The Role of Computation in Phonological Typology and Learning

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Computational Linguistics

Computational linguists pursue a variety of research goals:

- Algorithms and methods for handling natural language data.
  - Siri, Google Translate, Amazon Echo, etc.
- Using the study of computation to understand what language *is*.
  - Computational theory of language

Levels of language

Phonetics	Production and perception of speech sounds
Phonology	Sound patterns
Morphology	Word formation processes
Syntax	Sentence structure
Semantics	Meaning
Pragmatics	Social/cultural conventions

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Computational nature of phonology

- Central question: what is the nature of the computations involved in phonological systems?
- Main result: phonology is quite **restrictive** in its computational complexity, and this restrictiveness gives us insight into both **cognition** and **language learning**

Phonological patterns

Phonotactics	Processes
German: [zaːk] (*zaːg), ‘say’	/zaːg/ $\mapsto$ [zaːk]
English: [gɹeɪps] (*gɹeɪpz), ‘grapes’	/gɹeɪpz/ $\mapsto$ [gɹeɪps]

Phonotactics

Attested	Don't end a word with sound *x* Don't start a word with sound *x* Don't allow sequences of sound *x* followed by sound *y* etc.
Unattested	Don't have an even/odd number of sound *x* in a word If a word starts with sound *x* it can't end with sound *y* A word can have either sound *x* or sound *y*, but not both etc.

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Goal: Explain this boundary in terms of computational complexity.

Phonotactics as formal languages

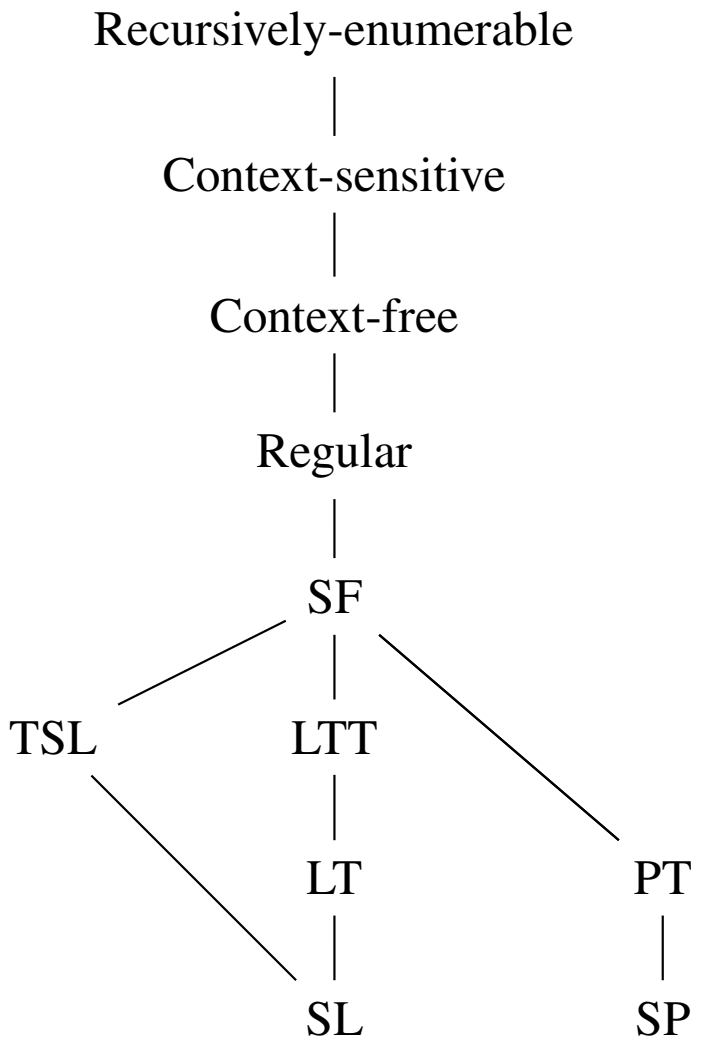
- A formal language is a set of strings built from an alphabet, or set of symbols, Σ

  (1) English: Σ = { p, t, k, b, d, g, m, n, ŋ, s, z, ʃ, ʒ, ... }

- A phonotactic constraint can be modeled with the set of strings that do **not** violate it.

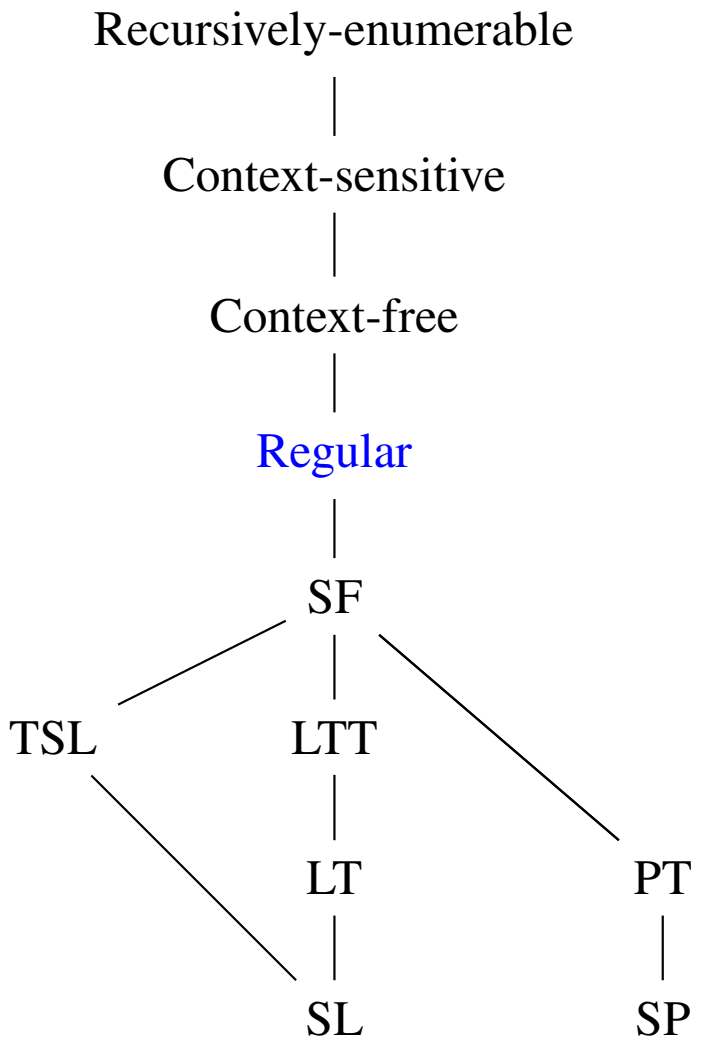
  (2) { gɹeɪps, æpl̩z, fɪgz, æpɹɪkɑts, ips, ... }

Classifying formal languages



(Chomsky, 1956; Rogers and Pullum, 2011; Rogers et al., 2013)

Hypothesis: phonotactics are regular



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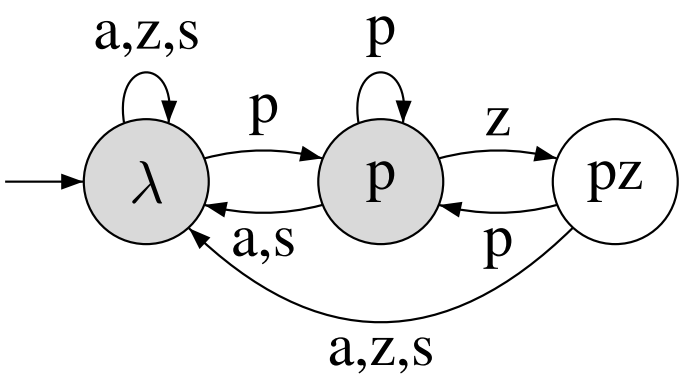

Don't have an odd number of [a]'s.

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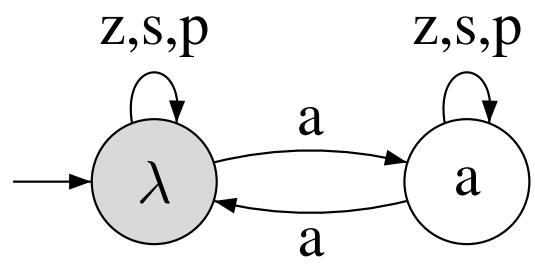

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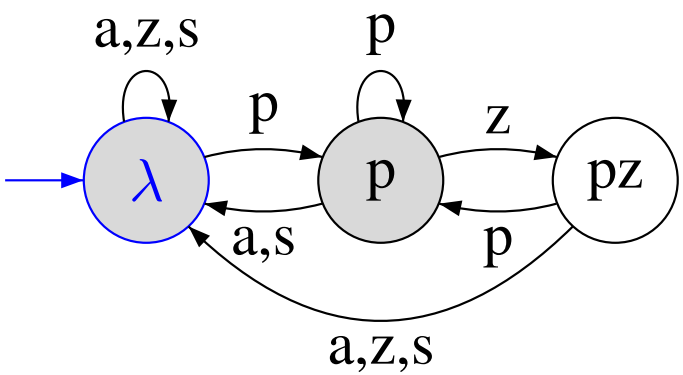

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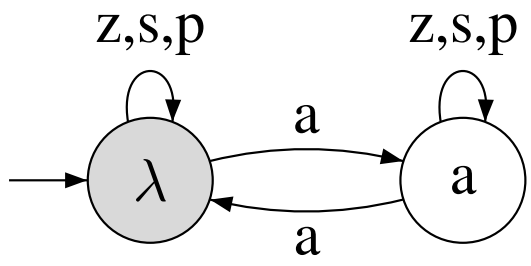

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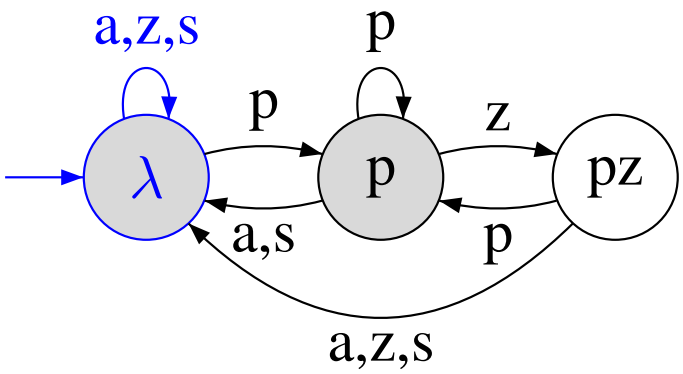

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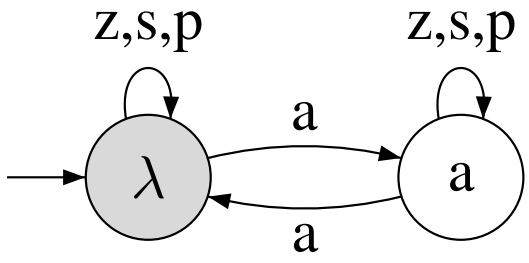

