Prosody: Thinking Outside the Box

Lecture 1. The Phonology of Prosody

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Specimens

So, what is Prosody?

1. Prosody: from ancient Greek προσῳδίᾱ, /prɔsoːˈdiaː/, meaning either syllabic accent, or accompaniment to a song
2. Poetic prosody:
   - genre-specific strong-weak patterns of metre in poems which determine the rhythm of poetry
   - the patterns may be varied and combined or overridden by other factors for aesthetic reasons
3. Speech prosody:
   - the timing of rhythms and melodies of speech (spoken language)
   - from phonetic or phonological perspectives
   - from structural or functional perspectives
4. Semantic prosody:
   - a metaphorical term referring to associative meanings of collocations

Theoretical and Practical Questions about Prosody

Basic ontology:

- Are prosodic properties categorial or continuous? - Both.
- By analogy with the phoneme and the morpheme, are there prosodemes? intonemes? tonemes? accenteme? - Yes.
- Are there clear relations with categories of written text such as character, word, phrase, clause, sentence, paragraph, text? - No.
- Are there paratones? - Yes.
- Is there a prosodic grammar? - Yes.
- Is there a prosodic lexicon? - Yes.

Basic epistemology:

- Why are we generally unaware of prosody?
- Is knowledge of prosody subconscious, conscious, behavioural?
- Is prosody teachable or only learnable?
- Do we share aspects of prosody with animals, e.g. apes?

Topic of the course

Prosody – which subfields and terminology?

- Empirical terms:
  - melody, pitch, F0, pitch accent
  - prominence, accent
  - duration, timing, rhythm
- Structural terms:
  - intonation, lexical tone
  - phrasal stress, lexical (word) stress, boundary marker
  - prosodic/phonological hierarchy
- Functional terms:
  - dialogue and speech act intonation
  - framing, focus, emphasis, contrast
  - sociophonetics of prosody

A terminological gallon of worms ...

- The assignment of prominence to words is confusingly referred to by different scholars as

  Stress – **Accent** – **Focus** – **Tone**

- Towards consistency:
  - **Stress** is a lexical or grammatical position in a word, phrase, sentence, text (cf. 'Nuclear Stress')
  - **Accent** is a phonetic interpretation of a stress position as a pitch-intensity-duration pattern
  - **Focus** is the information-relevant semantic interpretation of an accent at a stress position
  - And
    - **Tone** stands for for contrastive lexical and morphosyntactic functions of fundamental frequency.

Prosody: Thinking Outside the Box - Course Plan

1. The Phonology of Prosody: Ranks and Interpretations
   - Paradigms and Frameworks, Theories and Models
   - Computing prosody: from discourse to phoneme
2. The Phonetics of Prosody 1: Rhythm
   - Time Group Analysis: making Praat annotations useful
   - Measuring time: duration patterns
   - Measuring rhythm: oscillation, modulation and demodulation
3. The Phonetics of Prosody 2: Melody
   - Pitch Hierarchies: modelling prosodic structure
   - Pitch Stylisation: modelling prosodic percepts
4. The Sociophonetics of Prosody: Percepts and Opinions
   - OSCAR: opinion mining for prosody: tone and intonation
   - Prosody in discourse

