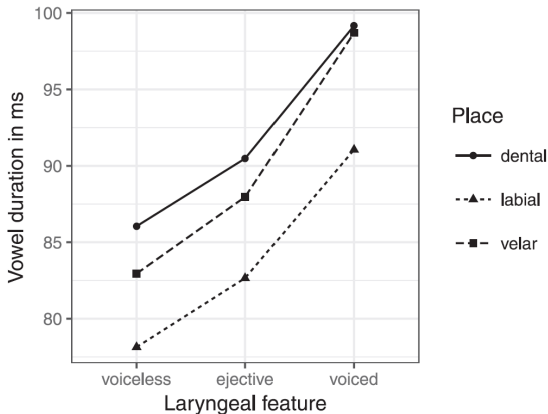


FIG. 2. Estimates of the effects of Laryngeal Features and Place of articulation on preceding vowel duration in ms (from a linear mixed effects model).

Georgian (Beguš, 2017)

# Gradient representation: Pros and Cons

‣ Weighted/gradient/valued (sub-)featural representation can easily handle language-specific phonetic granularity;

(Ladefoged, 1969, 1972, 1973; Keating, 1985)

‣ Cons:

  ‣ High degree of freedom;

  ‣ The empirical/laboratory evidence is not always available;

  ‣ Trade-off between granularity and **generality**;

    e. g. universal feature system; typology; similarity metrics; modular representation, etc.
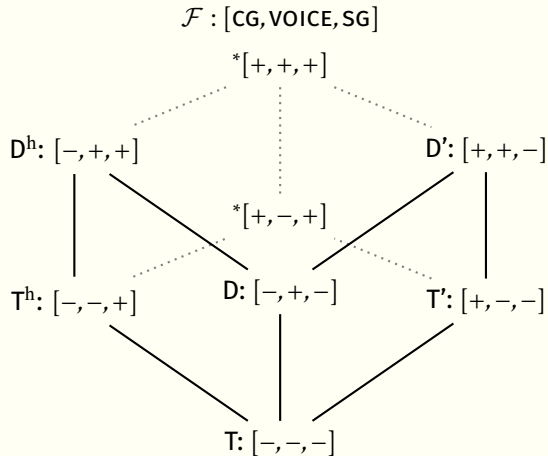
    see criticism in Mackenzie (2009)

# Representation

# Proposal: weighted featural lattice

Lattice: the universal feature system:
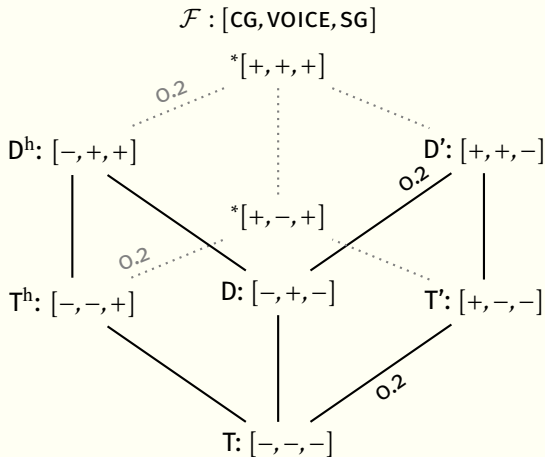
- Partial order;
- Relative distance;
- Bounds.

(Tesar, 2014; Magri, 2018)

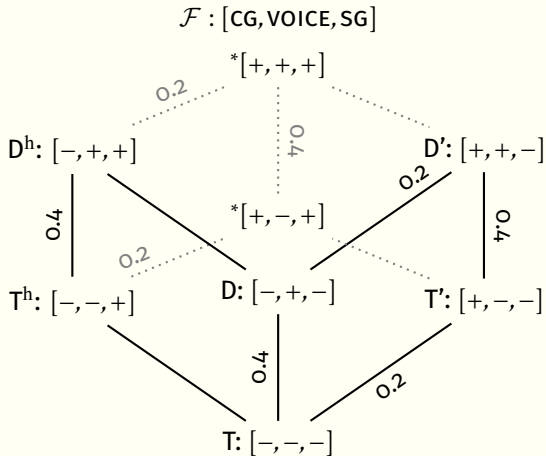$\mathcal{F} : [\text{CG}, \text{VOICE}, \text{SG}]$