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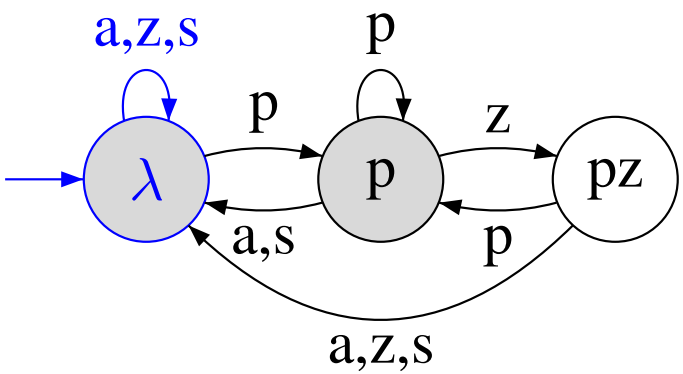

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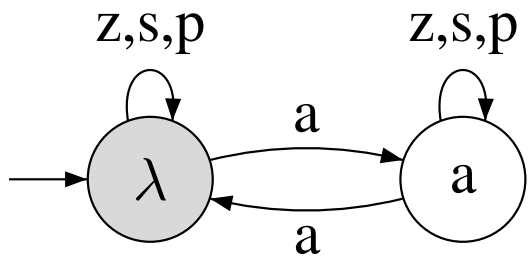

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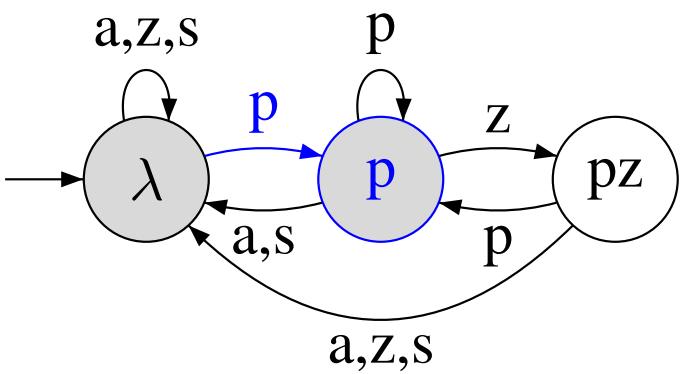

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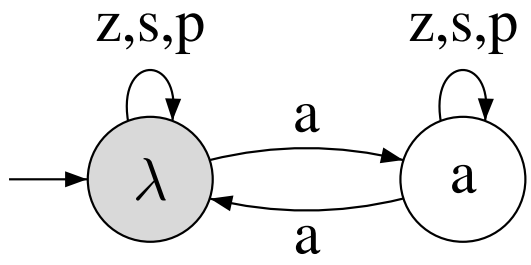

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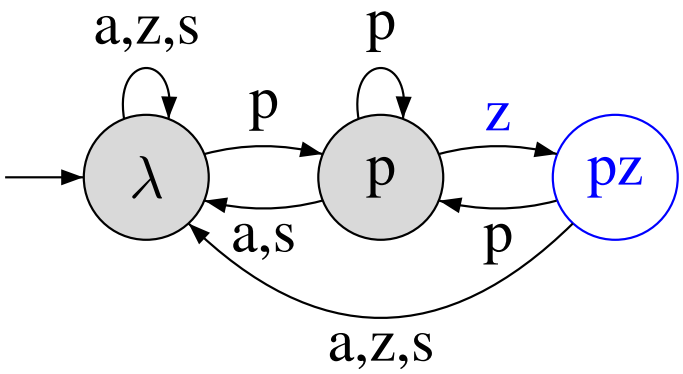

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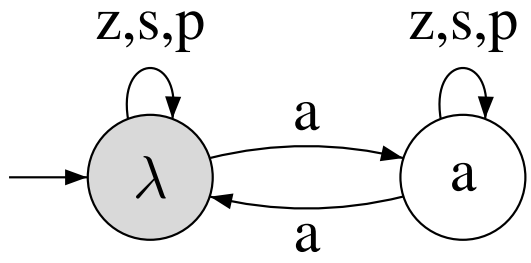

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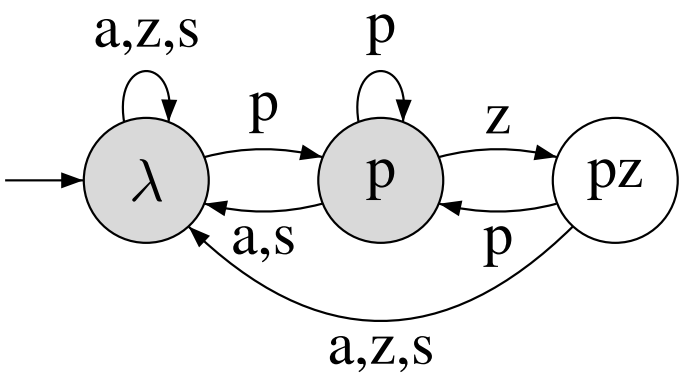

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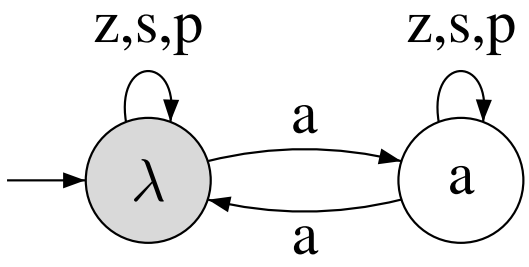

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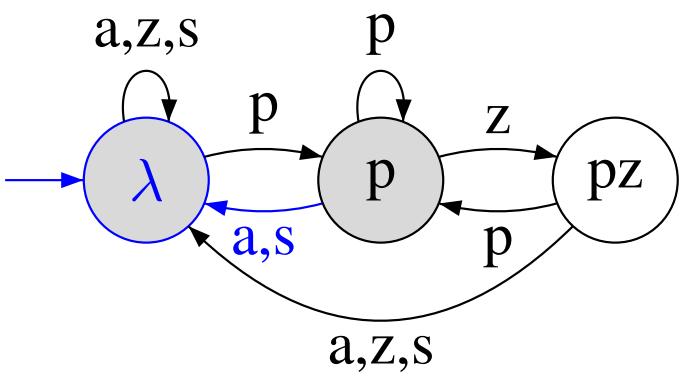

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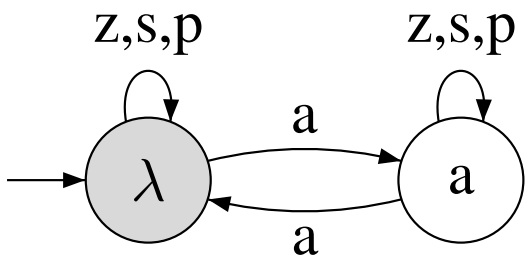

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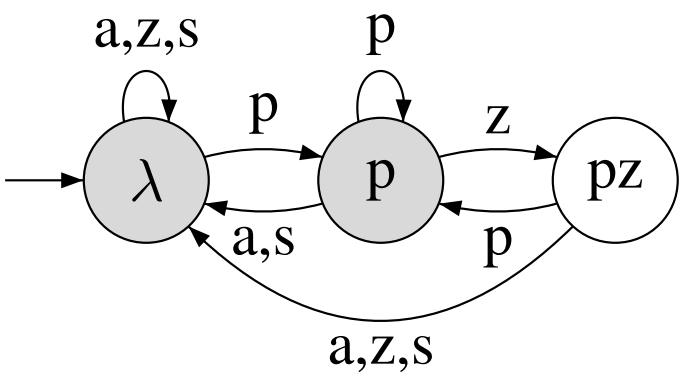

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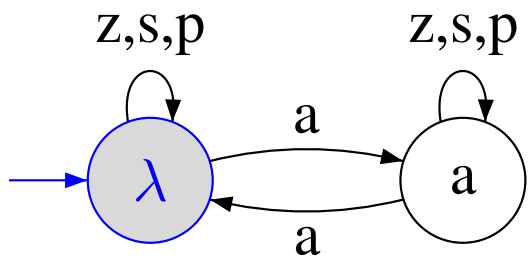

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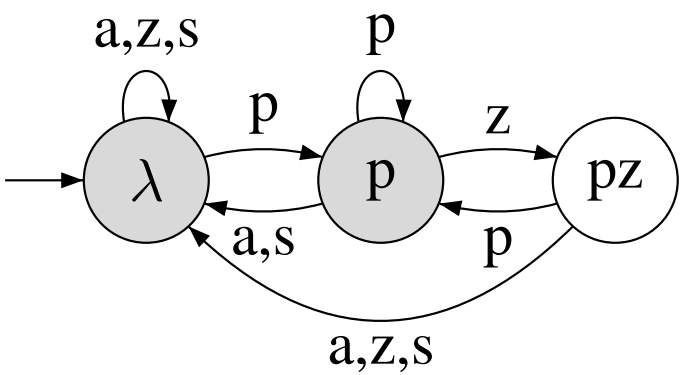

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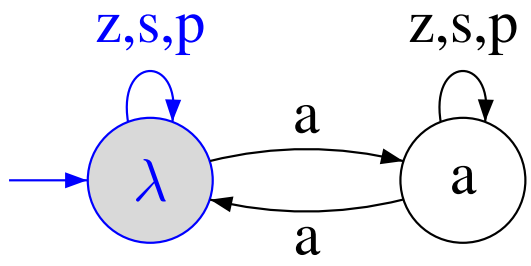

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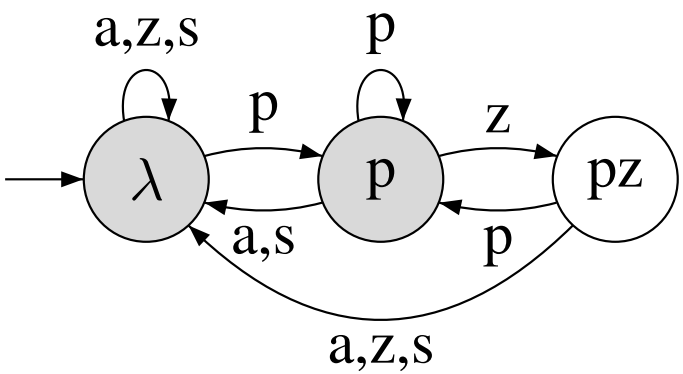

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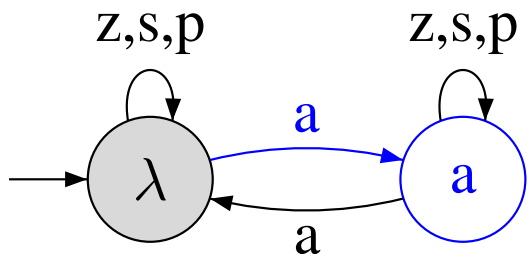

