Learning underlying representations via function decomposition

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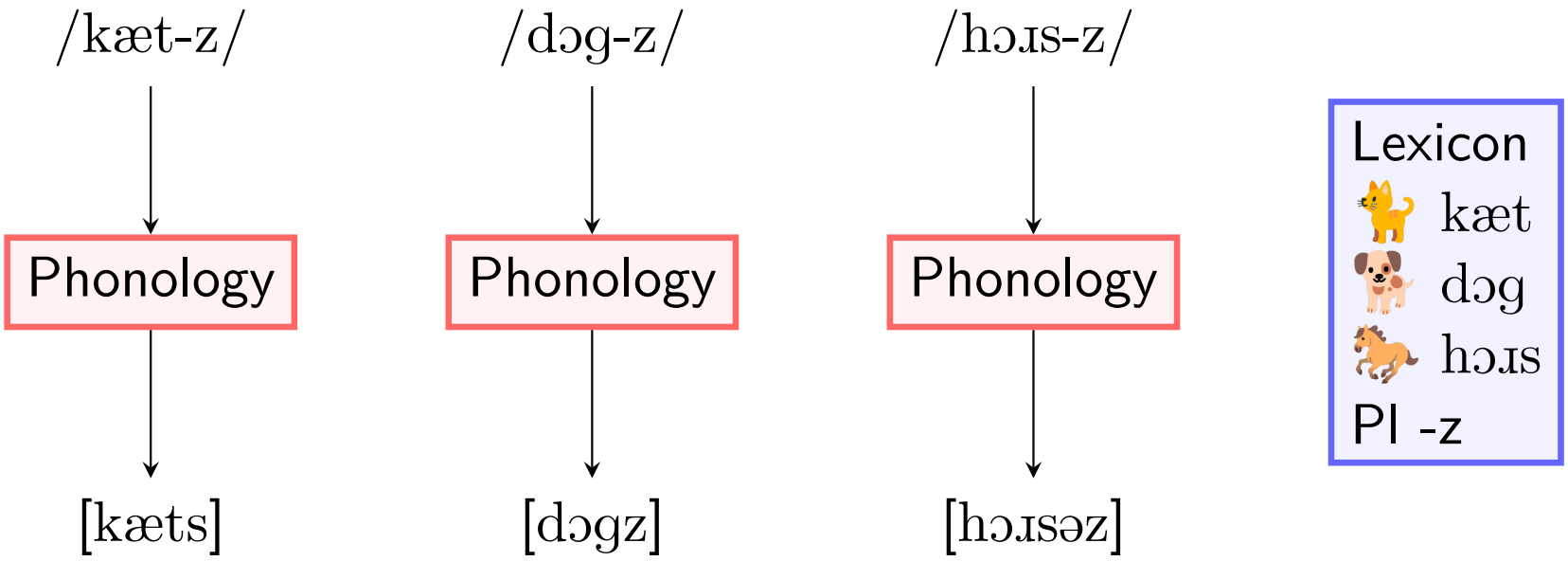
Underlying representations: a hidden structure problem



Previous work on learning URs

OT	Maximum Likelihood	Jarosz (2006a,b, 2009, 2015)
	GLA w/ UR constraints	Apoussidou (2007)
	Constraint Demotion w/ contrast pairs	Merchant (2008)
	CD w/ output-driven maps	Tesar (2014)
HG	MaxEnt	O'Hara (2017); Wang and Hayes (2022)
	MaxEnt w/ UR constraints	Pater et al. (2012); Nelson (2019)
SPE	Minimum Description Length	Rasin et al. (2020, 2021)

- Structured hypothesis space of grammars
- Rich conception of UG (e.g., innate CON)

Structural inference

- The invariant formal properties of phonological mappings also structure the hypothesis space in ways that can be leveraged by a learner.
- The phonological mapping is constant across theories of the grammar:
  - {(kætz, kæts), (dɔgz, dɔgz), (hɔɹsz, hɔɹsəz), ...}

Preliminaries

- **Morphology**, $\mathcal{M}$: orders sets of meanings
  - $\mathcal{M}(\{\text{PL}, \text{🐈}\}) = \text{🐈}\text{-PL}$
- **Lexicon**, $\mathcal{L}$: supplies the URs
  - $\mathcal{L}(\text{🐈}\text{-PL}) = /\text{kæt-z}/$
- **Phonology**, $\mathcal{P}$: maps URs to SRs
  - $\mathcal{P}(\text{kætz}) = [\text{kæts}]$

$$\mathcal{P} \circ \mathcal{L} \circ \mathcal{M}\ (\{\text{🐈}, \text{PL}\}) = [\text{kæts}]$$

(Adapted from Hua and Jardine (2021); see also Cotterell et al. (2015))

The learning problem

Given examples of $\mathcal{P} \circ \mathcal{L} \circ \mathcal{M}$, identify $\mathcal{M}$, $\mathcal{L}$, and $\mathcal{P}$.

- For today, though, the learning of $\mathcal{M}$ is being factored out and the learner is provided with explicit morphological knowledge.
- Learning approach: function decomposition (Hua et al., 2021)

$$\mathcal{P} \circ \mathcal{L}(\text{🐈Pl}) = [\text{kæts}]$$

$$\mathcal{P}(\mathcal{L}(\text{🐈Pl})) = \mathcal{P}(/\text{kætz}/) = [\text{kæts}]$$

Function decomposition

- In the general case, function decomposition is an unsolvable problem.

$$f(x) = x + 1$$
$$g(y) = y - 1$$
$$f \circ g(1) = 1, f \circ g(2) = 2, f \circ g(3) = 3...$$

- However, the learner capitalizes on the assumption that the phonological function is a **local function** (Berstel, 1982; Vaysse, 1986; Lind and Marcus, 1995; Chandlee, 2014).
- In addition, the learning paradigm is *semi-strong learning* (Hua and Jardine, 2021), rather than exact identification (Gold, 1967).

Malay alternations

Johor Malay (Austronesian; Peninsular Malaysia; Onn, 1976) /pəŋ-/ (nominalizer) and /məŋ-/ (active voice) both have five variants.

- Before obstruents: nasal place assimilation

/pəŋ-boroŋ/	[pəmboroŋ]	'wholesaler'
/pəŋ-jahit/	[pəɲjahit]	'tailor'
/pəŋ-daki/	[pəndaki]	'climber'
/pəŋ-gali/	[pəŋgali]	'digger'
/pəŋ-arah/	[pəŋarah]	'director'

- Before sonorant consonants: nasal deletion

/pəŋ-layan/	[pəlayan]	'waitress'
/pəŋ-ɲaɲi/	[pəɲaɲi]	'singer'
/pəŋ-malu/	[pəmalu]	'shame'
/pəŋ-rayu/	[pərayu]	'appeal'

Additional processes

- Final devoicing and regressive devoicing

/jawab/	[jawap]	'to answer'
/pəŋ-jawab-an/	[pəɲjawaban]	'the answering'
/məŋ-jawab-kan/	[məɲjawapkan]	'to cause to answer for'

- Velar stops become glottal in coda position

/masak/	[masaʔ]	'to cook'
/pəŋ-masak-an/	[pəmasakan]	'the cooking'
/məŋ-masak-kan/	[məmasaʔkan]	'to cause to cook for'

Additional processes

- /r/ deletes in coda position

/kisar/	[kisa]	‘revolve’
/kisar-an/	[kisaran]	‘revolution’
/kisar-kan/	[kisakan]	‘to cause to revolve for’

- Word-final /a/ reduces to schwa.

