

# Computational Complexity and the Morpho-phonological Interface

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# Introduction

- ▶ Phonological UR $\rightarrow$ SR maps have been characterized as computationally ‘simple’ using restrictive and well-defined classes of *subregular* functions.
- ▶ These previous results provide:
  - ▶ A way to compare patterns in different domains (i.e., phonology versus syntax).
  - ▶ A better fit to the observed typology.
  - ▶ Insights into learnability.
- ▶ What about morphology?

# Outline

- ▶ Establish a framework for classifying input-output maps based on their computational complexity.
  - ▶ Subregular hierarchy of function classes: ISL, OSL, subsequential
- ▶ Use this framework to classify a range of morphological phenomena.

# Computational complexity of phonological processes

- ▶ Phonological rules  $A \rightarrow B/C\_D$  are equivalent to *regular relations* provided they do not reapply to their own structural change (Johnson, 1972; Kaplan and Kay, 1994).
  - ▶ ‘regular relation’ = ‘finite state describable’
- ▶ However,
  - ▶ Some unattested processes (e.g., Sour Grapes vowel harmony) are also regular.
  - ▶ The class of regular relations isn’t learnable from positive data.
- ▶ Proposal: phonological processes are in fact *subregular* (i.e., describable with proper **subsets of regular relations**)

# Phonological maps

- ▶ A relation/function/map is a set of string *pairs*.
- ▶ A phonological map (i.e., ‘process’) is a set of (UR, SR) pairs.
  - (1) { (anba, amba), (nanta, nanta), (ama, ama), ... }
  - (2)  $n \rightarrow m / \_ [+labial]$
  - (3) \*nb  $\gg$  IDENT-PLACE
- ▶ Theory-independent way to think about phonological generalizations (see also Tesar, 2014; Baković and Blumenfeld, 2017).

# Computational complexity of phonological maps

REGULAR RELATIONS (Johnson, 1972; Kaplan and Kay, 1994)



SUBSEQUENTIAL FUNCTIONS (Mohri, 1997)



STRICTLY LOCAL FUNCTIONS (Chandlee, 2014)

# Strictly Local functions

- ▶ Output string is computed *locally*, depending only on a bounded number of previous segments.
  - ▶ Input Strictly Local (ISL): output depends on previous input symbols
  - ▶ Output Strictly Local: output depends on previous output symbols
    - ▶ LOSL: read the input from left-to-right
    - ▶ ROSL: read the input from right-to-left

# Computational complexity of phonological maps

REGULAR RELATIONS (Johnson, 1972; Kaplan and Kay, 1994)



SUBSEQUENTIAL FUNCTIONS (Mohri, 1997)

LEFT OSL

RIGHT OSL (Chandlee et al., 2015)

ISL (Chandlee et al., 2014)



## Example: Input Strictly Local (ISL) function

- (4) Korean (Lee and Pater, 2008)  
/pap**mul**/  $\mapsto$  [pam**mul**] ‘rice water’

⊗ p a p m u l ⊗  
λ

## Example: Input Strictly Local (ISL) function

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/papmul/  $\mapsto$  [pammul] ‘rice water’

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λ pa λ

## Example: Input Strictly Local (ISL) function

- (4) Korean (Lee and Pater, 2008)  
/pap**mul**/  $\mapsto$  [p**ammul**] ‘rice water’

⊗ p a p m u l ⊗  
λ pa λ mm

## Example: Input Strictly Local (ISL) function

- (4) Korean (Lee and Pater, 2008)  
/pap**mul**/  $\mapsto$  [p**ammul**] ‘rice water’

|   |   |    |   |    |   |   |   |
|---|---|----|---|----|---|---|---|
| × | p | a  | p | m  | u | l | × |
|   | λ | pa | λ | mm | u |   |   |

## Example: Input Strictly Local (ISL) function

- (4) Korean (Lee and Pater, 2008)  
/papmul/  $\mapsto$  [pammul] 'rice water'

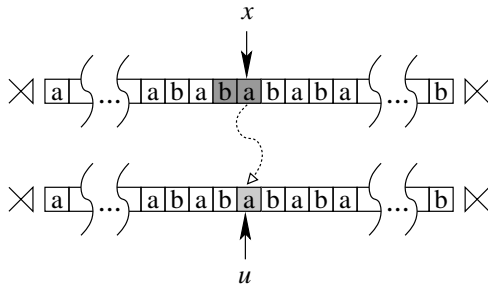
|   |   |    |   |    |   |   |   |
|---|---|----|---|----|---|---|---|
| × | p | a  | p | m  | u | l | × |
|   | λ | pa | λ | mm | u | l |   |

## Example: Input Strictly Local (ISL) function

- (4) Korean (Lee and Pater, 2008)  
/pap**mul**/  $\mapsto$  [pam**mul**] ‘rice water’

Window size is 2: this map is 2-ISL.