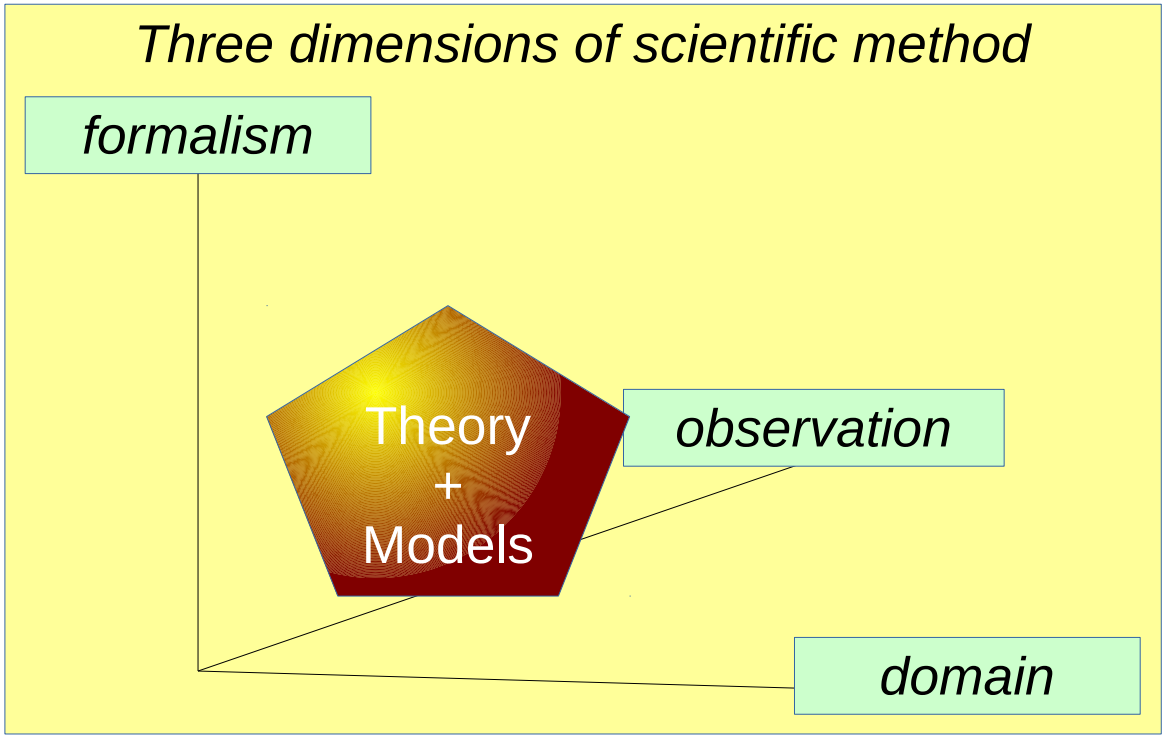
Phonology and Phonetics of Prosody:

The view of a practical scientist

A Scientist at Work Making a Model

1. Pick something to observe:
   - in paradigmatic relations: consonants, vowels, syllables, …
   - in syntagmatic relations: clusters, syllables, feet, words, phrases, ...
2. Pick a method:
   - fieldwork observation and elicitation
   - phonetic confirmation
   - systematic mental data
3. Pick a formalism or notation:
   - intuitive description, trad models
   - GP, AM, OT, …, algebra, logic
   - Make a *working model*:
     - data structures and algorithms
     - implementation

A Scientist at Work Making a Model



Models

A model is not a theory, and a theory is not a model.

How would you define “model”?

Models

A model is not a theory, and a theory is not a model.

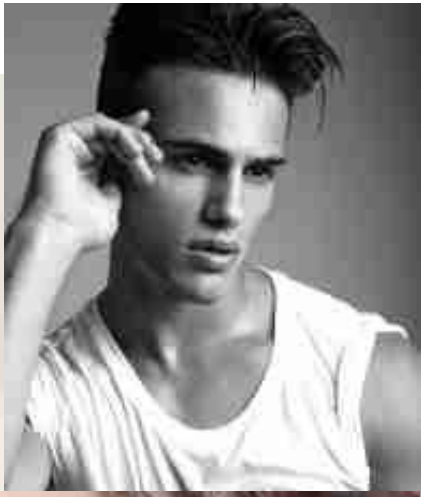
How would you define “model”?