/bawa/	[bawə]	‘to carry’
/bawa-kan/	[bawakan]	‘to cause to carry for’

Data

A	/ikat/	‘tie’	B	/asut/	‘instigate’
D	/gali/	‘dig’	E	/bayar/	‘pay’
F	/bawa/	‘carry’	I	/dakap/	‘embrace’
L	/ladaŋ/	‘farm’	M	/naik/	‘ascend’
N	/jawab/	‘answer’	P	/cərca/	‘revile’
S	/rompak/	‘rob’	T	/ŋaŋa/	‘open’
U	/main/	‘play’	V	/ɲaɲi/	‘sing’

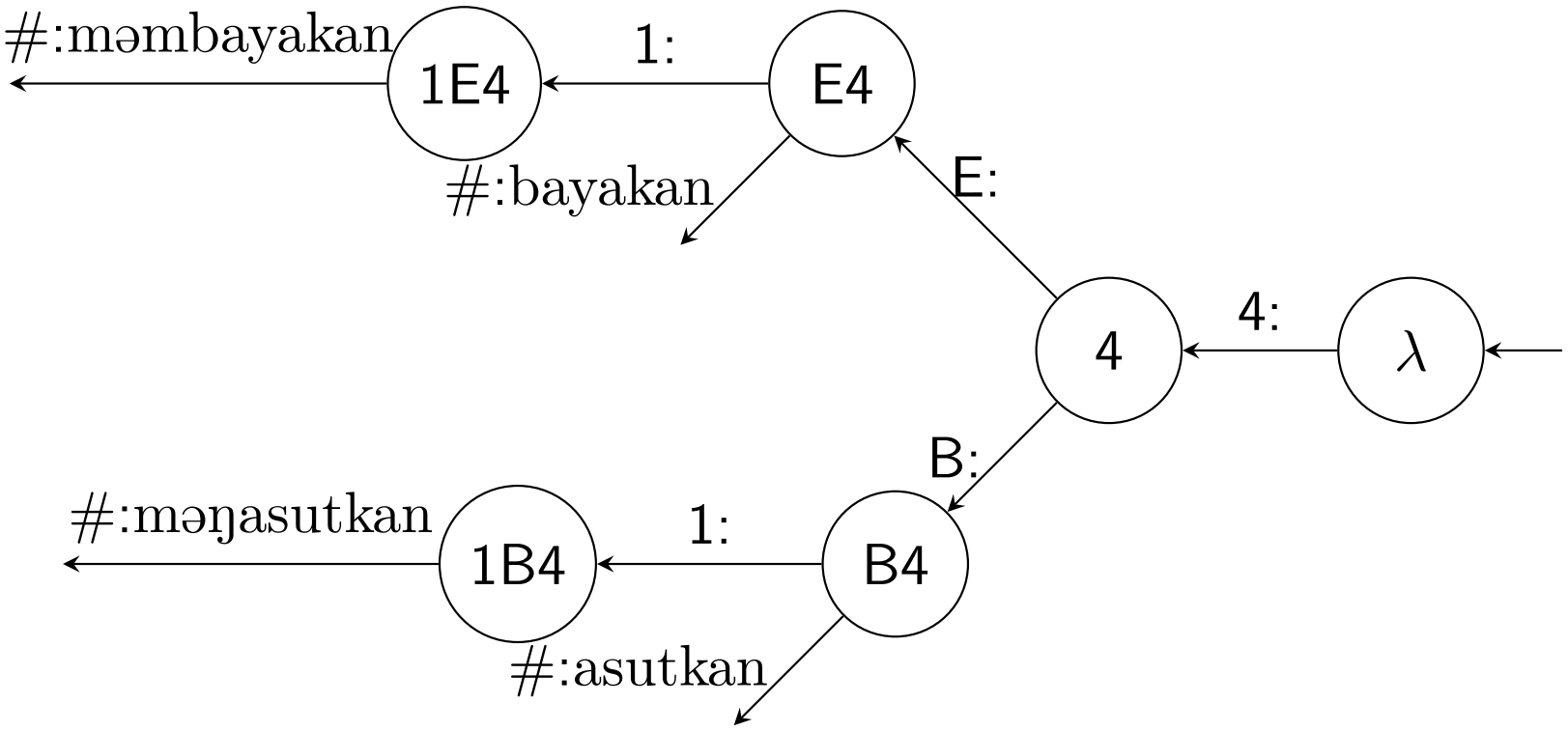
1	/məŋ-/	active
2	/pəŋ-/	nominalizer
3	/-i/	causative
4	/-kan/	causative benefactive
5	/-an/	nominalizer

Data

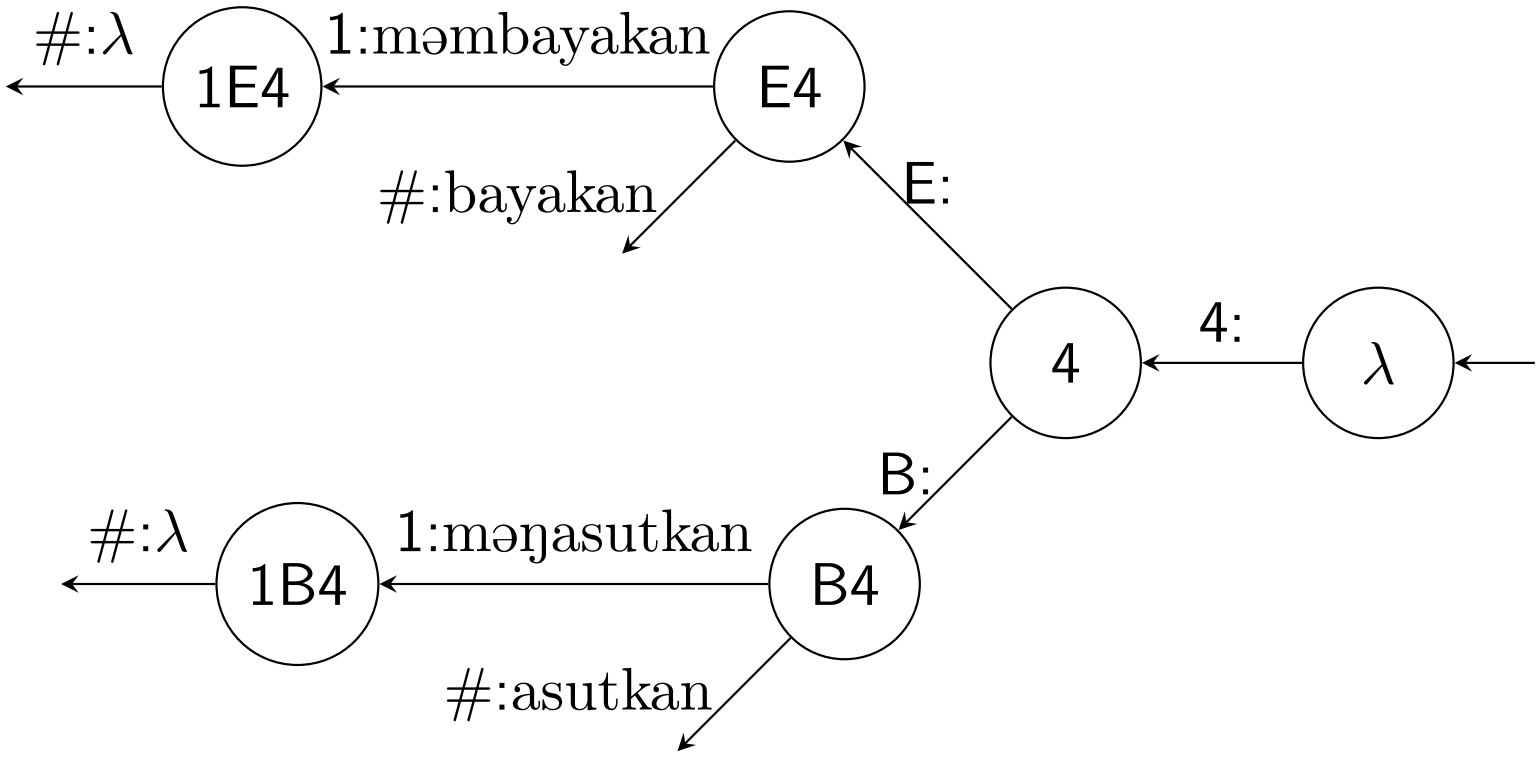
/bayar/	
baya	‘to pay’
məmbaya	‘to pay (active)’
bayari	‘to cause to pay’
bayakan	‘to cause to pay for’
məmbayari	‘to cause to pay (active)’
məmbayakan	‘to cause to pay for (active)’
pəmbaya	‘payment’

- {(E, baya), (1E, məmbaya), (E3, bayari), (E4, bayakan), (1E3, məmbayari), (1E4, məmbayakan), (2E, pəmbaya), ...}