$*[+,+,+]$

$D^h: [-,+,+]$          $D': [+,+,-]$

$*[+,-,+]$

$T^h: [-,-,+]$     $D: [-,+,-]$     $T': [+,-,-]$

$T: [-,-,-]$

# Proposal: weighted featural lattice

Weight: the phonetic distance between [+] and [-]

$w_{[CG]} < w_{[VOICE]}, w_{[SG]}$

Restriction: $0 < w_f < 1$
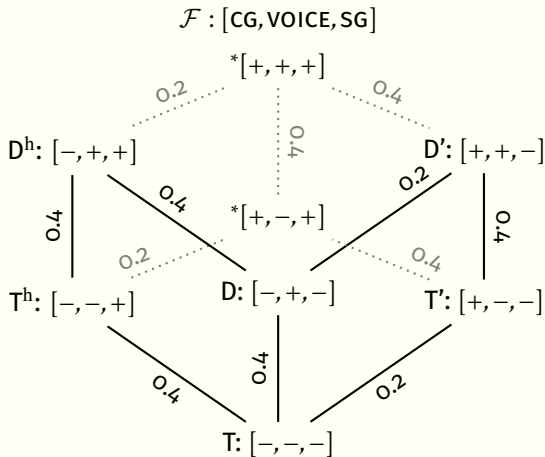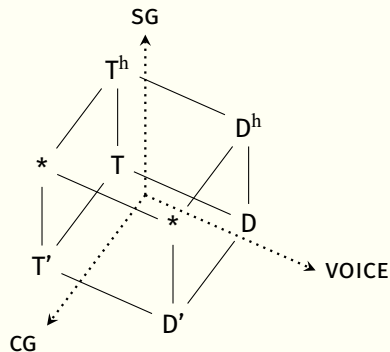
"How likely two **features** are non-identical?"

$\mathcal{F} : [\mathsf{CG}, \mathsf{VOICE}, \mathsf{SG}]$

*[+, +, +]

$D^h$: [−, +, +]

D': [+, +, −]

*[+, −, +]

0.2

0.2

0.2

$T^h$: [−, −, +]

D: [−, +, −]

T': [+, −, −]

0.2

0.2

T: [−, −, −]

0.2

# Proposal: weighted featural lattice



Weight: the phonetic distance between [+] and [-]

$w_{[CG]} < w_{[VOICE]}, w_{[SG]}$

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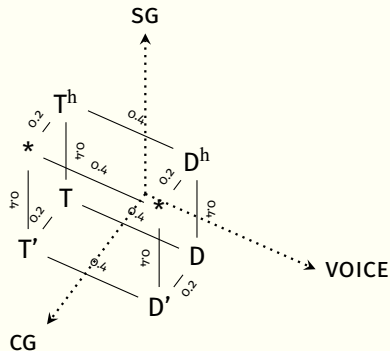
"How likely two **features** are non-identical?"

$\mathcal{F} : [\text{CG}, \text{VOICE}, \text{SG}]$

*[+,+,+]

0.2        0.4

$D^h$: [−,+,+]        D': [+,+,−]

*[+,−,+]        0.2

0.4        0.4

0.2

$T^h$: [−,−,+]        D: [−,+,−]        T': [+,−,−]

0.4        0.2

T: [−,−,−]

# Proposal: weighted featural lattice

- Weight: the phonetic distance between [+] and [-]

- $w_{[\text{CG}]} < w_{[\text{VOICE}]}, w_{[\text{SG}]}$

- Restriction: $0 < w_f < 1$

  "How likely two **features** are non-identical?"