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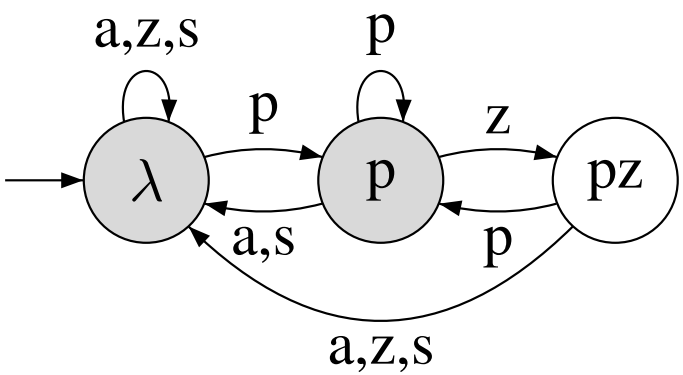

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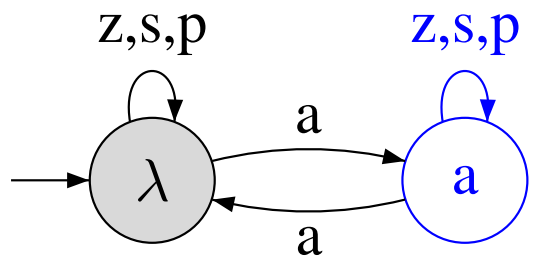

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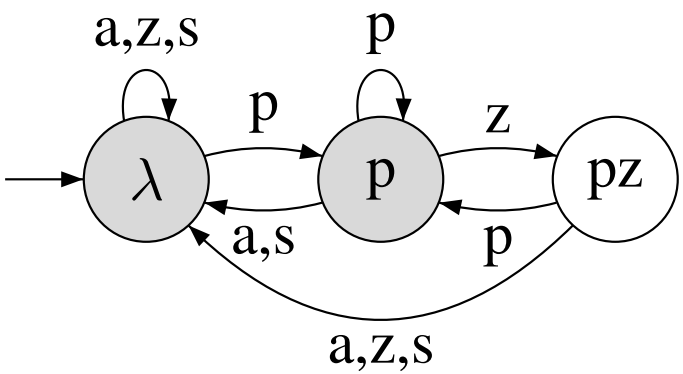

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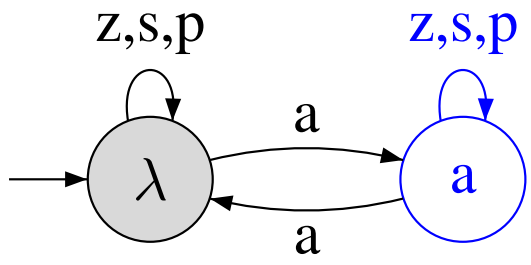

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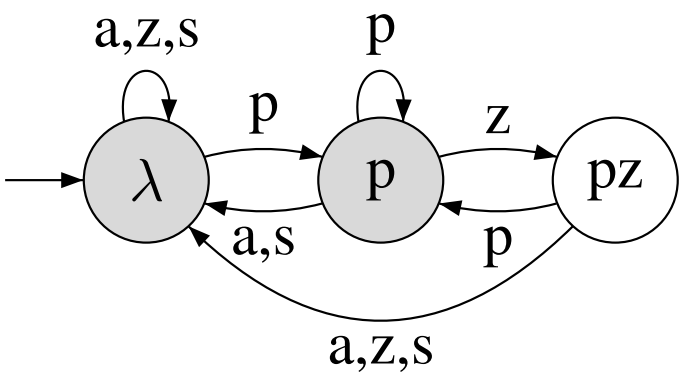

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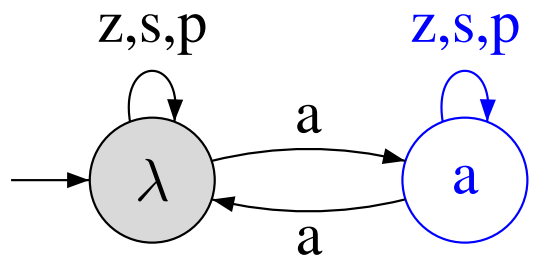

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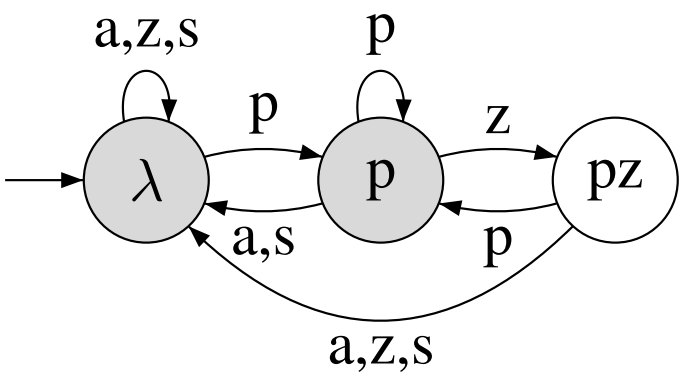

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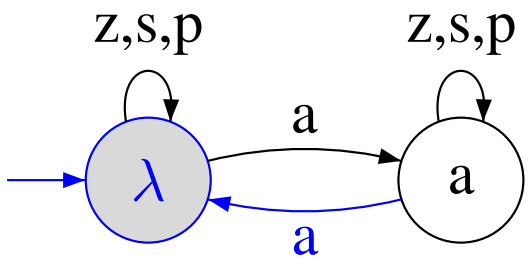


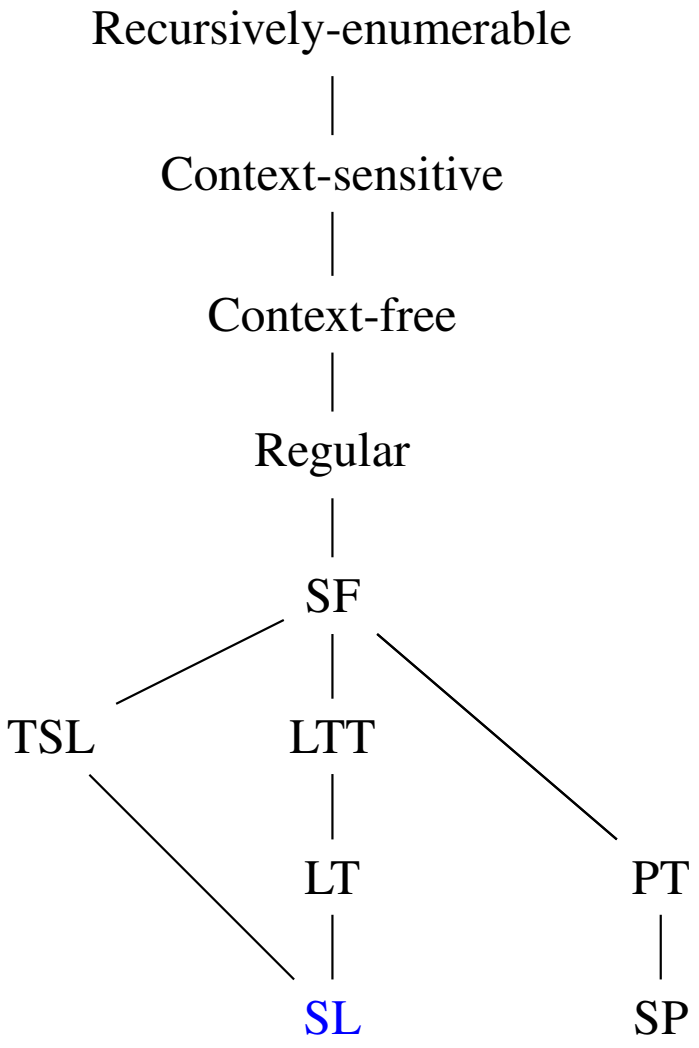
z a p a

✓

✓ Hypothesis: phonotactics are regular

However,...

Hypothesis: phonotactics are *subregular*



(Chomsky, 1956; Heinz, 2007; Rogers and Pullum, 2011; Rogers et al., 2013)

Strictly Local FSAs

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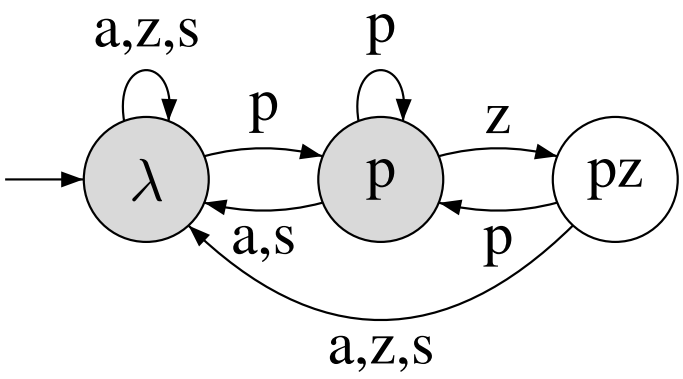
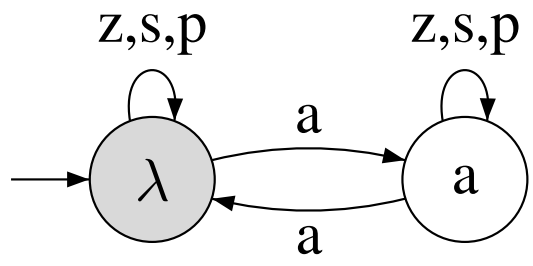


States represent last segment(s) seen.

Don't have an odd number of [a]'s.

$\Sigma = \{p, z, s, a\}$



States represent even/odd [a]'s.

Phonological processes

- Assumption: the English plural suffix is /z/, but in some cases it is pronounced [s].

bags	bægz
maps	mæps

- To avoid sequences of [pz], we have a *process* that changes /z/ in this context to [s].

$$\text{mæpz} \mapsto \text{mæps}$$

Phonological processes as functions

- A processes can be represented with a *function* that maps mæpz to mæps
- A function is a set of string pairs:

  (3) { (mæpz, mæps), (bægz, bægz), ... }

- I'll call these phonological maps (see also Tesar (2012)).