Morpheme segmentation: onward prefix tree transducer



Morpheme segmentation: onward prefix tree transducer



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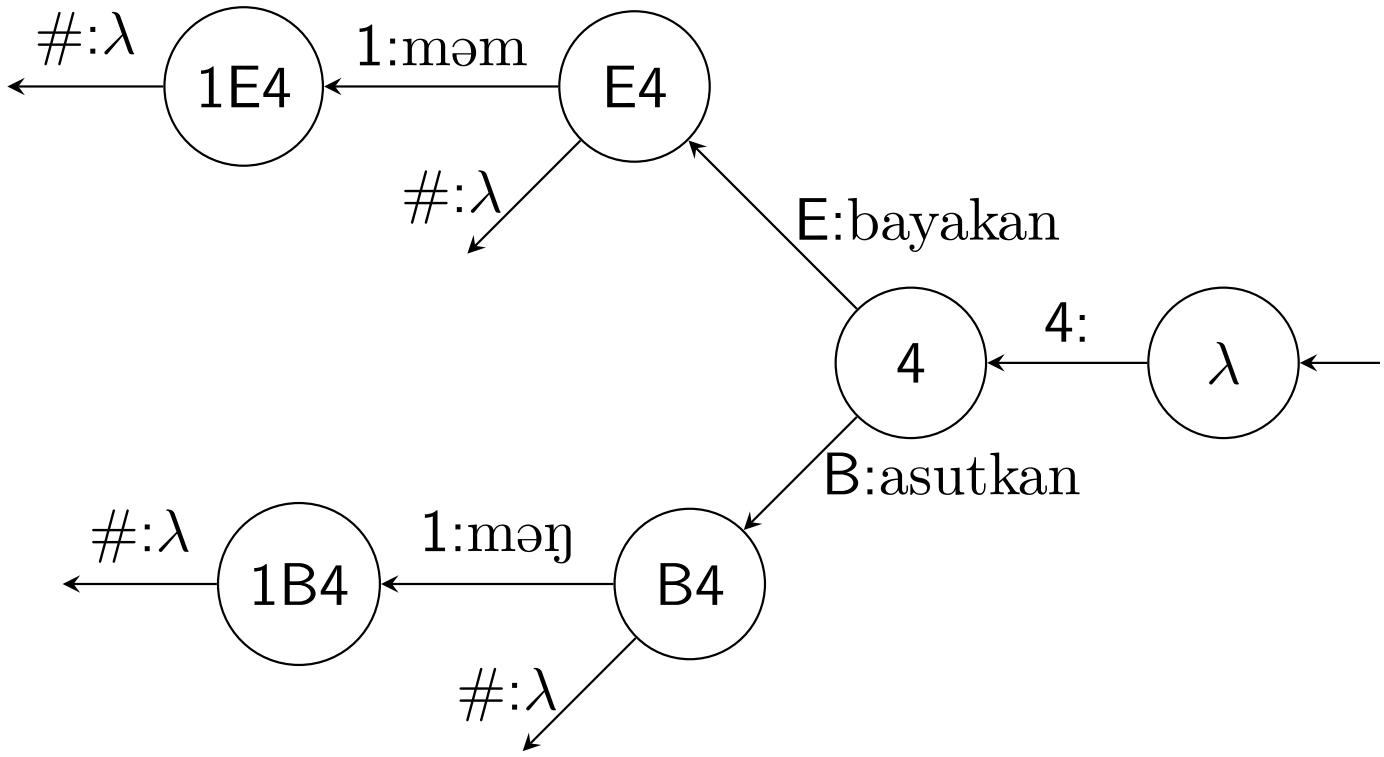

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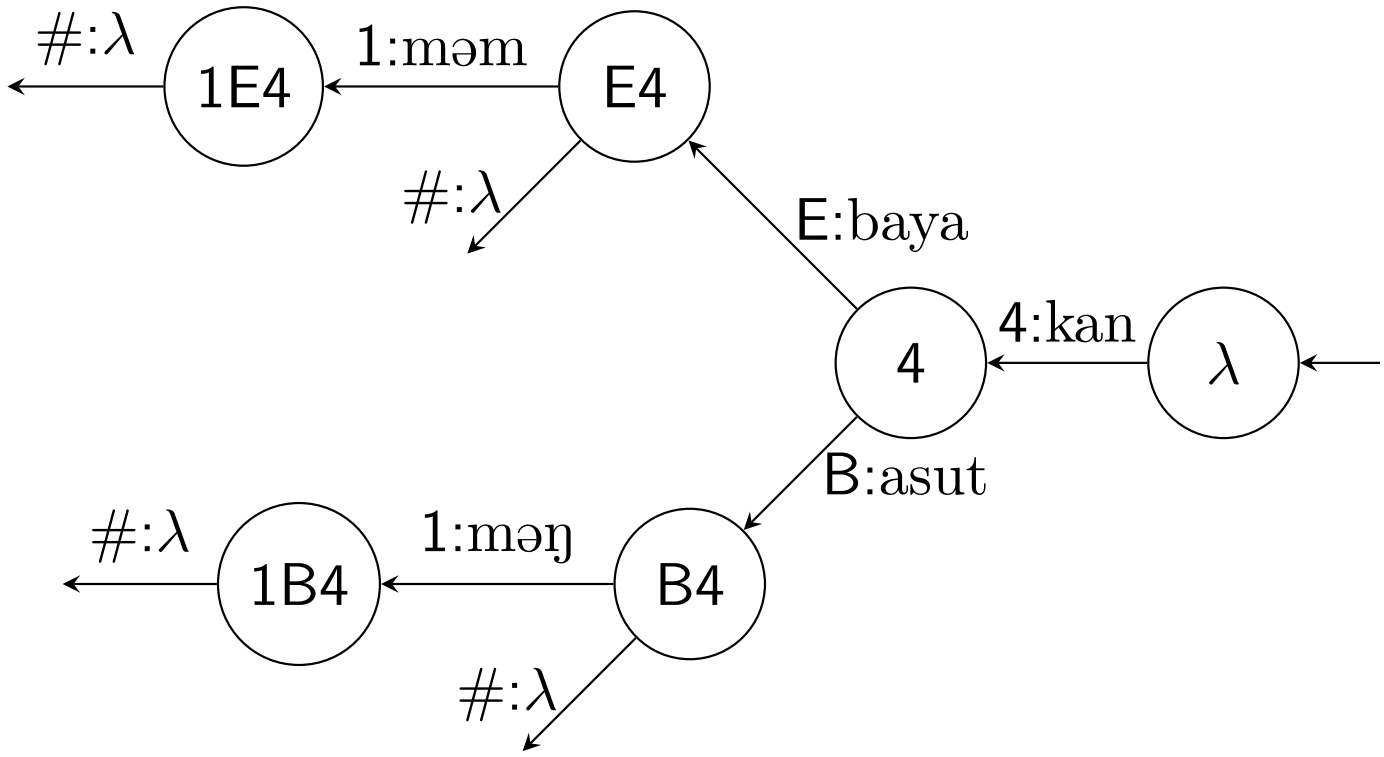