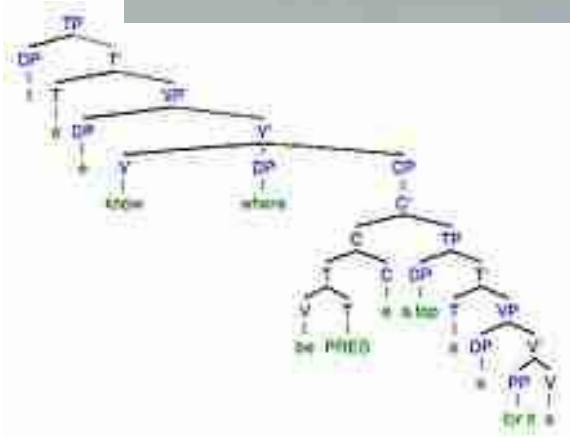
A model is a simplified representation of reality.

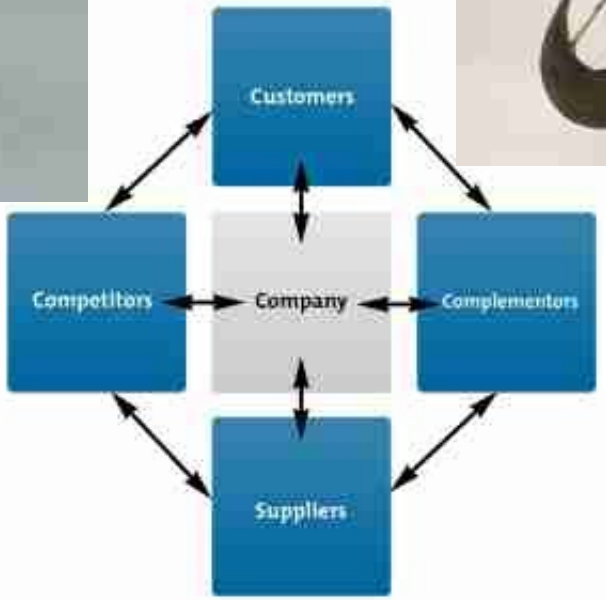
Models resemble reality, in colour, shape, ...

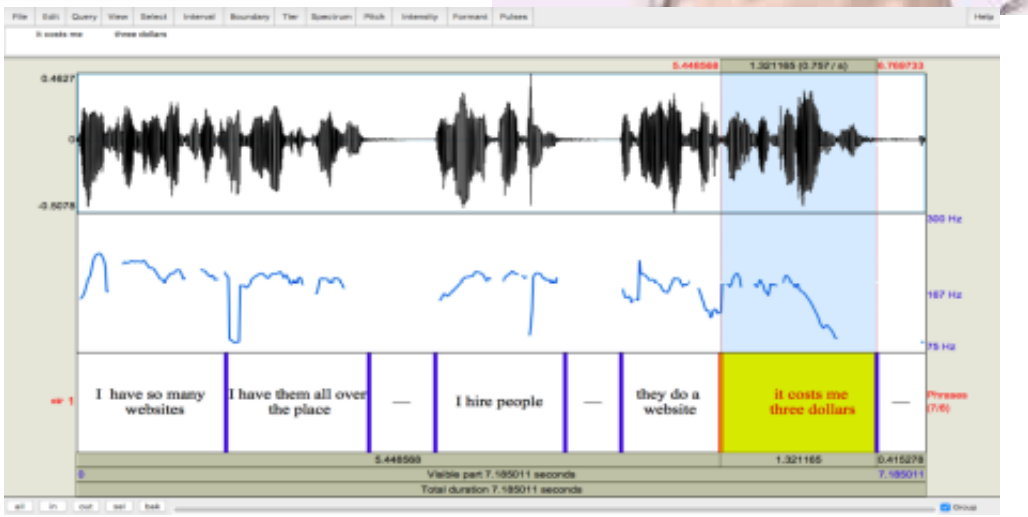
Models differ from reality, in material, size, dimensionality, ...