Complexity of phonological maps

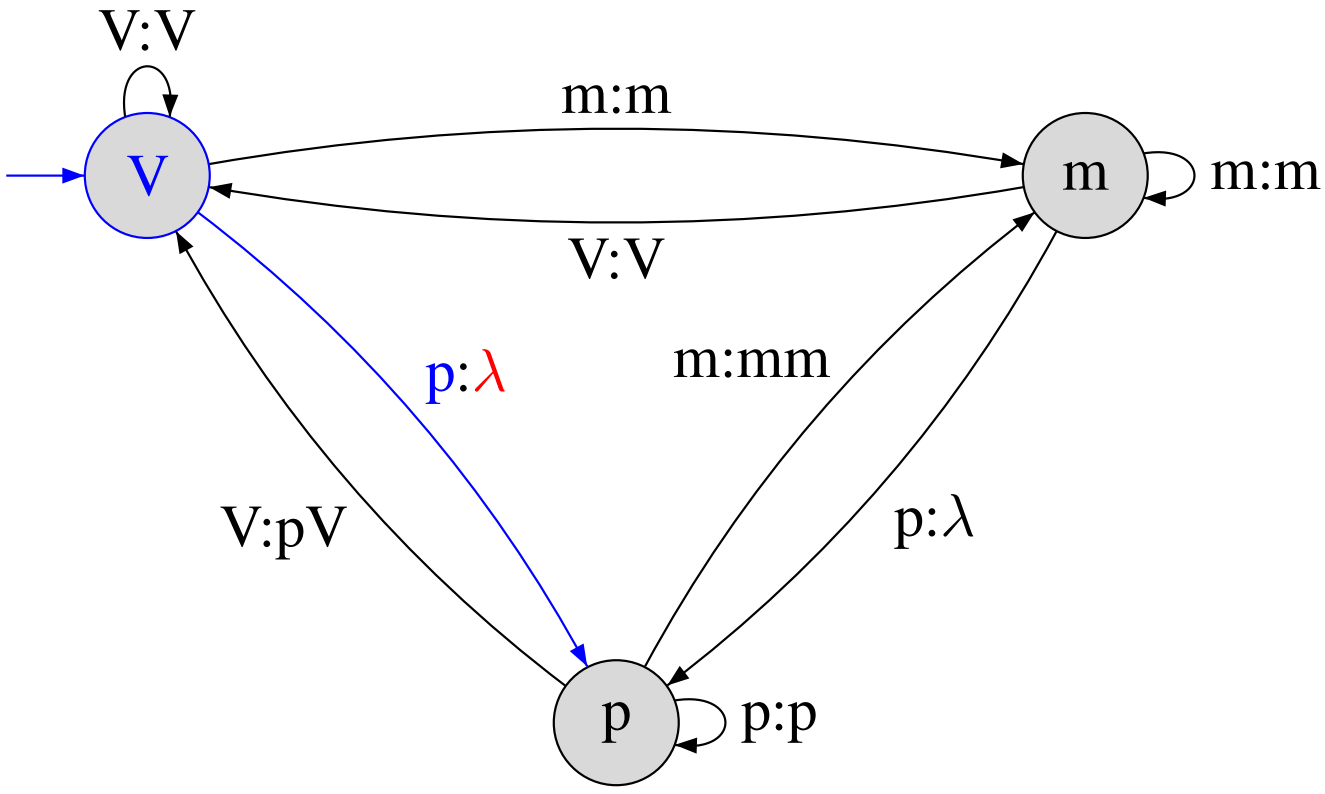
REGULAR RELATIONS (Johnson, 1972; Kaplan and Kay, 1994)

SUBSEQUENTIAL FUNCTIONS (Mohri, 1997)

STRICTLY LOCAL FUNCTIONS (Chandlee, 2014)

Strictly Local function

(4) Korean (Lee and Pater, 2008)
/pa**pm**ul/ ↦ [pa**mm**ul] ‘rice water’



⋊ p a p m u l ⋉
λ

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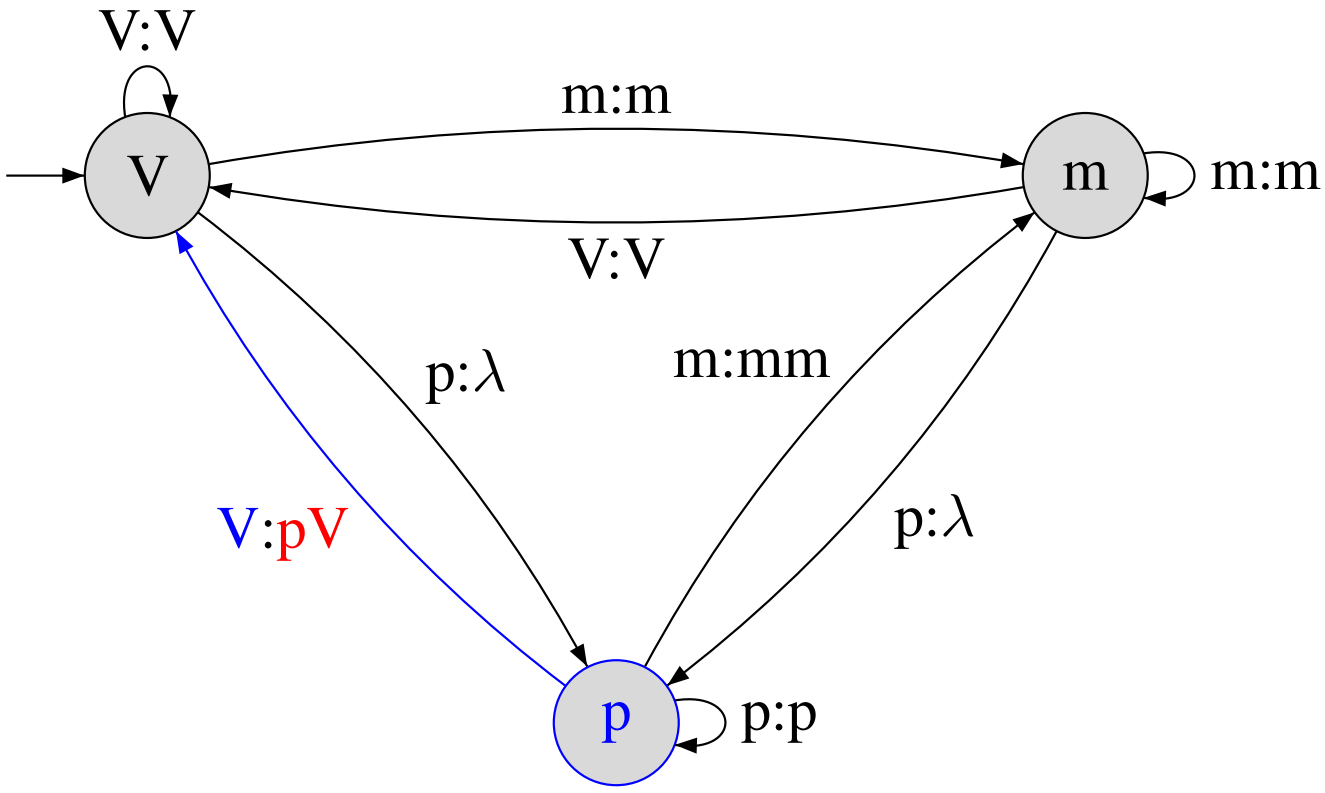

⋊ p a p m u l ⋉
λ pa

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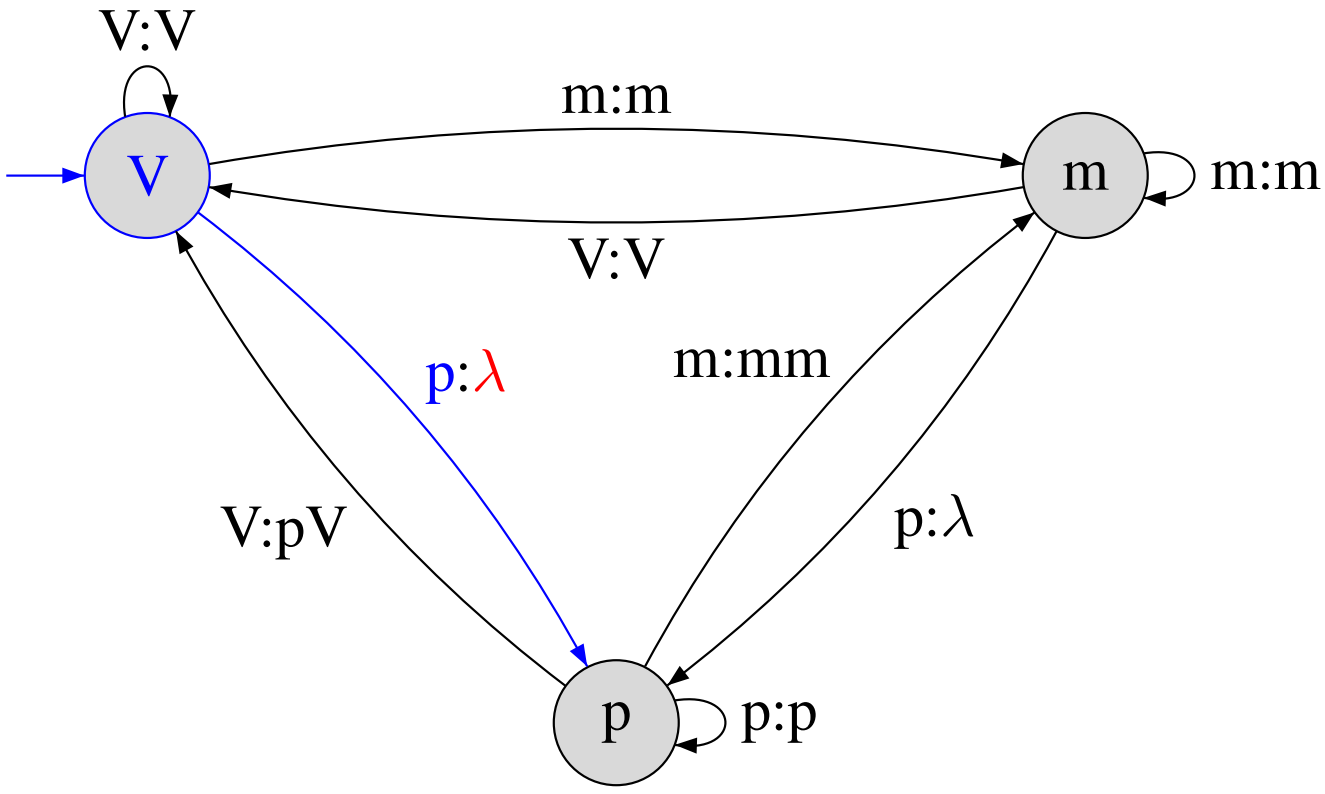