# Input Strictly Local (ISL) function





## Example: Left Output Strictly Local (LOSL) function

- (5) Johore Malay (Onn, 1980)  
/pəŋawasan/  $\mapsto$  [pəŋãwãsan] ‘supervision’

× p e ŋ a w a s a n ×  
p

## Example: Left Output Strictly Local (LOSL) function

- (5) Johore Malay (Onn, 1980)  
/pəŋawasan/  $\mapsto$  [pəŋãwãsan] ‘supervision’

× p e ŋ a w a s a n ×  
p e

## Example: Left Output Strictly Local (LOSL) function

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p e ŋ

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- (5) Johore Malay (Onn, 1980)  
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× p e ŋ a w a s a n ×  
p e ŋ ã

## Example: Left Output Strictly Local (LOSL) function

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|   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|
| × | p | e | ŋ | a | w | a | s | a | n | × |
|   | p | e | ŋ | ã | ã |   |   |   |   |   |

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- (5) Johore Malay (Onn, 1980)  
/pəŋawasan/  $\mapsto$  [pəŋãwãsan] ‘supervision’

|   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|
| × | p | e | ŋ | a | w | a | s | a | n | × |
|   | p | e | ŋ | ã | w | ã |   |   |   |   |

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- (5) Johore Malay (Onn, 1980)  
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|   |   |   |   |   |    |   |   |   |   |   |
|---|---|---|---|---|----|---|---|---|---|---|
| × | p | e | ŋ | a | w  | a | s | a | n | × |
|   | p | e | ŋ | ã | wã | ã | s |   |   |   |

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- (5) Johore Malay (Onn, 1980)  
/pəŋawasan/  $\mapsto$  [pəŋãwãsan] ‘supervision’

|   |   |   |   |   |    |   |   |   |   |   |
|---|---|---|---|---|----|---|---|---|---|---|
| × | p | e | ŋ | a | w  | a | s | a | n | × |
|   | p | e | ŋ | ã | wã | ã | s | a |   |   |



## Example: Left Output Strictly Local (LOSL) function

- (5) Johore Malay (Onn, 1980)  
/pəŋawasan/  $\mapsto$  [pəŋãwãsan] ‘supervision’

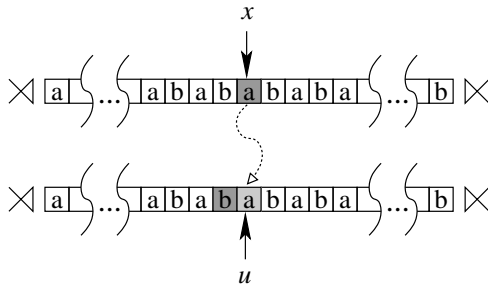
|   |   |   |   |   |    |   |   |   |   |   |
|---|---|---|---|---|----|---|---|---|---|---|
| × | p | e | ŋ | a | w  | a | s | a | n | × |
|   | p | e | ŋ | ã | wã | ã | s | a | n |   |

## Example: Left Output Strictly Local (LOSL) function

- (5) Johore Malay (Onn, 1980)  
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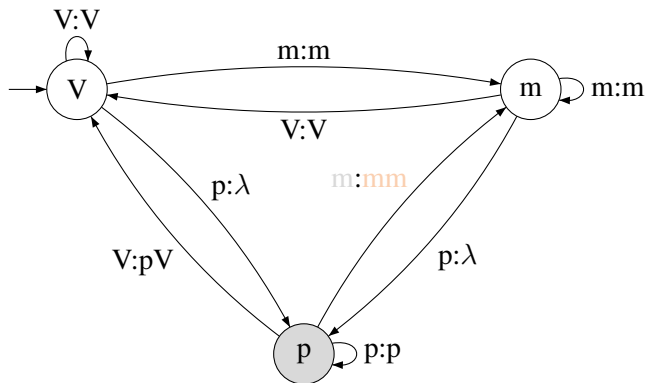
Window size is 2: this map is 2-LOSL.