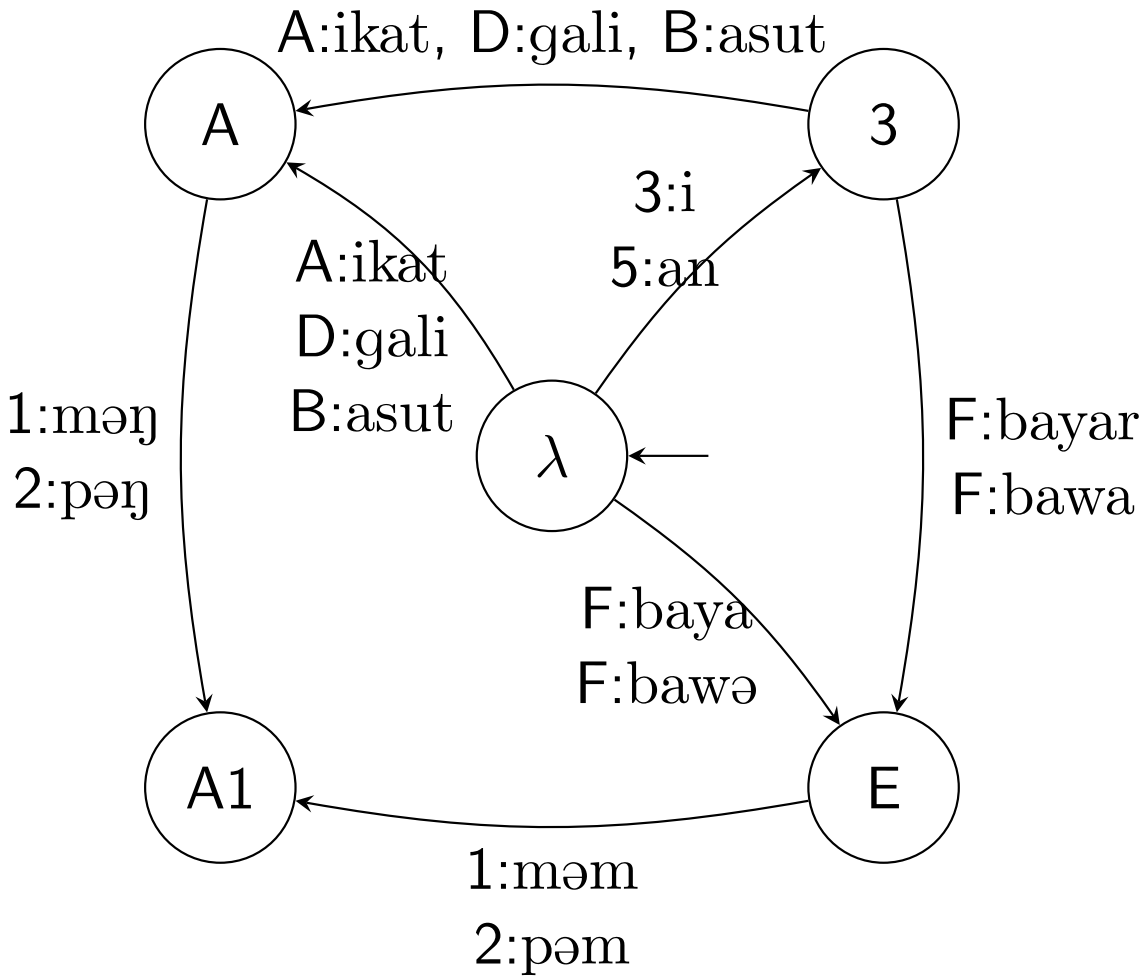
State merging

- Same method used by Oncina et al. (1993) for learning subsequential (i.e., deterministic) functions (Onward Subsequential Transducer Inference Algorithm).
- States are merged provided they have the same sets of **tails**:

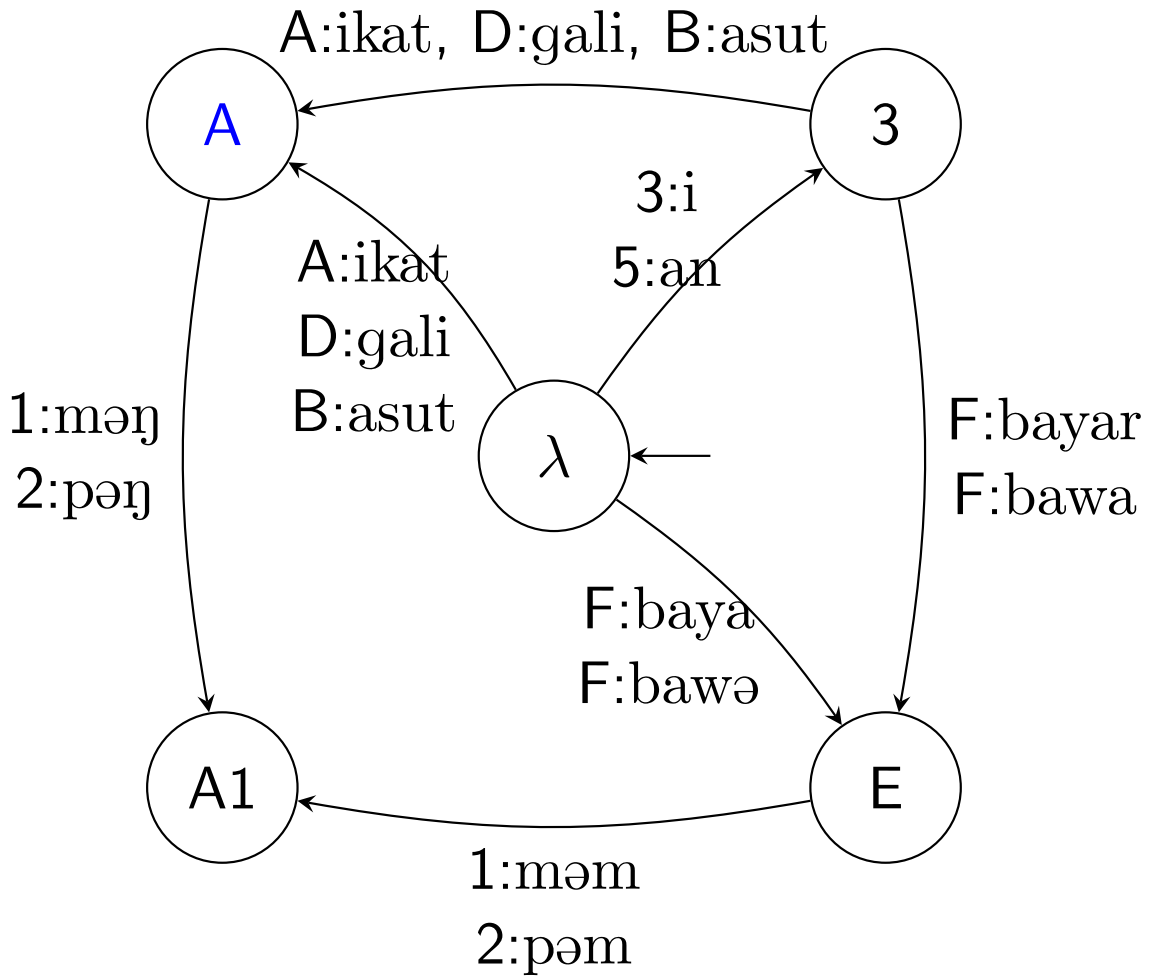
$$\texttt{tails}_f(x) = \{(y, v) | f(xy) = uv \wedge u = \texttt{lcp}(f(x\Sigma^*))$$

- Any merge that creates irreparable non-determinism is rejected.

After state merging (partial result)