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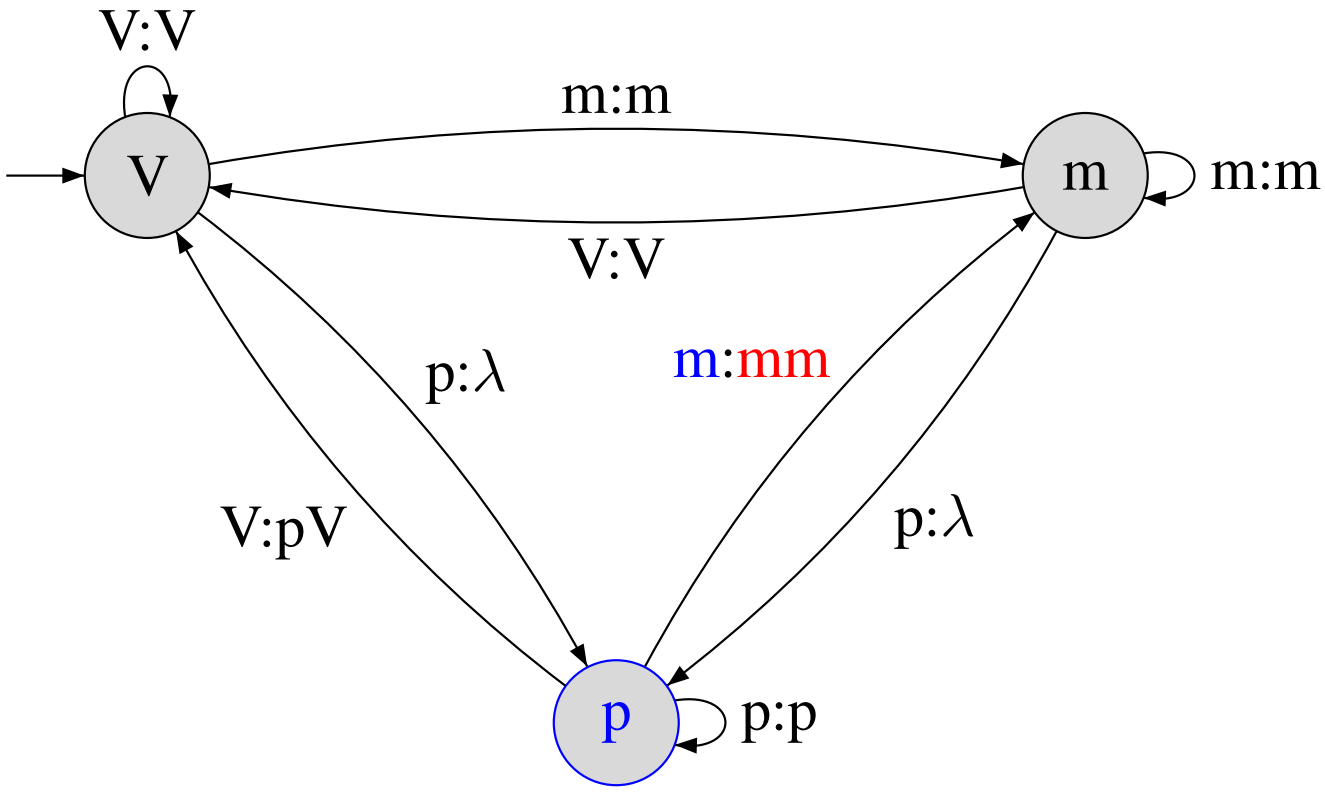

⋊	p	a	p	m	u	l	⋉
	λ	pa	λ	mm			

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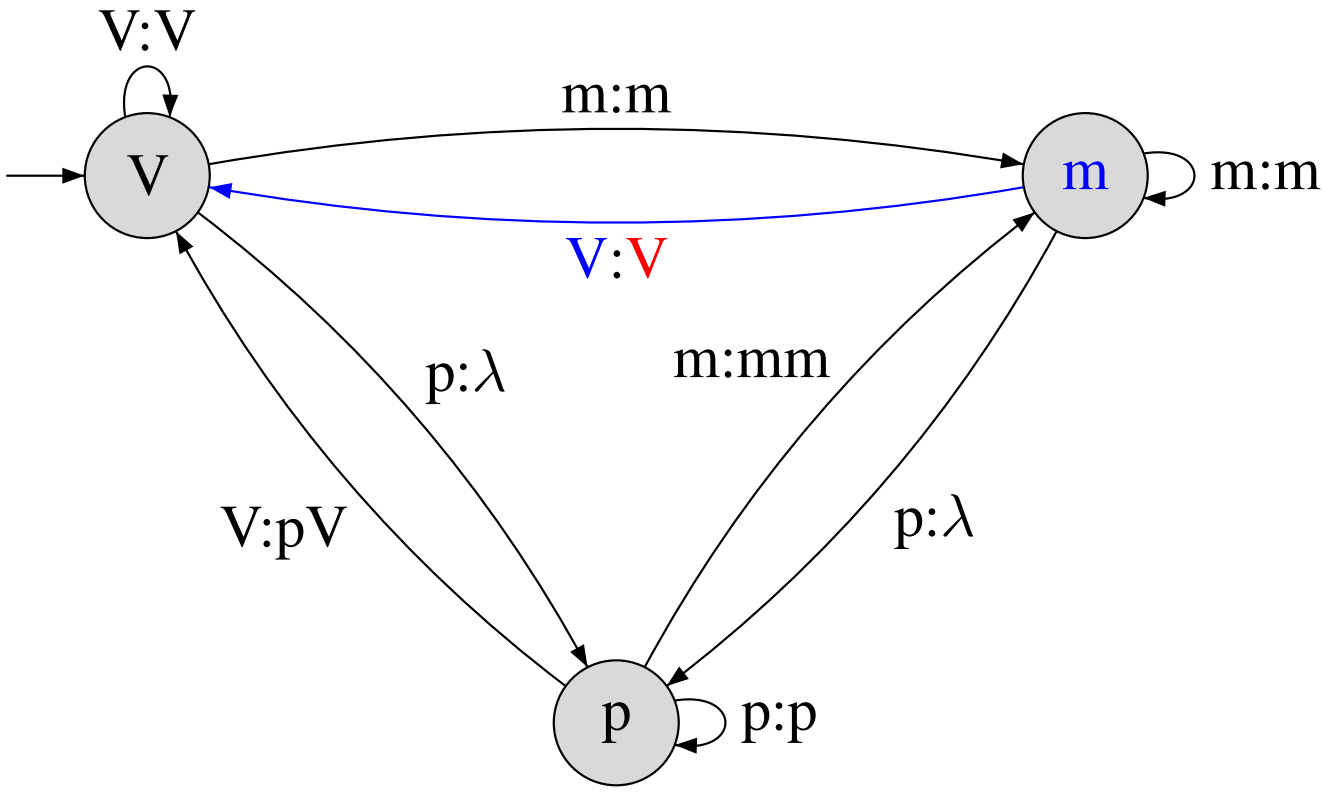
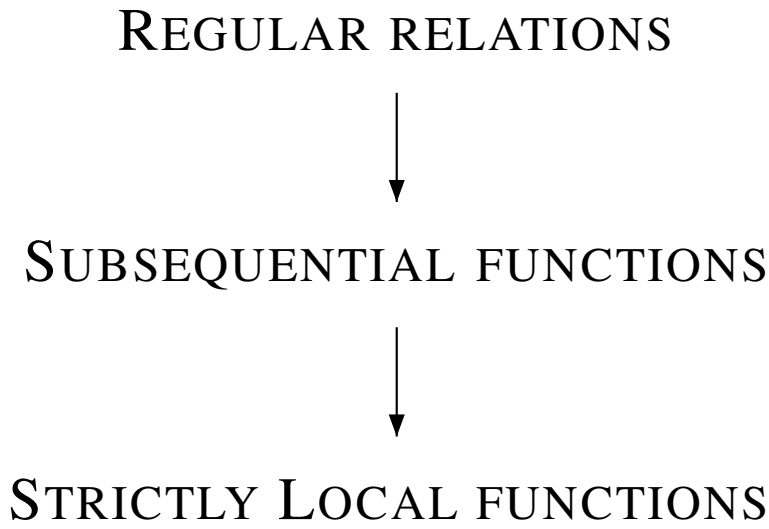


⋊	p	a	p	m	u	l	⋉
	λ	pa	λ	mm	u		

Complexity of phonological maps

- Local phonological processes are Strictly Local functions (Chandlee, 2014)



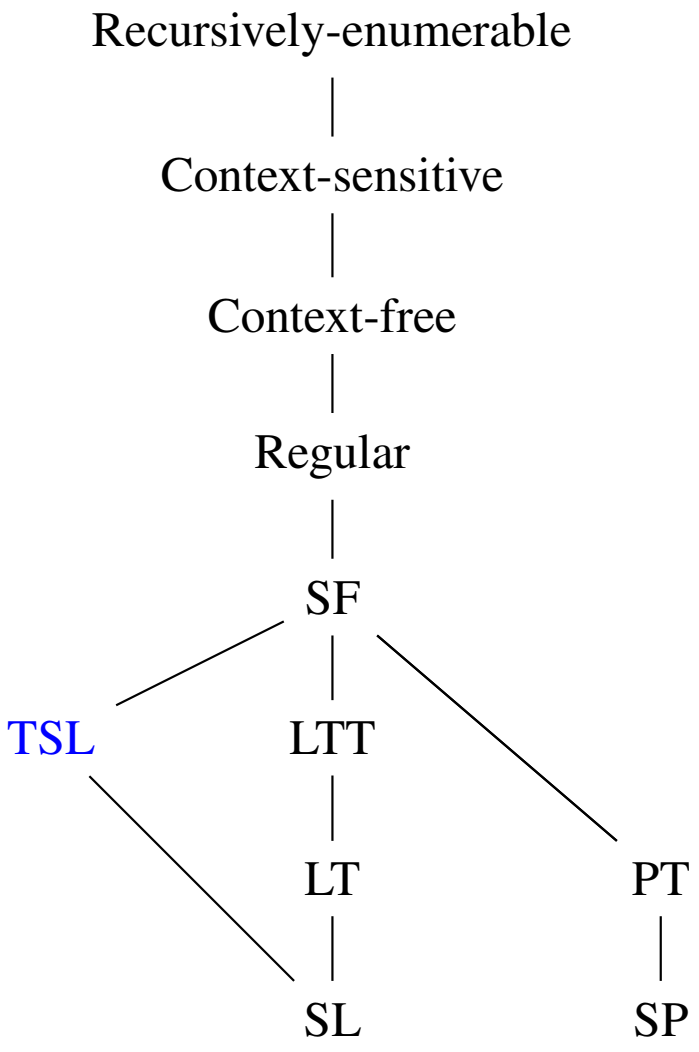
Long-distance phonology

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

/tu**n**ik-i**d**i/ $\mapsto$ [tu**n**ik-i**n**i] ‘we ground’

- SL version of this phonotactic constraint: don’t have [d] after [niki]

Long-distance phonotactics are TSL

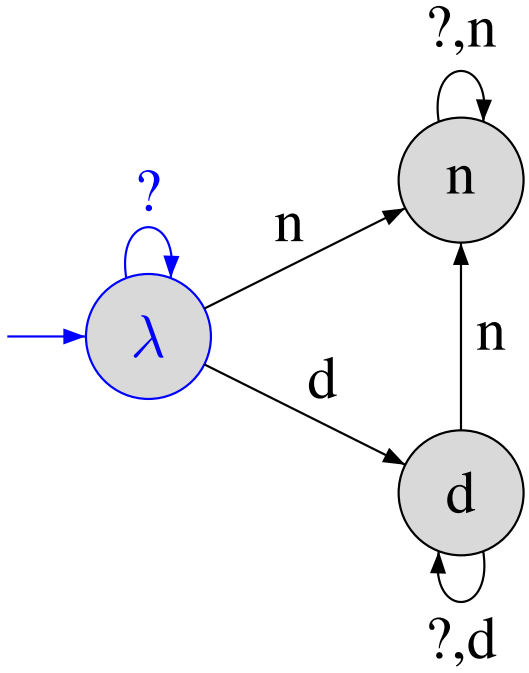


(Heinz et al., 2011; McMullin, 2016)