$\mathcal{F} : [\text{CG}, \text{VOICE}, \text{SG}]$

*[+,+,+]

0.2    0.4    0.4

$D^h$: [−,+,+]    D': [+,+,−]

*[+,−,+]

0.4    0.4    0.2    0.4

$T^h$: [−,−,+]    0.2    D: [−,+,−]    0.4    T': [+,−,−]

0.4    0.4    0.2

T: [−,−,−]

phonological structure $\Longleftrightarrow$ discrete lattice

phonetic substance ⟺ weighted lattice: scaled by [0.2, 0.4, 0.4]
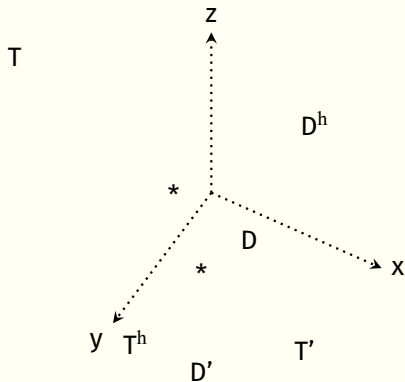
e. g. *Hilbert space* in Smolensky et al. (2014)
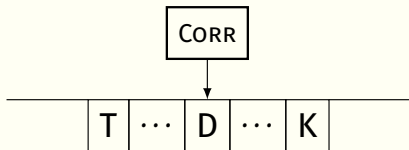
# Alternative: segmental similarity scale

- One-dimensional totally-ordered similarity scale;

- The relative similarity is encoded by **adjacency**.



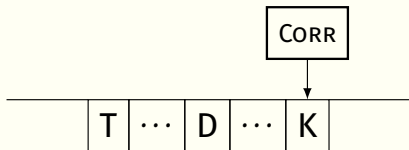(Rose & Walker, 2004, P.505)

# Alternative: segmental similarity scale

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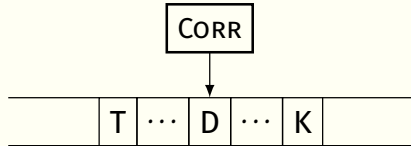
(Rose & Walker, 2004, p.505)

# Alternative: segmental similarity scale

- One-dimensional totally-ordered similarity scale;
- The relative similarity is encoded by **adjacency**.



(Rose & Walker, 2004, P.505)

# Alternative: segmental similarity scale

CORR[T↔D] ≫ CORR[K↔T] ≫ CORR[K↔D]

   ✓*similarity*(T,D) > *similarity*(T,K)

# Alternative: segmental similarity scale

Corr[T↔D] ≫ Corr[K↔T] ≫ Corr[K↔D]

$\checkmark$*similarity*(T,D) > *similarity*(T,K)

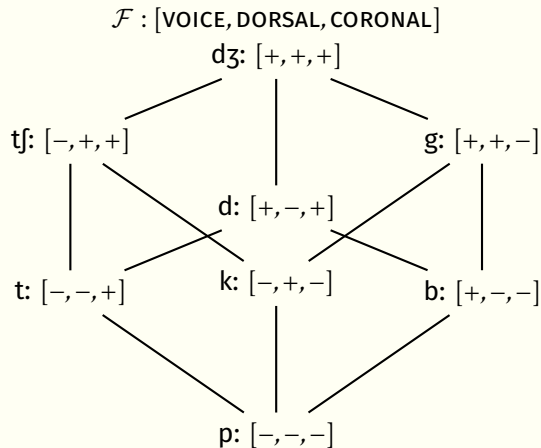\**similarity*(K,D) > *similarity*(K,T)
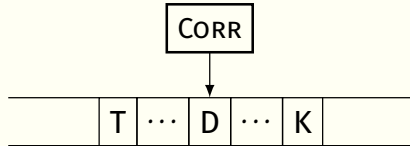
# Alternative: segmental similarity scale

A lattice represents a higher dimensional space which captures the insights lost in an one-dimensional similarity scale.

Similar problem exists in many other scales.