Locality assumption: collect 1-suffixes



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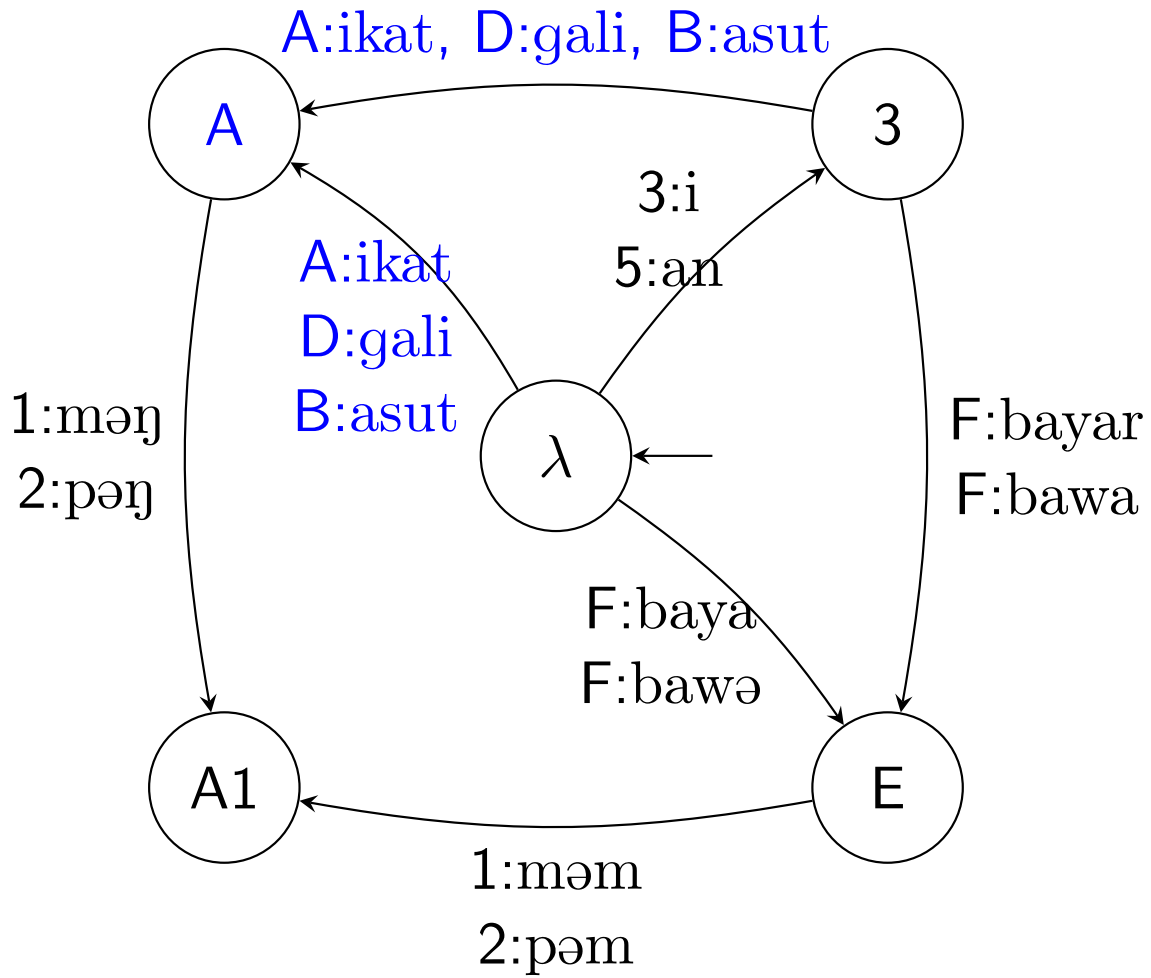

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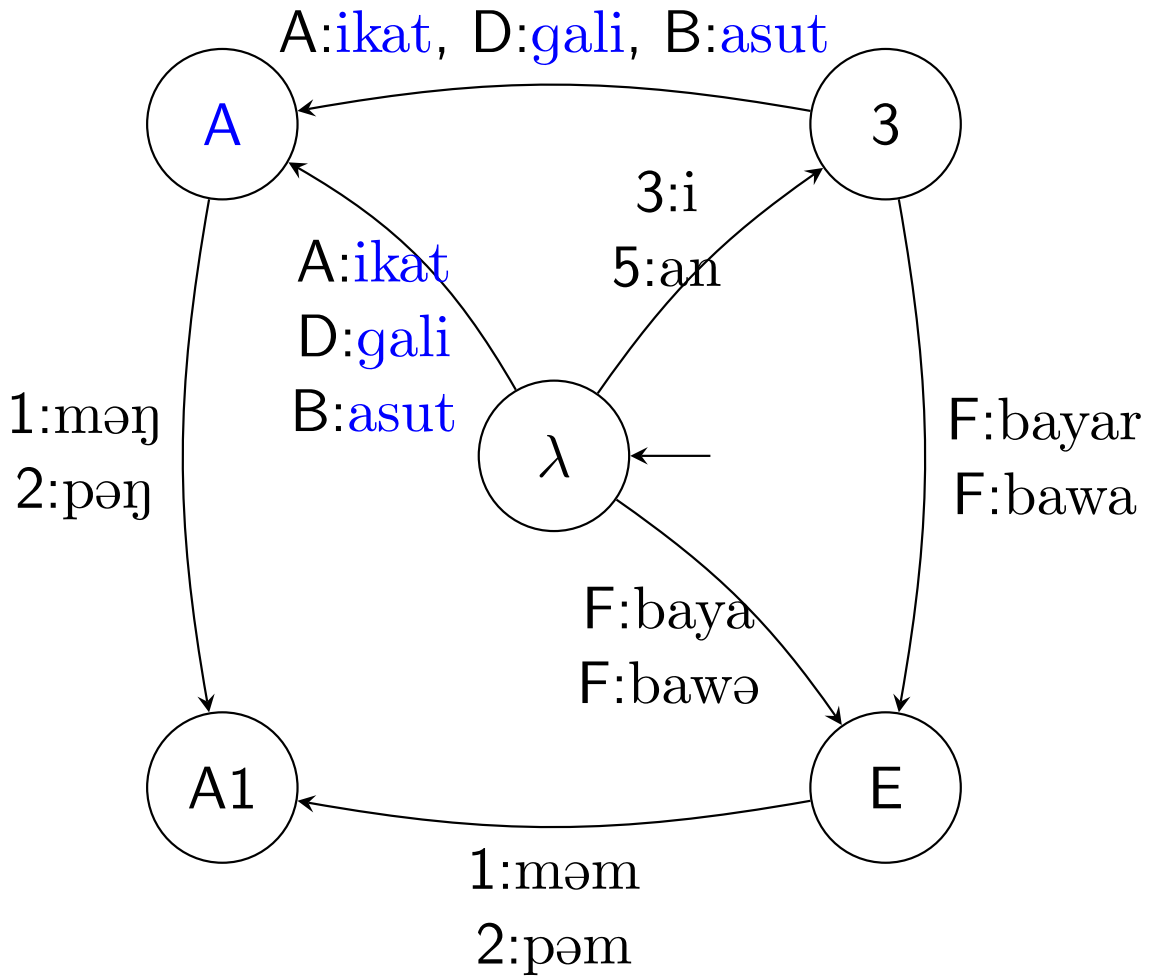

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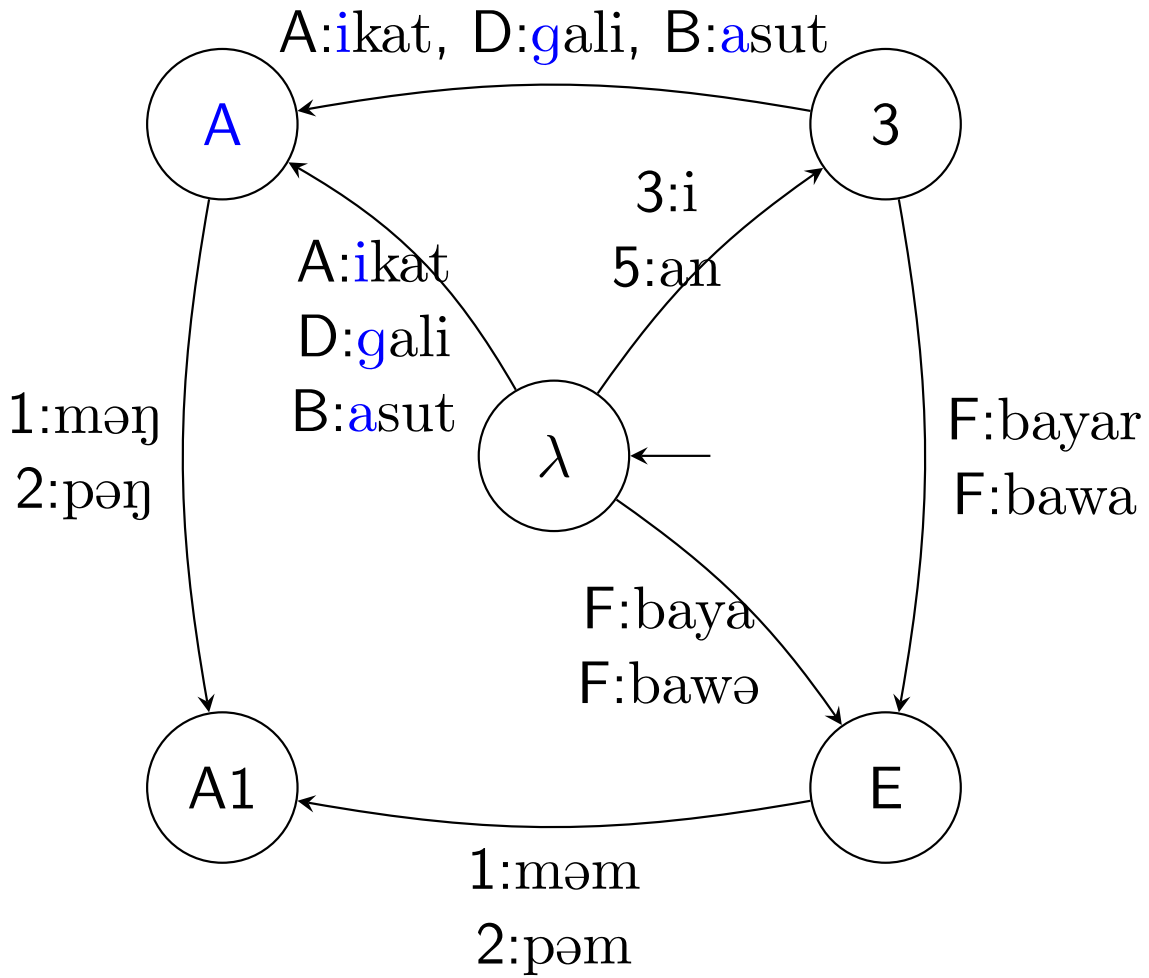