Tier-based Strictly Local Languages

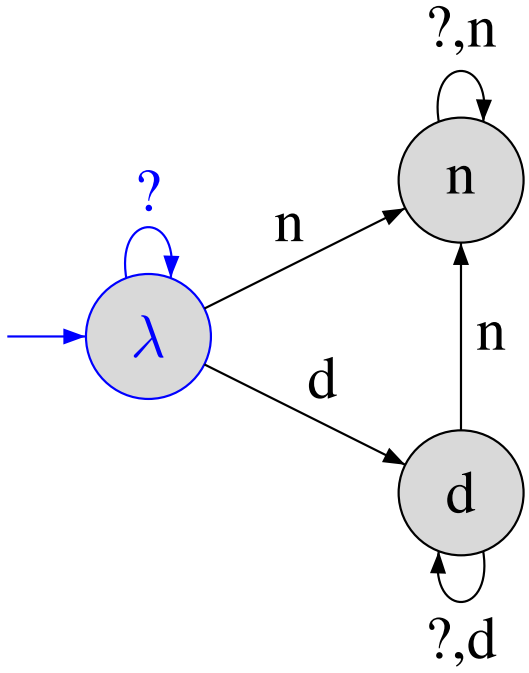
- First designate a subset of the alphabet, called the *tier*:
  $T = \{n, d\}$
- Ignoring non-tier symbols, the constraint is:
  'Don't have [d] after [n].'

Tier-based Strictly Local FSA



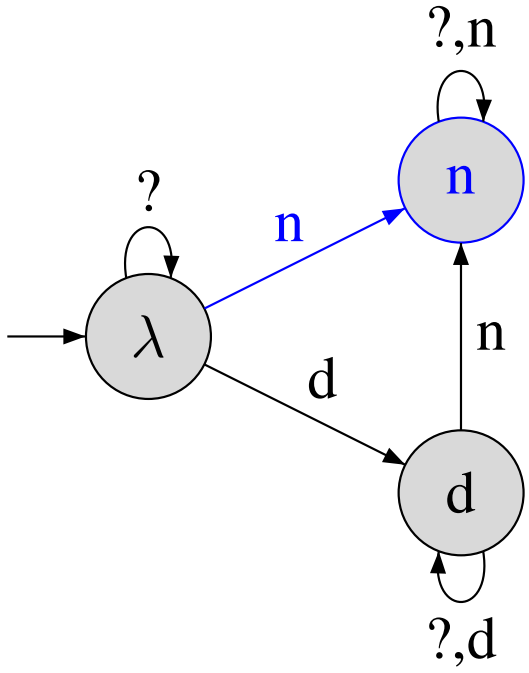
t u n i k i d i

Tier-based Strictly Local FSA



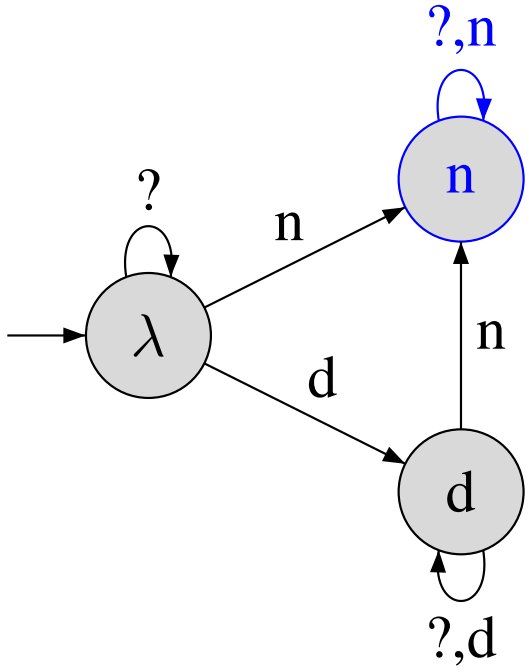
t u n i k i d i

Tier-based Strictly Local FSA



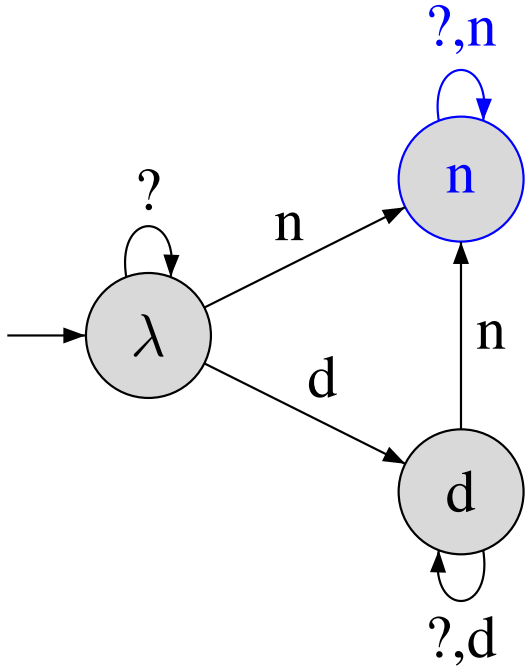
t u n i k i d i

Tier-based Strictly Local FSA



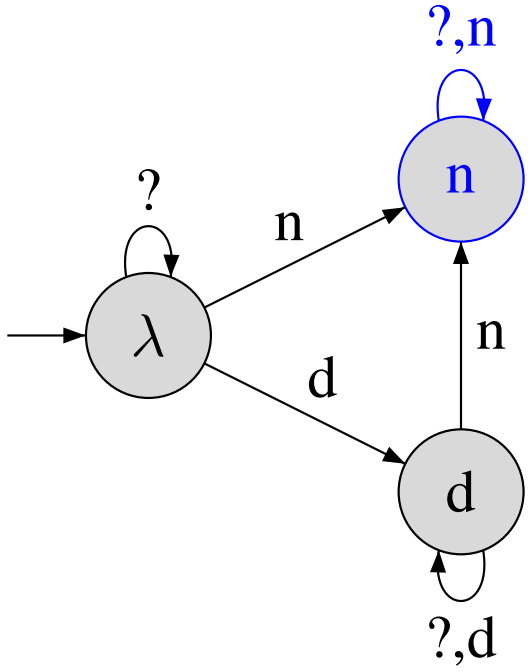
t u n i k i d i

Tier-based Strictly Local FSA



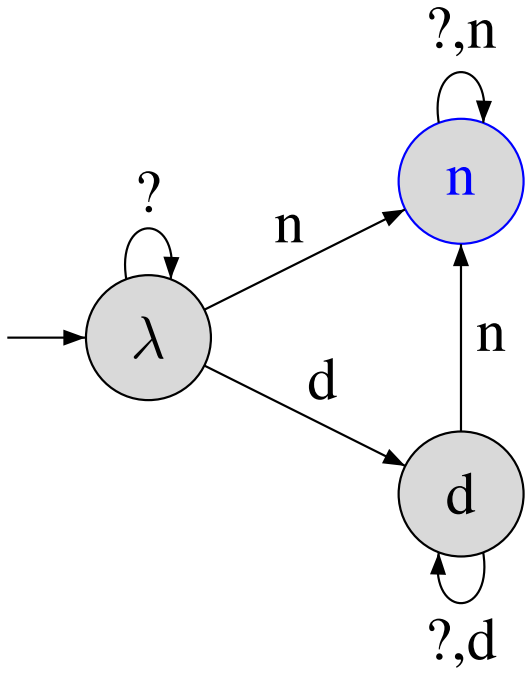
t u n i k i d i

Tier-based Strictly Local FSA



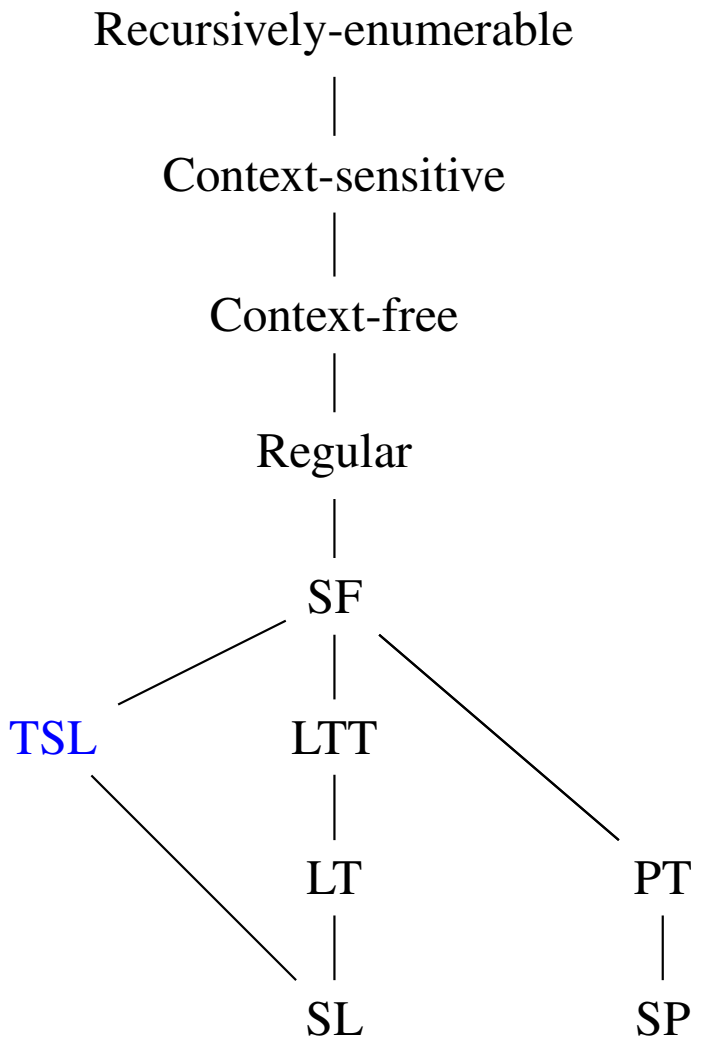
t u n i k i d i

Tier-based Strictly Local FSA



t u n i k i d i

Long-distance phonotactics are TSL (and therefore subregular)