# Left Output Strictly Local function



# Input Strictly Local (ISL): FST characterization

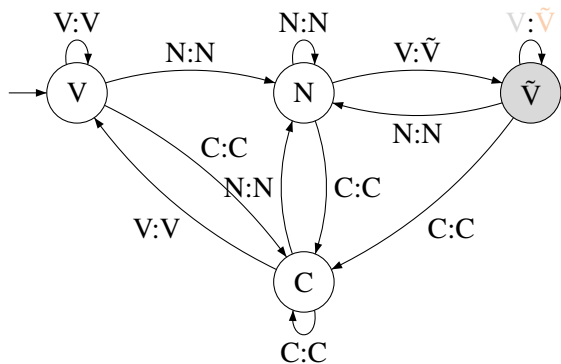
(6) /papmul/  $\mapsto$  [pammul]



$\times$  p a p m u l  $\times$   
 $\lambda$  pa  $\lambda$  mm

# Output Strictly Local (OSL): FST characterization

(7) /pəŋawasan/  $\mapsto$  [pəŋãwãsan]



|   |   |   |   |   |    |   |   |   |   |   |
|---|---|---|---|---|----|---|---|---|---|---|
| × | p | e | ŋ | a | w  | a | s | a | n | × |
|   | p | e | ŋ | ã | wã |   |   |   |   |   |

## Long-distance maps

- (8) Kikongo (Meinof, 1932; Odden, 1994; Rose and Walker, 2004)
- /tunikidi/ ↦ [tunikini]                    ‘we ground’
- /kudumukisila/ ↦ [kudumukisina]    ‘to cause to jump for’

## Long-distance maps

- (8) Kikongo (Meinof, 1932; Odden, 1994; Rose and Walker, 2004)

/tunikidi/ ↦ [tunikini] ‘we ground’

/kudumukisila/ ↦ [kudumukisina] ‘to cause to jump for’

× t u n i k i d i ×  
t u n i k i n

× k u d u m u k i s i l a ×  
k u d u m u k i s i l

# Computational complexity of phonological maps

REGULAR RELATIONS (Johnson, 1972; Kaplan and Kay, 1994)



SUBSEQUENTIAL FUNCTIONS (Mohri, 1997)

LEFT OSL

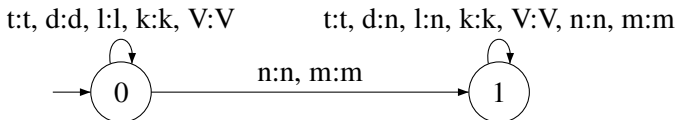
RIGHT OSL (Chandlee et al., 2015)

ISL (Chandlee et al., 2014)



## Long-distance maps

- (9) Kikongo  
/tunikidi/  $\mapsto$  [tunikini] 'we ground'  
/kudumukisila/  $\mapsto$  [kudumukisina] 'to cause to jump for'



## Classifying phonological maps

- ▶ ‘Local’ or ‘bounded’ phonological processes (assimilation, dissimilation, insertion, deletion, metathesis) are ISL, LOSL, or ROSL (Chandlee, 2014).
- ▶ Interactions of local processes, including opaque interactions, are also ISL (Chandlee et al., 2018).
- ▶ Long distance maps are **(at least)** subsequential:
  - ▶ Vowel harmony (Gainor et al., 2012)
  - ▶ Consonant harmony (Luo, 2013)
  - ▶ Dissimilation (Payne, 2017)

## What about morphology?

- ▶ Finite-state models of morpho-phonological systems have been developed for many languages (Beesley and Karttunen, 2003; Hulden, 2009; Washington et al., 2012)
- ▶ This again tells us these systems are regular relations, but are they also *subregular*?

# What is a ‘morphological map’?

- ▶ A morphological map corresponds to a morphological operation:

$$(10) \quad f_{prog}(\text{walk}) = \text{walk} + \text{ɪŋ}$$

- ▶ What kinds of functions do we need for the attested range of morphological operations?
  - ▶ Affixation
  - ▶ Partial reduplication

# Affixation

Suffixation:  $f(\text{walk}) = \text{walk} + \text{ing}$

1-ISL

|   |   |   |   |   |      |
|---|---|---|---|---|------|
| × | w | a | l | k | ×    |
|   | w | a | l | k | +ing |

# Affixation

Prefixation:  $f(\text{wæt}f) = \text{ɪ}+\text{wæt}f$

1-ISL

|    |   |   |    |   |
|----|---|---|----|---|
| ×  | w | a | tʃ | × |
| ɪ+ | w | a | tʃ |   |

# Affixation

Circumfixation:

(11) Chickasaw (Fromkin et al., 2014)

- a.  $f(\text{chokma}) = \text{ik} + \text{chokm} + \text{o}$   
(He is good. → He isn't good.)
- b.  $f(\text{lakna}) = \text{ik} + \text{lakn} + \text{o}$   
(It is yellow. → It isn't yellow.)