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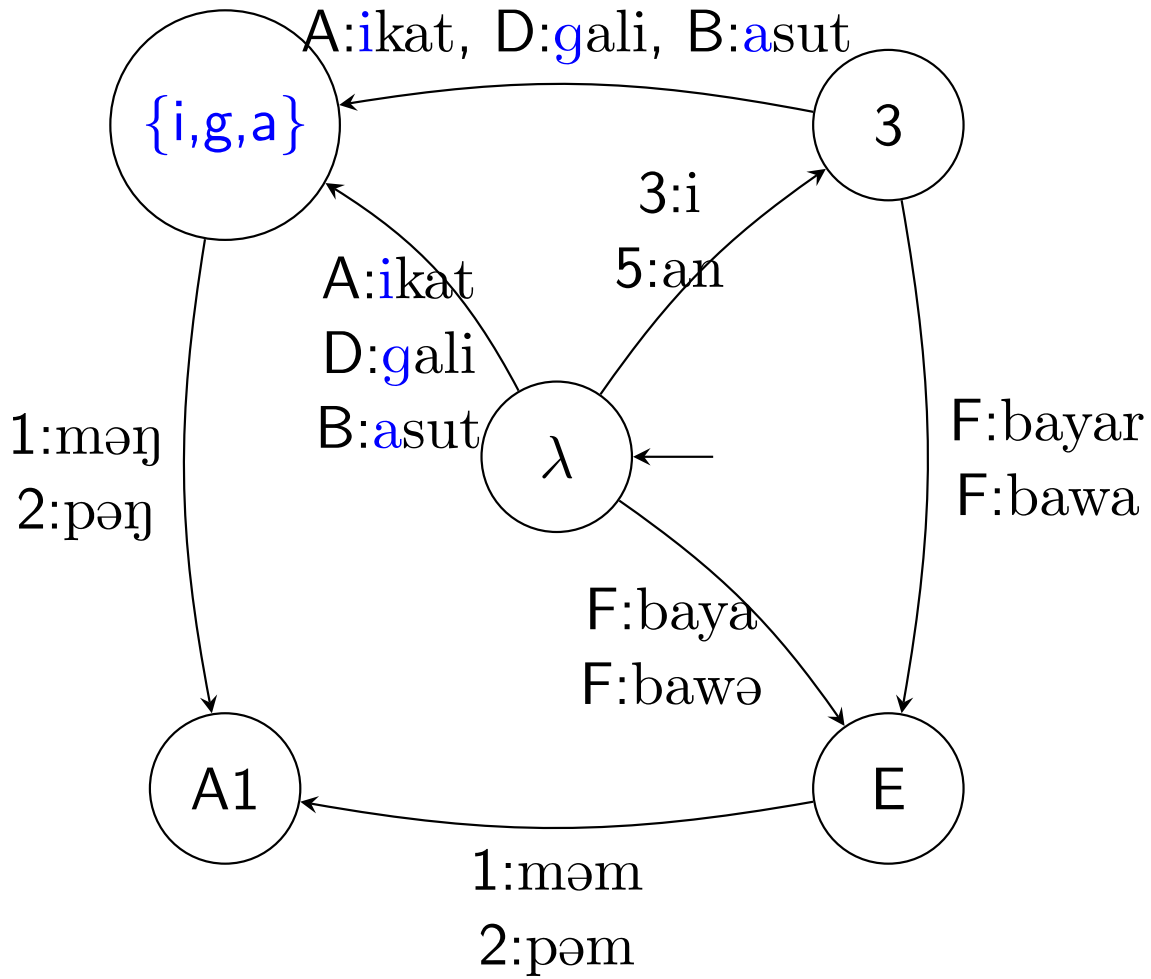