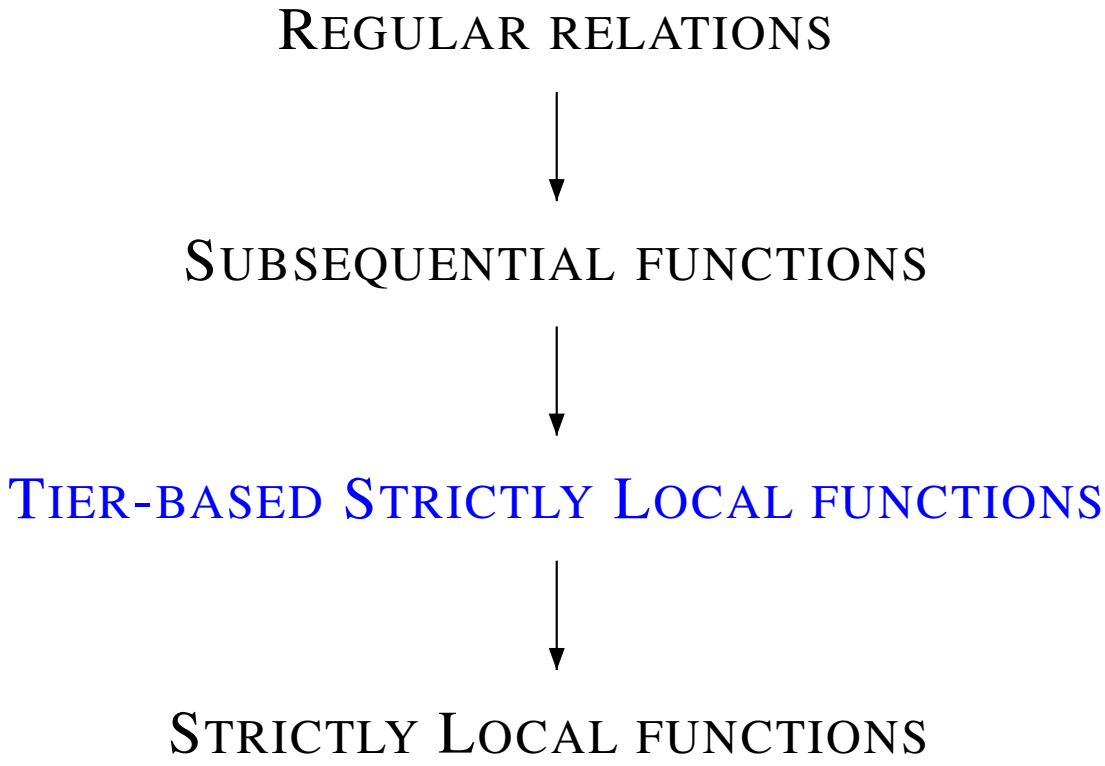


(Heinz et al., 2011; McMullin, 2016)

Long-distance processes

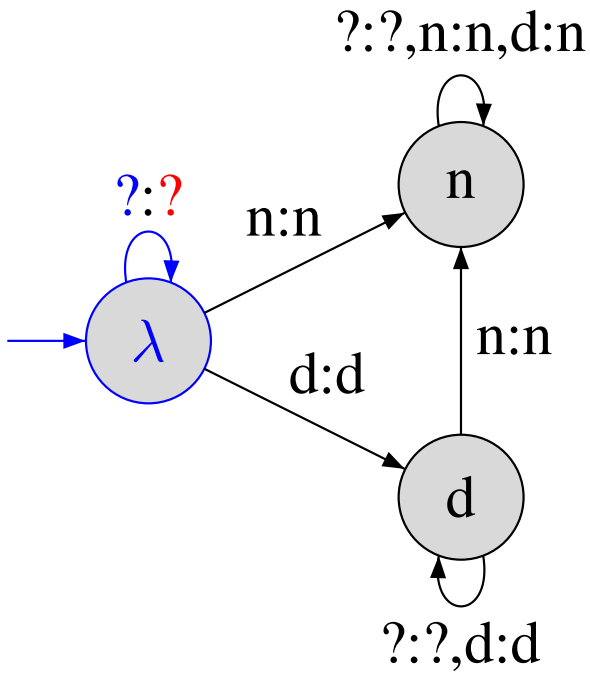
What about long-distance maps?

Hierarchy of maps



Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

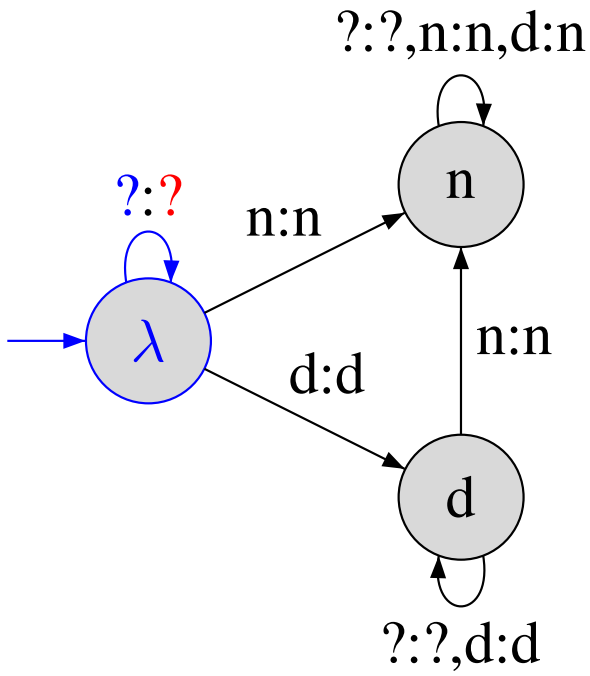


⋊ t u n i k i d i ⋉

t

Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

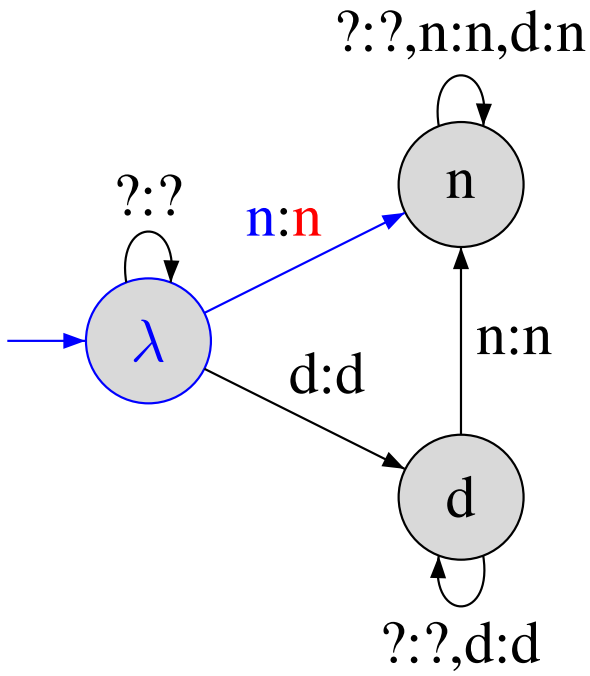


⋊ t u n i k i d i ⋉

t u

Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

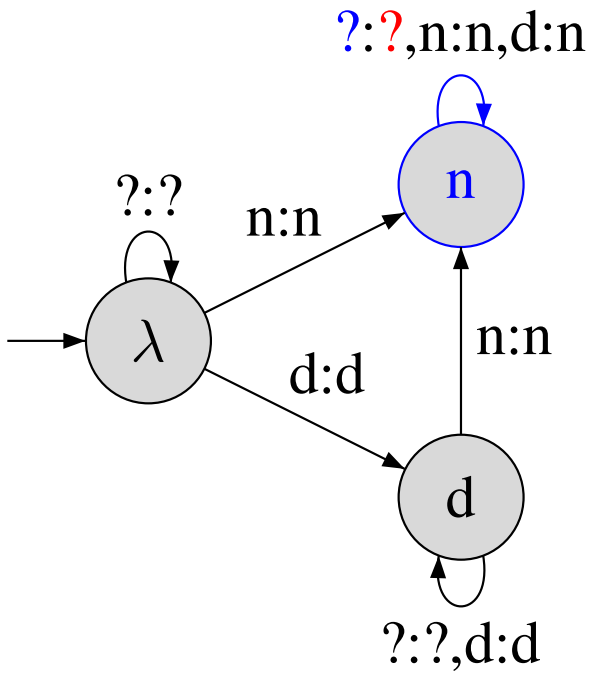


⋊ t u n i k i d i ⋉

t u n

Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

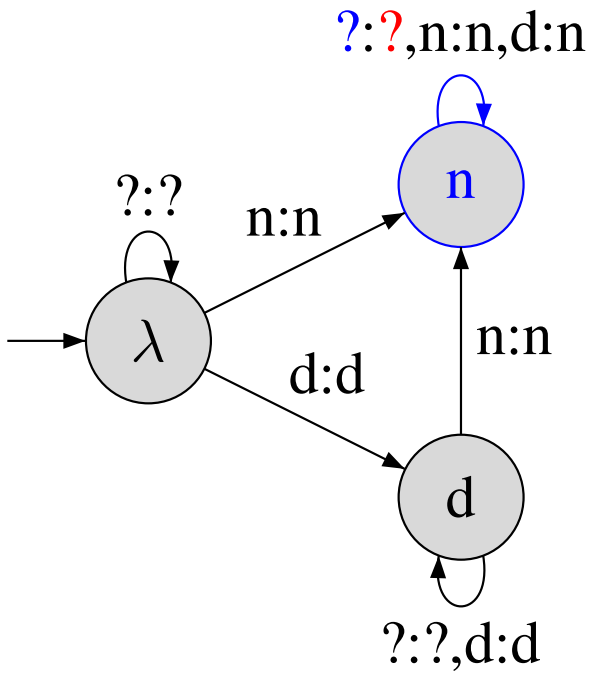


⋊ t u n i k i d i ⋉

t u n i

Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

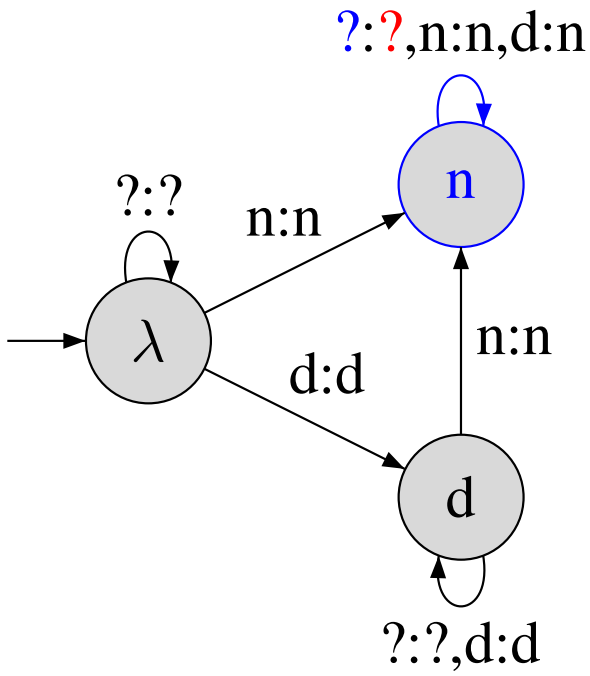


⋊ t u n i k i d i ⋉

t u n i k

Tier-based Strictly Local functions

(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]