$\mathcal{F} : [\text{VOICE}, \text{DORSAL}, \text{CORONAL}]$

dʒ: $[+, +, +]$

tʃ: $[-, +, +]$

g: $[+, +, -]$

d: $[+, -, +]$

t: $[-, -, +]$

k: $[-, +, -]$

b: $[+, -, -]$

p: $[-, -, -]$

# Computation

# Phonetic distance

- The phonetic distance between two segments $x$ and $y$ is computed over a weighted featural lattice $\mathbf{w}$:

$$distance_{\mathbf{w}}(x, y) = \sum_{f \in \mathcal{F}} w_f \cdot \delta_f(x, y), \qquad \text{(summed weights of nonshared features)}$$

$$\delta_f(x, y) = \begin{cases} 0, & \text{if } x \text{ and } y \text{ share the feature } f \\ 1, & \text{else} \end{cases}$$

(Wilson & Obdeyn, 2009)

# Similarity as Bayesian probability

- **Phonological similarity** is the belief that $x$ and $y$ are (non-)identical, which is updated by the observed **phonetic distance** between two segments.

$$similarity_{\mathbf{w}}(x, y) = 1 - dissimilarity_{\mathbf{w}}(x, y)$$
$$= 1 - \frac{distance_{\mathbf{w}}(x, y)}{\sum_{f \in \mathcal{F}} w_f}$$

- This function converts the *phonetic distance* to a probability in $[0, 1]$.
- The sum of all featural weights $\sum_{f \in \mathcal{F}} w_f$ is the **maximal distance** between two segments (0 shared features). This knowledge is encoded in the lattice.
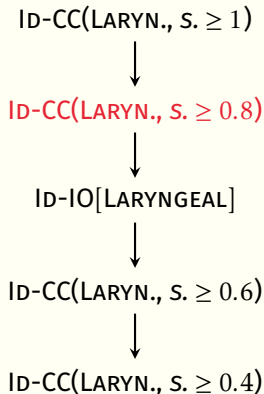
# Similarity of LARYNGEAL pairs

| C1↓C2→ | T' | T | D' | D | $T^h$ | $D^h$ |
|---|---|---|---|---|---|---|
| T' | 1 | 0.8 | 0.6 | 0.4 | 0.4 | 0 |
| T | 0.8 | 1 | 0.4 | 0.6 | 0.6 | 0.2 |
| D' | 0.6 | 0.4 | 1 | 0.8 | 0 | 0.4 |
| D | 0.4 | 0.6 | 0.8 | 1 | 0.2 | 0.6 |
| $T^h$ | 0.4 | 0.6 | 0 | 0.2 | 1 | 0.6 |
| $D^h$ | 0 | 0.2 | 0.4 | 0.6 | 0.6 | 1 |

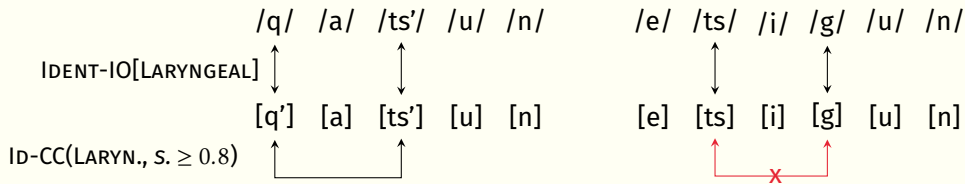Whatever the alphabet is, the set of thresholds is always **finite**.

# Agreement by similarity

- IDENT-CC(LARYNGEAL, *SIMILARITY* $\geq k$):
  if *similarity* $\geq k$ in a 2-long **subsequence**,
  penalize any difference in LARYNGEAL.

- IDENT-IO[LARYNGEAL]:
  penalize any input-output difference in
  LARYNGEAL.

- The critical threshold is determined by the
  lowest similarity that triggers harmony.