1-ISL

|     |   |   |   |   |   |    |
|-----|---|---|---|---|---|----|
| ×   | l | a | k | n | a | ×  |
| ik+ | l | a | k | n | a | +o |

# Affixation

Infixation:

- (12) Tagalog (French, 1988; McCarthy and Prince, 1993; Orgun and Sprouse, 1999)
- a.  $f(\text{abot}) = \text{um+abot}$  'to reach for'
  - b.  $f(\text{sulat}) = \text{s+um+ulat}$  'to write'
  - c.  $f(\text{gradwet}) = \text{gr+um+adwet}$  'to graduate'

4-ISL

|   |   |   |         |   |   |   |   |   |
|---|---|---|---------|---|---|---|---|---|
| × | g | r | a       | d | w | e | t | × |
|   |   |   | gr+um+a | d | w | e | t |   |



# Partial reduplication

Local reduplicative suffixation:

(13) Marshallese (Byrd, 1993)

$f(\text{ebbok}) = \text{ebbok} + \text{bok}$  ('to make full' → 'puffy')

4-ISL

|   |   |   |   |   |   |      |
|---|---|---|---|---|---|------|
| × | e | b | b | o | k | ×    |
|   | e | b | b | o | k | +bok |

# Partial reduplication

Local reduplicative prefixation:

(14) Tagalog (Blake, 1917)

$f(\text{sulat}) = \text{su+sulat}$  ('write' → 'will write')

3-ISL

|   |   |      |   |   |   |   |
|---|---|------|---|---|---|---|
| × | s | u    | l | a | t | × |
|   | s | u+su | l | a | t |   |

## Partial reduplication

Non-local reduplicative suffixation:

(15) Chukchee (Bogoras, 1969)

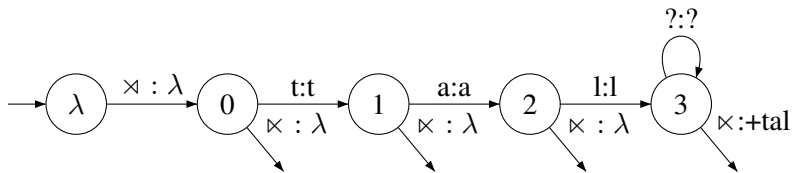
a.  $f(\text{nute}) = \text{nute} + \text{nut}$  'land'

b.  $f(\text{tala}) = \text{tala} + \text{tal}$  'meat'

Not ISL! But it is subsequential.

|   |   |   |   |   |      |
|---|---|---|---|---|------|
| × | n | u | t | e | ×    |
|   | n | u | t | e | +nut |

## Non-local reduplicative suffixation



## Partial reduplication

Non-local reduplicative prefixation:

- (16) Madurese (McCarthy and Prince, 1995; Inkelas and Zoll, 2005)

$f(\text{mõwã}) = \tilde{\text{wã}}+\text{mõwã}$  ('face' → 'faces')

Not ISL! But it is subsequential.

|     |   |   |   |   |   |
|-----|---|---|---|---|---|
| ×   | m | õ | ẽ | ã | × |
| ẽã+ | m | õ | ẽ | ã |   |

## Interim summary

| <b>Map</b>                     | <b>Language</b> | <b>Classification</b> |
|--------------------------------|-----------------|-----------------------|
| suffixation                    | English         | 1-ISL                 |
| prefixation                    | English         | 1-ISL                 |
| circumfixation                 | Chickasaw       | 1-ISL                 |
| infixation                     | Tagalog         | 4-ISL                 |
| redup. suffixation (local)     | Marshallese     | 4-ISL                 |
| redup. prefixation (local)     | Tagalog         | 3-ISL                 |
| redup. suffixation (non-local) | Chukchee        | subsequential         |
| redup. prefixation (non-local) | Madurese        | subsequential         |

## Mafa imperfective

(17) Mafa (Barreteau and Bleis, 1990; Ettliger, 2004)

- a.  $f(\text{tsap}) = \text{tʃep}$  'is spackling with clay'
- b.  $f(\text{lubat}) = \text{lybet}$  'is twisting'
- c.  $f(\text{səban}) = \text{ʃiben}$  'is working'

s ʃ

z ʒ

ts tʃ

dz dʒ

u y

a e

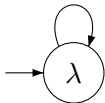
ə i

## Mafa imperfective: featural affixation

- (18) Mafa (Barreteau and Bleis, 1990; Ettliger, 2004)
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  - c.  $f(\text{səban}) = \text{ʃiben}$  'is working'

Palatalization is 1-ISL

?:?, s:ʃ, z:ʒ, ts:tʃ, dz:dʒ, u:y, a:e, ə:i





## Mafa imperfective: featural affixation

(19) Mafa (Barreteau and Bleis, 1990; Ettliger, 2004)

- a.  $f(\text{tsap}) = \text{tʃep}$  ‘is spackling with clay’
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- c.  $f(\text{səban}) = \text{ʃiben}$  ‘is working’
- d.  $f(\text{gudza}) = \text{gudza+j}$  ‘is trembling’

Palatalization is 1-ISL.