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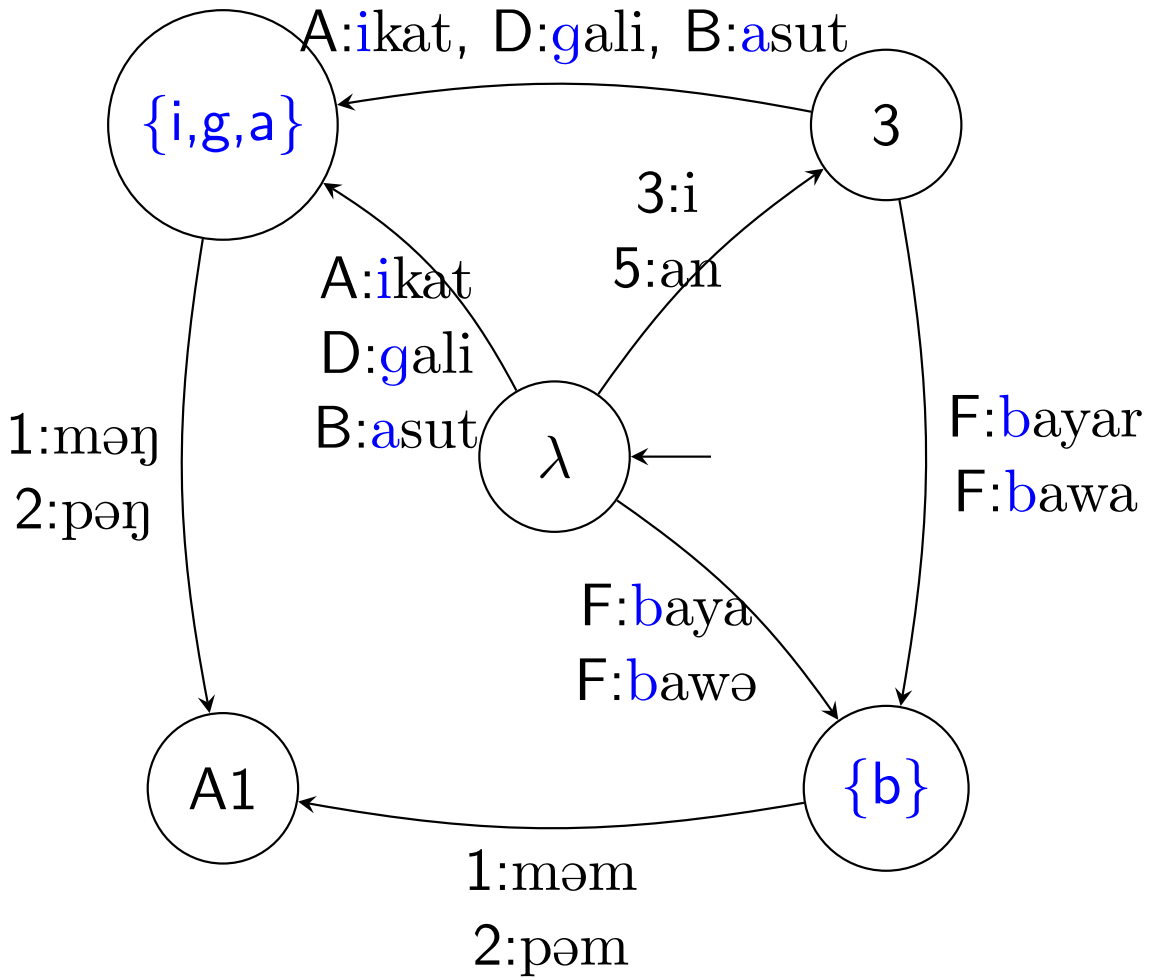
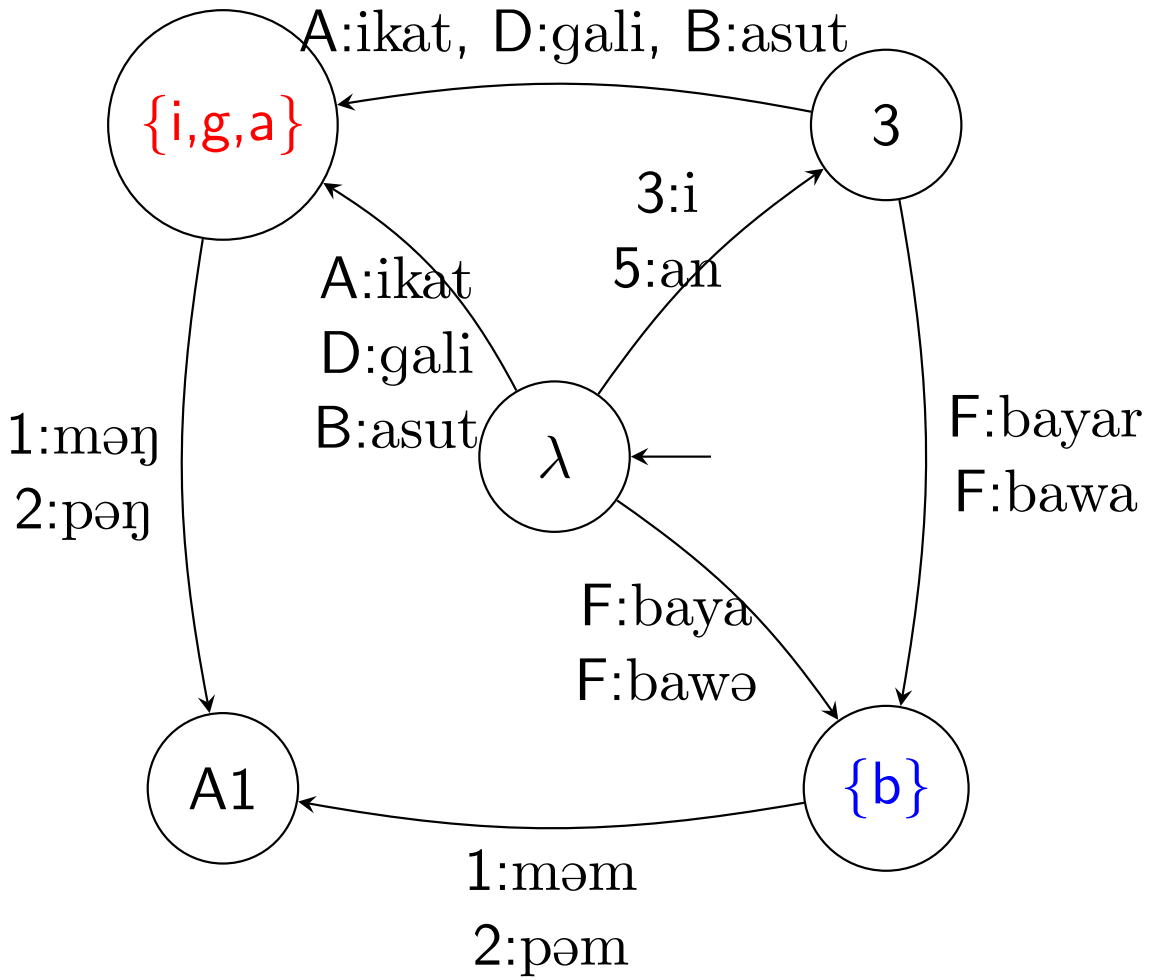
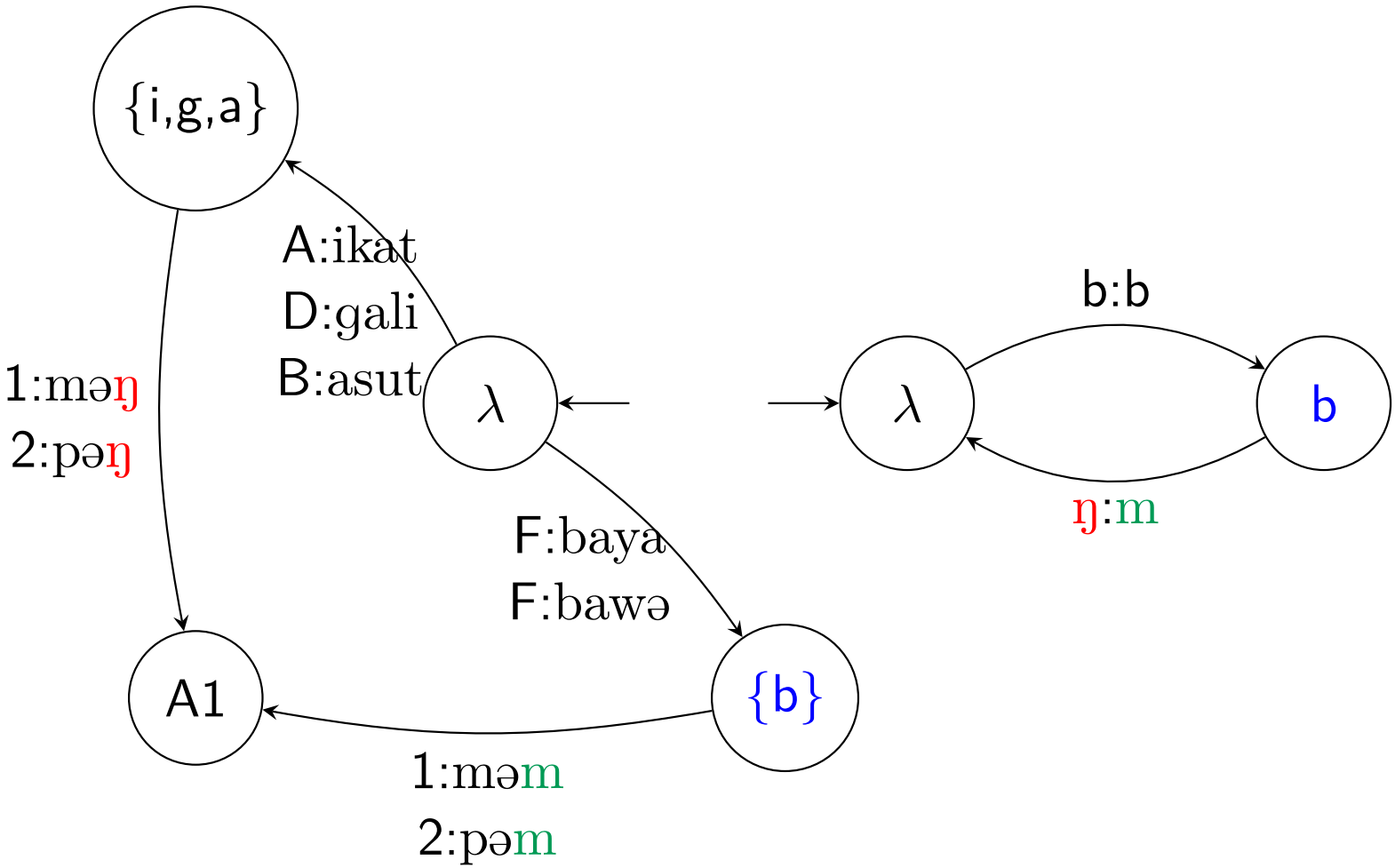


UR selection: natural class bias



Constructing phonology function



Malay test case results

- Original lexicon successfully reconstructed, and the resulting phonology function enacts multiple processes simultaneously:

  $\eta \rightarrow [\alpha\text{place}] \; / \; \_\_ \; [-\text{son}, \alpha\text{place}]$

  $\eta \rightarrow \emptyset \; / \; \_\_ \; [+\text{son}, -\text{syl}]$

  $[-\text{son}] \rightarrow [-\text{voice}] \; / \; \_\_ \; \{[-\text{voice}], \#\}$