ID-CC(LARYN., $s. \geq 1$)

$\downarrow$

ID-CC(LARYN., $s. \geq 0.8$)

$\downarrow$

ID-IO[LARYNGEAL]

$\downarrow$

ID-CC(LARYN., $s. \geq 0.6$)

$\downarrow$

ID-CC(LARYN., $s. \geq 0.4$)

The 2-long **subsequences** in *[qats'un] include {q…a, **q…ts'**, q…u, q…n, a…ts', a…u, a…n, ts'…u, ts'…n, u…n}  (Heinz, 2010)



/q/  /a/  /ts'/  /u/  /n/        /e/  /ts/  /i/  /g/  /u/  /n/

Ident-IO[Laryngeal]

[q']  [a]  [ts']  [u]  [n]        [e]  [ts]  [i]  [g]  [u]  [n]

Id-CC(Laryn., s. ≥ 0.8)

(Q & A: "Agreement by similarity vs. by projection")

# Constraint-based analysis

| /qats'un/ | ID-CC(Laryn., s. ≥ 0.8) | ID-IO[Laryn.] | ID-CC(Laryn., s. ≥ 0.6) |
|---|---|---|---|
| a.   qats'un [s. = 0.8] | *! | | * |
| b. ☞ q'ats'un [s. = 1] | | * | |

| /etsigun/ | ID-CC(Laryn., s. ≥ 0.8) | ID-IO[Laryn.] | ID-CC(Laryn., s. ≥ 0.6) |
|---|---|---|---|
| a.   edzigun [s. = 1] | | *! | |
| b. ☞ etsigun [s. = 0.6] | | | * |

Classical OT (Prince & Smolensky, 2004)

# Typology

The typology of laryngeal harmony is predicted by varying critical thresholds.

| Inventory | Thresholds | Pairs | Languages |
|-----------|------------|-------|-----------|
| T', T | 0.8 | *T↔T' | Gitksan, Chol |
| T', T, D' | 0.8 | *T↔T', ✓T'↔D', ✓T↔D' | Tzotzil, Tzutujil, Yucatec |
| T', T, D, D' | 0.8 | *T↔T', *D'↔D, ✓T↔D, ... | Hausa |
| T', T, T$^h$, D | 0.8 | *T↔T', ✓T↔D, ✓T$^h$↔T ... | Ndebele, Lezgian |
| T, D, D' | 0.8 | *D'↔D, ✓T↔D, ✓T↔D' | Bumo Izon, Kalabari Ijo |
| T', T, D | 0.8 | *T↔T', ✓T↔D, ✓T'↔D | Amharic |
| | 0.4 | *T↔T', *T↔D, *T'↔D | Chaha |
| T', T, T$^h$ | 0.4 | *T↔T', *T↔T$^h$, *T'↔T$^h$ | Peruvian & Bolivian Aymara |

# Theoretical consequences

# Modular representation

- Lattice:
  - the phonological, abstract, symbolic, universal structure of feature system;
  - it tells you how many (non-)shared features between two segments.

Representation

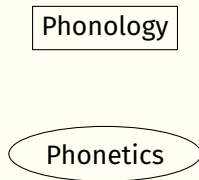Phonology

Phonetics

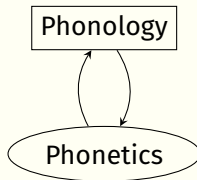Computation

Phonology
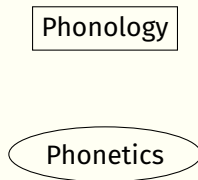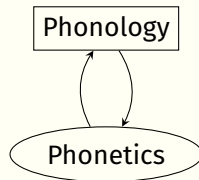
Phonetics

# Modular representation

- Weight:
  - the phonetic, fine-grained, gradient, language-specific **substance**;
  - not in UR, and **only** available to SR in the **computation** of input-output and surface correspondence.
  - The only addition is one vector!

Representation        Computation

# Structure + Gradience

- Contrastive hierarchy: **structure** matters – phonetic similarity doesn't participate in phonological processes at all;

  (Mackenzie, 2009, 2011)

- Perceptual grounding approach: supplement the universal feature system with **language-specific** auditory features, such as [long VOT], to account for perceptual similarity.