Suffixation is 1-ISL

## Mafa imperfective: featural affixation

- (19) Mafa (Barreteau and Bleis, 1990; Ettliger, 2004)
- a.  $f(\text{tsap}) = \text{tʃep}$  ‘is spackling with clay’
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  - d.  $f(\text{gudza}) = \text{gudza+j}$  ‘is trembling’

Palatalization is 1-ISL.

Suffixation is 1-ISL Determining whether to apply palatalization OR suffixation is *not* ISL.

## Mafa imperfective: featural affixation

(20) Mafa (Barreteau and Bleis, 1990; Ettliger, 2004)

- a.  $f(\text{tsap}) = \text{tʃep}$  'is spackling with clay'
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- d.  $f(\text{gudza}) = \text{gudza+j}$  'is trembling'

|   |   |   |   |   |   |    |
|---|---|---|---|---|---|----|
| × | g | u | d | z | a | ×  |
|   |   |   |   |   | a | +j |

## Mafa imperfective: featural affixation

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|   |   |   |   |   |   |    |
|---|---|---|---|---|---|----|
| × | g | u | d | z | a | ×  |
|   |   |   |   | ? | a | +j |

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|   |   |   |   |   |   |    |
|---|---|---|---|---|---|----|
| × | g | u | d | z | a | ×  |
|   |   |   |   | ? | a | +j |

The two operations are ISL, but their *interaction* makes the ‘imperfective map’ subsequential.

## Even/odd allomorphy

(22) Yidij (Dixon, 1977; Hayes, 1999)

- a. buŋa+ŋgu  $\mapsto$  buŋa: +ŋ ‘woman (ergative)’
- b. giŋdanu+ŋgu  $\mapsto$  giŋdanu+ŋgu ‘moon (ergative)’

The ‘ergative map’ appends -ŋ to words with an even number of syllables and -ŋgu to words with an odd number of syllables.

## Even/odd allomorphy

(23) Yidij (Dixon, 1977; Hayes, 1999)

a. bupa+ŋgu  $\mapsto$  bupa: +ŋ          ‘woman (ergative)’

b. gindanu+ŋgu  $\mapsto$  gindanu+ŋgu      ‘moon (ergative)’

- ▶ Not ISL: for any value of  $k$  we can't distinguish  $CV(CV)^k$  from  $(CV)^k$ .
- ▶ Subsequential functions **can** track even/odd.

## Even/odd allomorphy

- ▶ Hayes (1982): Deletion targets final unparsed syllables.

(24)    a.    [buɲaŋ]gu ↦ [buɲa:ŋ]  
          b.    [ginda][nuŋgu] ↦ [ginda][nuŋgu]

- ▶ **IF** the input is already parsed for foot structure, the ergative map is ISL.
  - ▶ If input ends in ‘]’, append -ŋ.
  - ▶ If input does not end in ‘]’, append -ŋgu.



## Summary

| <b>Map</b>                            | <b>Language</b>       | <b>Classification</b>              |
|---------------------------------------|-----------------------|------------------------------------|
| suffixation                           | English               | 1-ISL                              |
| suffixation                           | Yidij                 | subsequential<br>2-ISL (with feet) |
| prefixation                           | English               | 1-ISL                              |
| circumfixation                        | Chickasaw             | 1-ISL                              |
| infixation                            | Tagalog ( <i>um</i> ) | 4-ISL                              |
| redup. suffixation (local)            | Marshallese           | 4-ISL                              |
| redup. prefixation (local)            | Tagalog               | 3-ISL                              |
| redup. suffixation (non-local)        | Chukchee              | subsequential                      |
| redup. prefixation (non-local)        | Madurese              | subsequential                      |
| featural affixation<br>'imperfective' | Mafa                  | 1-ISL<br>subsequential             |

## What's next?

- ▶ Additional operations (esp. templatic morphology)
- ▶ What about full reduplication?
- ▶ Comprehensive set of interactions and their consequences for computational complexity.

## Conclusion

- ▶ Like phonological maps, many morphological operations can be modeled with subregular classes of functions.
- ▶ These classifications provide a way of understanding morpho-phonological interactions in terms of how individual maps/operations can affect each other.
- ▶ Importantly these subregular classes have been proven to be learnable from positive data.

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