Models






Customers
Competitors
Company
Complementors
Suppliers


I have so many websites
I have them all over the place
I hire people
they do a website
it costs me three dollars

More useful terminology ...

Paradigm, framework, approach:

- a set of related domains and theoretical and heuristic discovery techniques shared and taught by a scientific community

  e.g.: Optimality Theory, Autosegmental, Functional, Cognitive, …

Theory:

- a set of premises (assumptions, basic theorems) with a set of inference rules for deducing testable theorems
  - e.g. set theory, propositional and predicate logic, categorial grammar, rewriting systems

Model:

- an object as a simplified representation of a segment of reality

  In Model Theory: Interpretation of a theory with a set of rules mapping theorems of a theory to the components of a model
  - e.g. string, phrase structure tree, autosegmental diagram, metrical grid, waveform, spectrogram

One needs to specialise, but also ...

In addition to picking your paradigm, theory, model, look at

- different methods and method combinations
- cooperation with other disciplines
  - computational linguistics
  - biology, ethology
- the value of visualisations
- the role of **computation**
  - software user (Praat,; office software; statistical software)
  - script developer (Praat, R, Python, …)
  - software developer (speech engineering)
- exploratory rather than confirmatory research
  - so many papers with lots of statistics and few examples
  - so here: lots of examples and not so much statistics

Description and Computation: Different Strategies

Linguistic and phonetic paradigms:

- Pick part of a domain
  - consonants, vowels, syllables
  - words, phrases
- Gradually include other parts

Computational, technological paradigms:

- Pick the whole domain
- First, simplify the domain
  - e.g. one, two, three word utterances; fixed expressions
- Second, increase complexity
  - add complex expressions

Prosody

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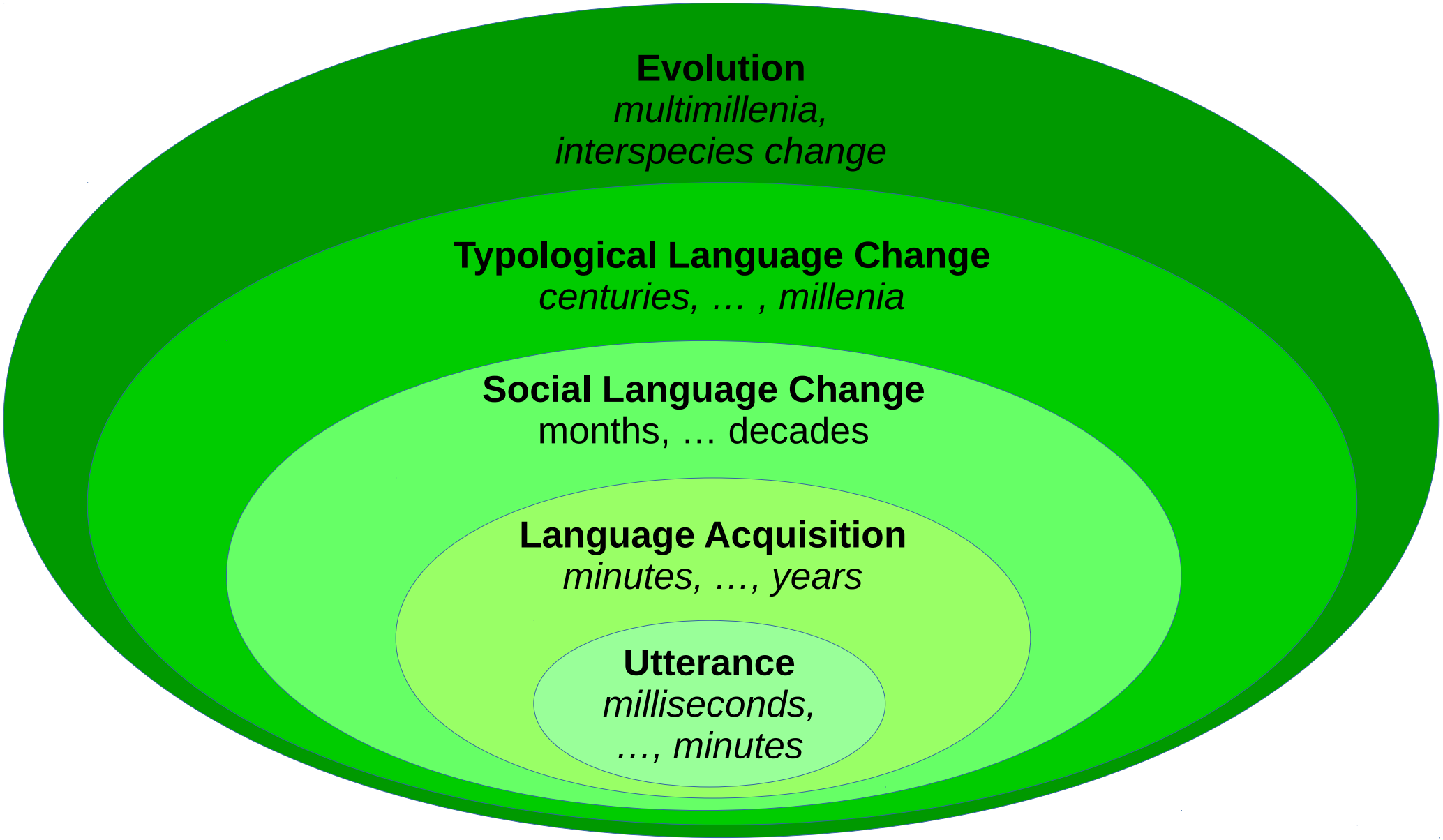
   - a metaphorical term referring to associative meanings of collocations