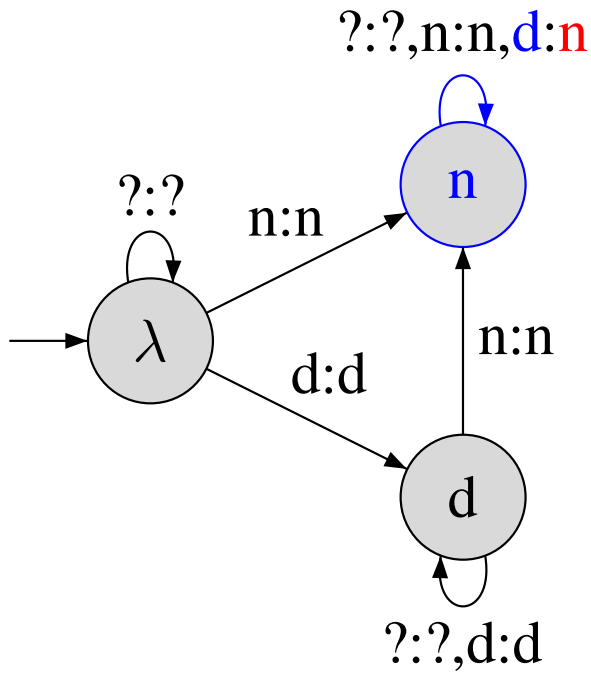


⋊ t u n i k i d i ⋉

t u n i k i

Tier-based Strictly Local functions

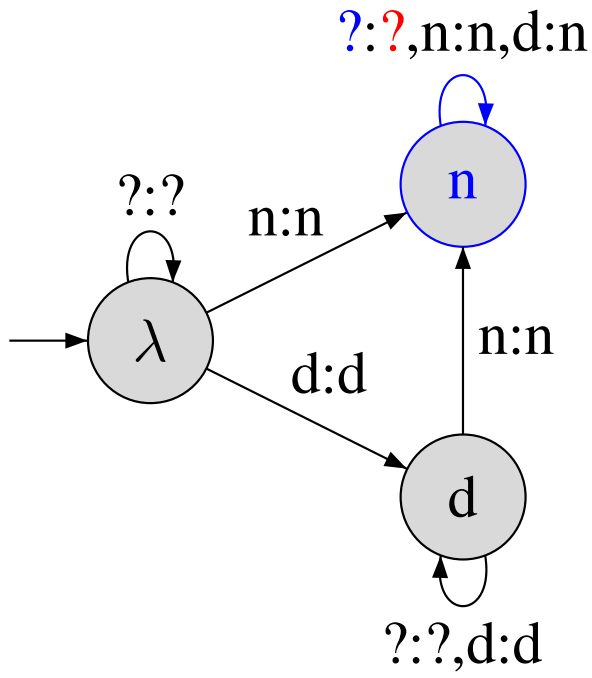
(6) /tu**n**iki**d**i/ $\mapsto$ [tu**n**iki**n**i]



⋊	t	u	n	i	k	i	d	i	⋉
	t	u	n	i	k	i	n		

Tier-based Strictly Local functions

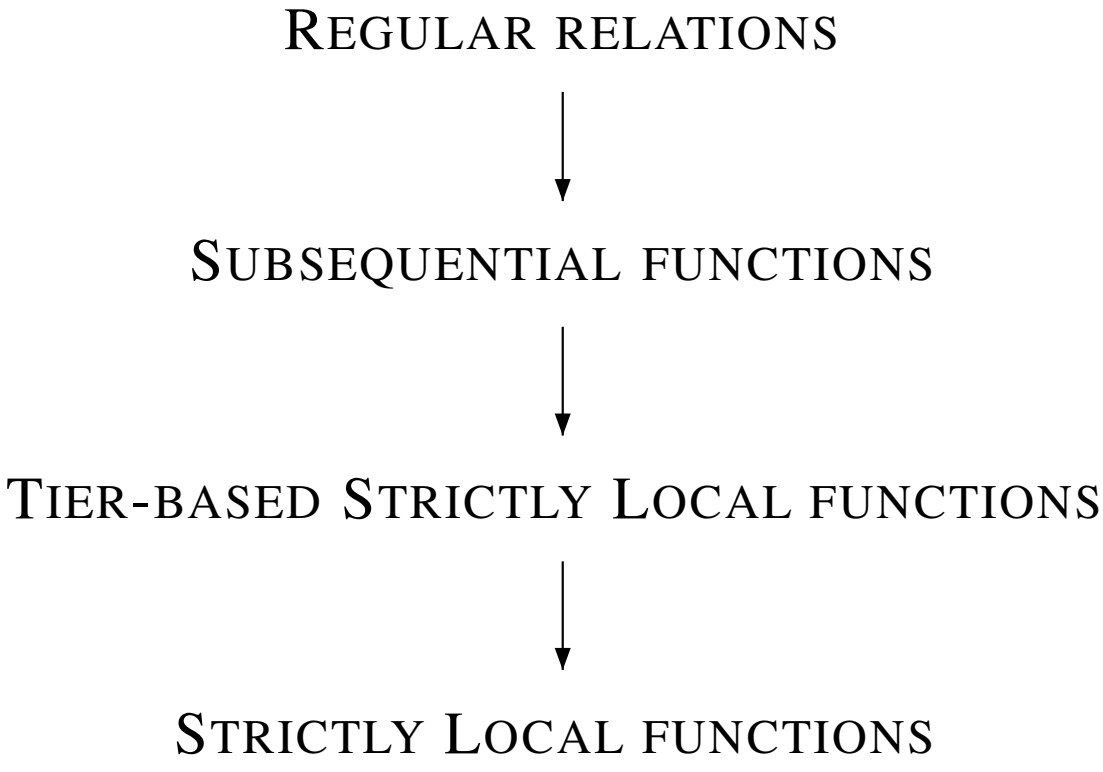
(6) /tu**n**iki**d**i/ ↦ [tu**n**iki**n**i]



⋊	t	u	n	i	k	i	d	i	⋉
	t	u	n	i	k	i	n	i	

Complexity of phonological maps

- Long-distance phonological processes are conjectured to be Tier-based Strictly Local functions (Chandlee et al., 2017)



Main result

- Both types of phonological patterns (phonotactics and processes) belong to subregular classes of formal languages and functions.
  - SL or TSL
- These classes provide a better fit to the typology than the regular languages and relations.

Implications for phonological learning

- The regular relations are not learnable from positive data...
- but the SL languages and functions are (Chandlee et al., 2014; Jardine et al., 2014)!

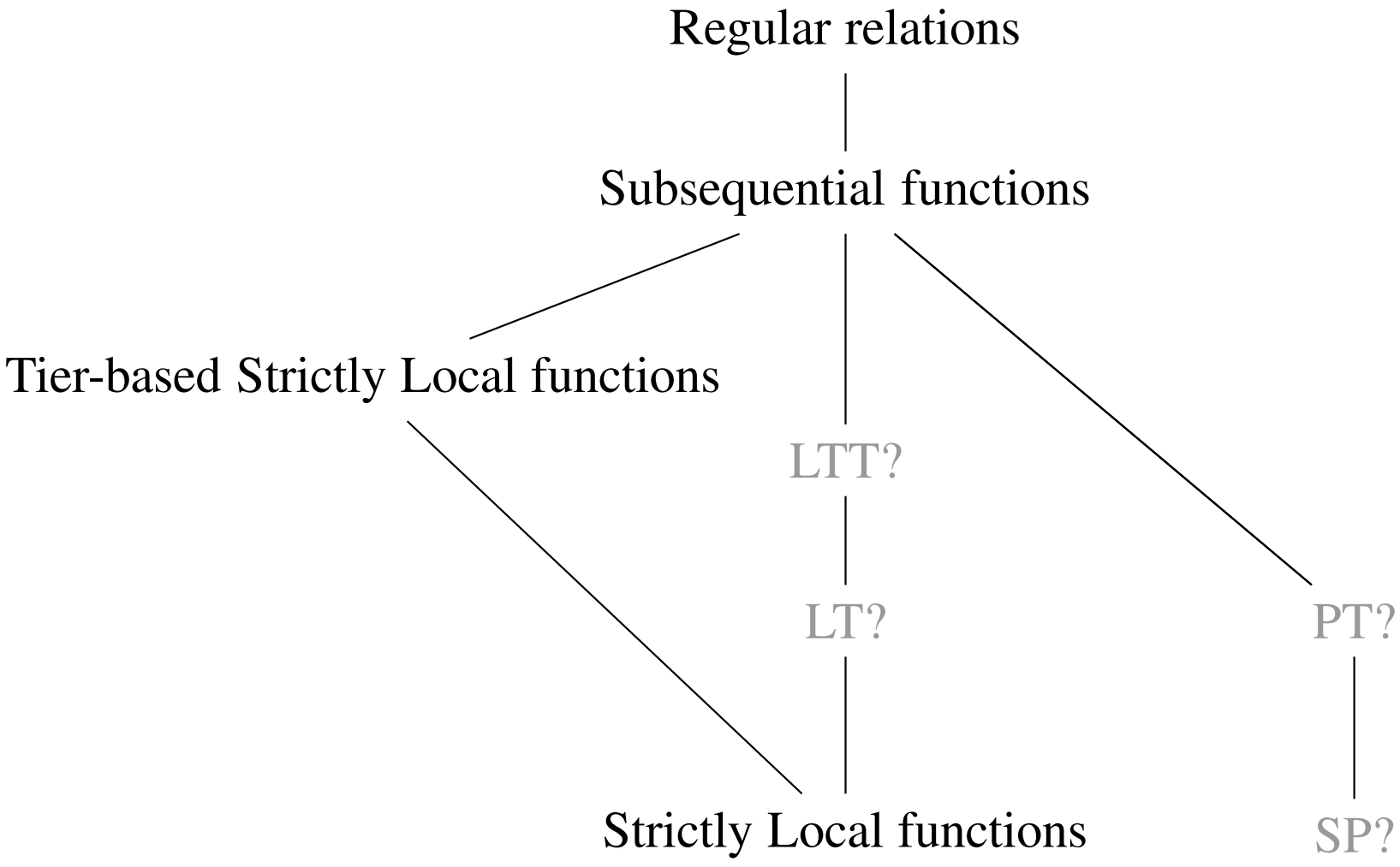
Implications for cognition

- What kind of information must we keep track of when performing phonological computations?
- Subregular analyses suggest it's very limited.

Future work and open questions

- Fill out the hierarchy of subregular functions.

Subregular hierarchy of maps



Future work and open questions

- Fill out the hierarchy of subregular functions.
- Identify logical characterizations of the various classes.
- Test whether subregular classes of FSTs improve efficiency of various NLP/HLT algorithms:
  - grapheme-to-phoneme conversion
  - pronunciation variation
  - etc.

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