  $\{\text{k}, \text{g}\} \rightarrow \text{ʔ} \; / \; \_\_ \; \{\text{C}, \#\}$

  $\text{r} \rightarrow \emptyset \; / \; \_\_ \; \{\text{C}, \#\}$

  $\text{a} \rightarrow \text{ə} \; / \; \_\_ \; \#$

Scaling up

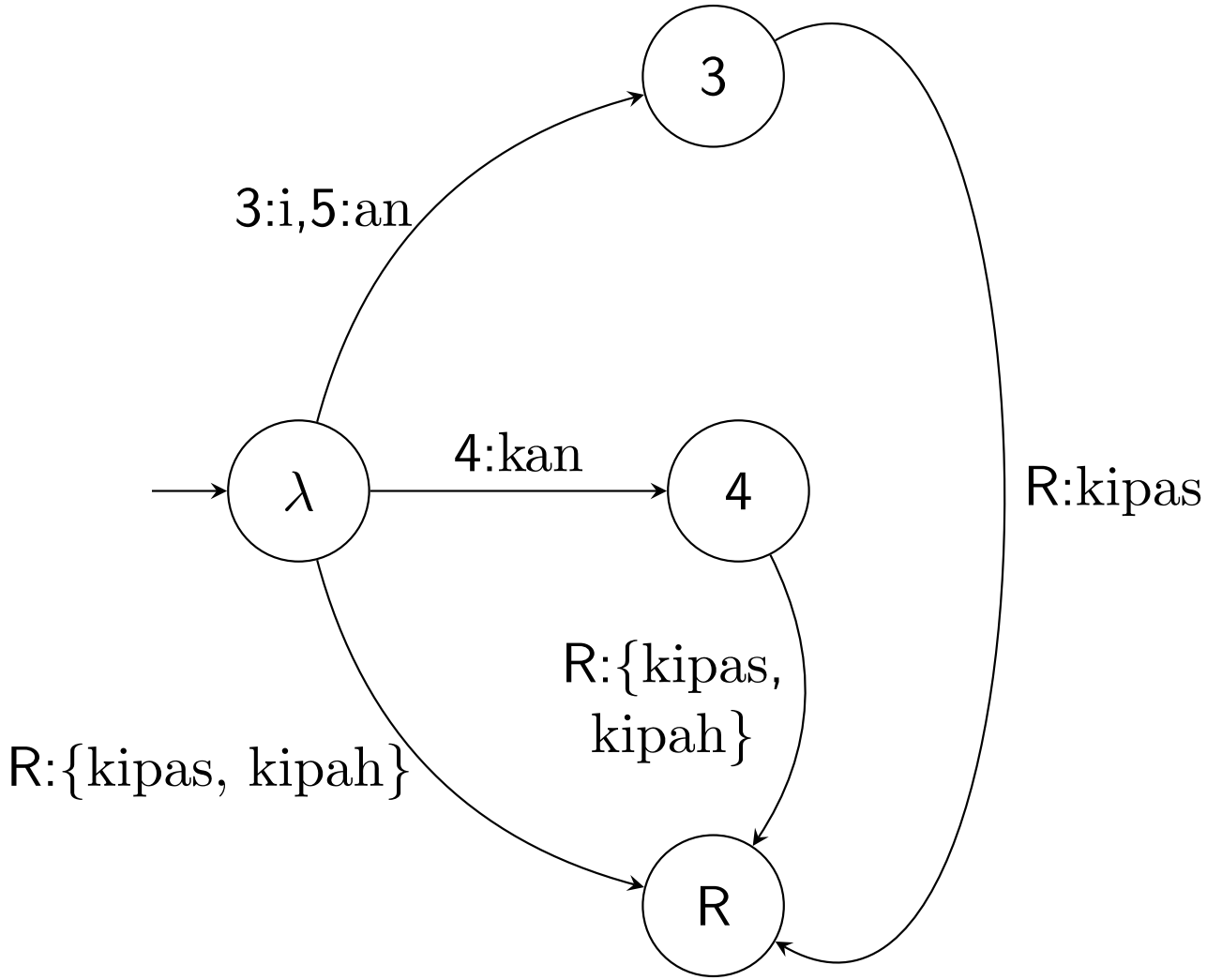
- Directionality (right-to-left, left-to-right) and locality window (2-local, 3-local, etc.) are parameters of the learner, but the presence of non-determinism in the output of state merging can be used as a cue that they are set incorrectly.

Semi-determinism

- Data that reflects optionality and variation can be addressed using *semi-determinism* (Beros and de la Higuera, 2016; Heinz, 2020)
- /s/ optionally becomes [h] in coda position

/kipas/	[kipas] ∼ [kipah]	'fan'
/kipas-kan/	[kipaskan] ∼ [kipahkan]	'to cause to fan for'

Semi-determinism

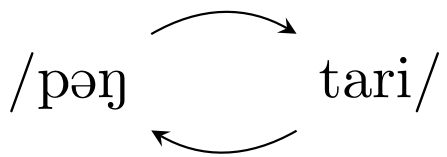


Advantages

- **Modular** approach that can be used with alternative:
  - formalizations of locality (e.g., tier-based, autosegmental)
  - theories of possible URs
  - UR selection heuristics
- **Interpretable**, bottom-up approach:
  - We know exactly what can be learned under what conditions (i.e., data content and parameter settings).

Fusion allomorph

- /pəŋ-tari/ → [pənari], ‘dancer’
- 2-local, but bidirectional



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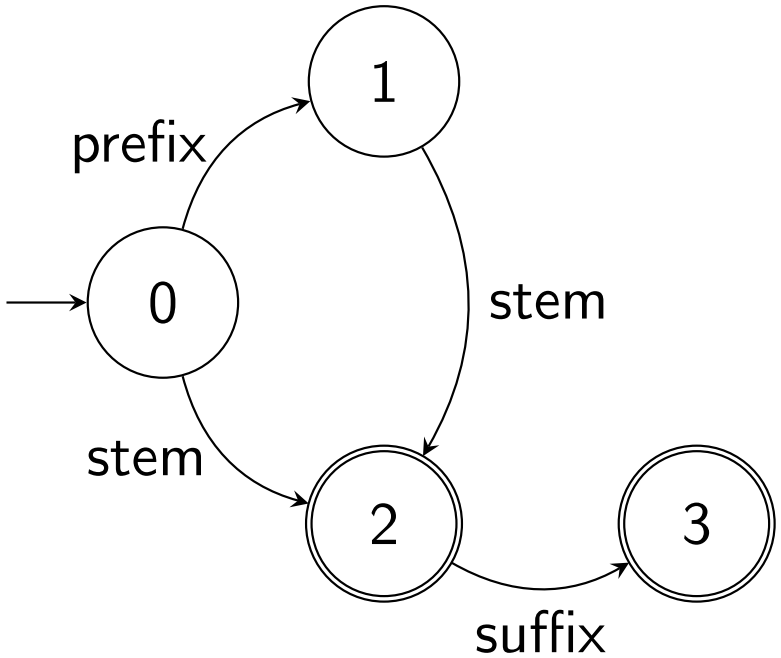
State merging using domain information

- Modified version of Oncina and Varò (1996) adds a condition: merged states must have the same tails *and* reach the same state in an FSA representation of the domain of the function (in this case the output language of $\mathcal{M}$).

Domain FSA



Epenthesis

- Glide epenthesis if first vowel is high:
  /bantu-an/ [bantuwan] 'aid, relief'
  /tari-an/ [tariyan] 'dance'
- Otherwise glottal epenthesis:
  /məŋ-gula-i/ [məŋgulaʔi] 'to cause to sweeten'
  /pəŋ-buka-an/ [pəmbukaʔan] 'opening'
- At prefix boundary, always glottal:
  /di-ambil/ [diʔambel] 'to take (passive)'
- Nonderived environment blocking:
  /main/ [main] 'to play'
  /naik/ [naik] 'to ascend'

Epenthesis

- Adirectional and still 2-local, but requires a more detailed UR decision procedure

/cərca/, 'to revile'

SRs:	[cərcə]	[cərcaʔ]	[cərca]
Contexts:	__#	__V	__C

Hypothesis testing

/cərcə/	/cərcaʔ/	/cərca/
ə → a / __ C	aʔ → ə / __ #	a → ə / __ #
ə → aʔ / __ V	ʔ → ∅ / __ C	∅ → ʔ / V __ V
*[carcakan]	ʔ isn't phonemic	