  (Gallagher, 2010a,b, 2012)

# The interplay of phonology and phonetics
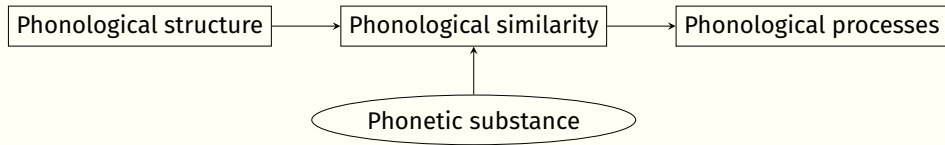


The similarity is computed w.r.t phonological structure and phonetic substance, and this information is further used in phonological computation.

# Future directions

- How general is the relation $w_{[CG]} < w_{[VOICE]}, w_{[SG]}$?

- Laboratory evidence:
  - Confusion matrix (Miller & Nicely, 1955; Johnson & Babel, 2010)
  - Neural featural encoding (Mesgarani et al., 2014, Q & A)

- Learning weighted features from distribution/patterning

  (Wilson & Obdeyn, 2009; Mayer & Daland, 2019; Mayer, 2020)

# Take-home message

▶ Given a well-defined **representational structure** and **similarity metric**, gradient representation is not orthogonal to universal feature system and discrete symbolic computation;

Find the slides and code on `http://hutengdai.com`, and feel free to contact me for questions and collaborations!

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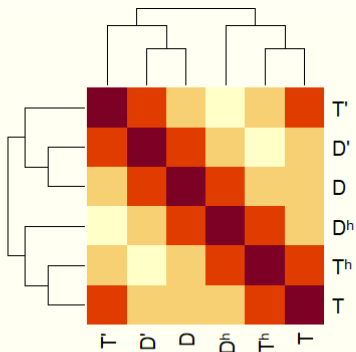
# Q & A

# Abstractness of gradient representation

- Phonetic measurement ≠ weight on featural lattice:
  - Phonetic invariance doesn't exist; (Pierrehumbert, 2016; Zellou & Tamminga, 2014)
  - Real-numbered representation is still an **abstraction**!



THE ABSTRACT-O-METER

too realistic          just right          too abstract

# Categorical vs. weighted similarity metrics



Categorical similarity metrics ☹
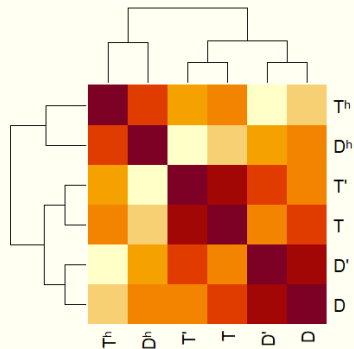


Gradient similarity metrics ☺

# Neural featural encoding



Mesgarani et al. (2014)

# Reference

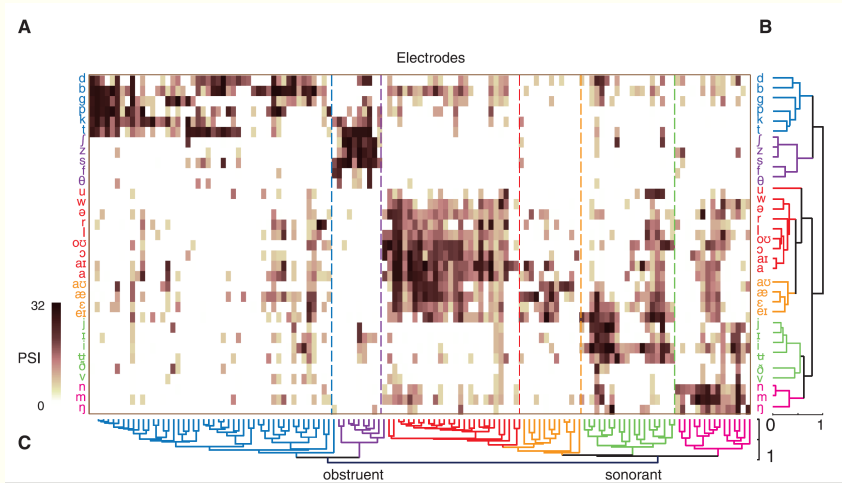Beguš, G. (2017). Effects of ejective stops on preceding vowel duration. *The Journal of the Acoustical Society of America*, *142*(4), 2168–2184.

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