Prosody has to do with the paths of feature trajectories through TIME

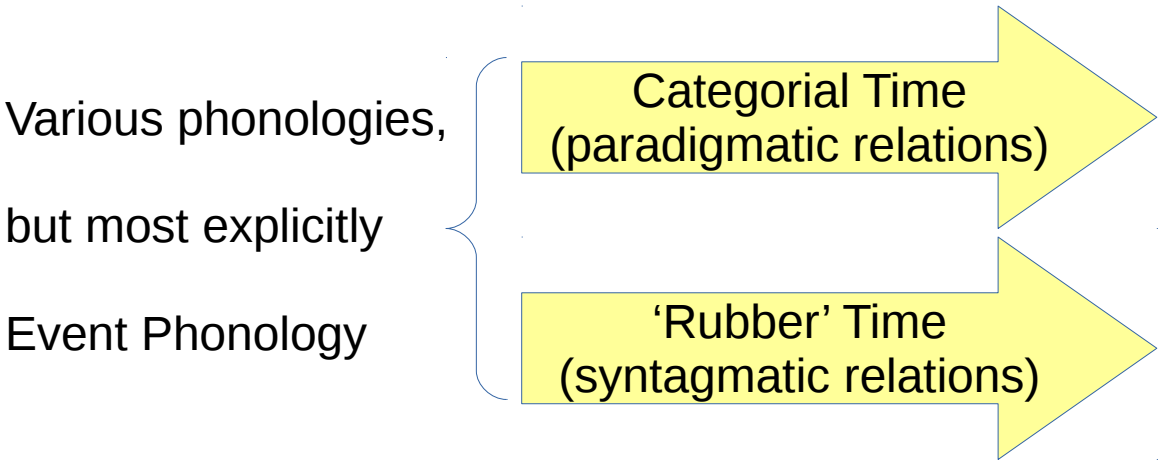
So let's look at the many facets of TIME.

First point: There is no time without events.
Second point: There are no events without change.
Third point: Time is dynamic.

One way to look at time: epochal time domains



Another way to look at time: Time Types



Thanks to **Andras Kornai**, for the concept 'Rubber Time'

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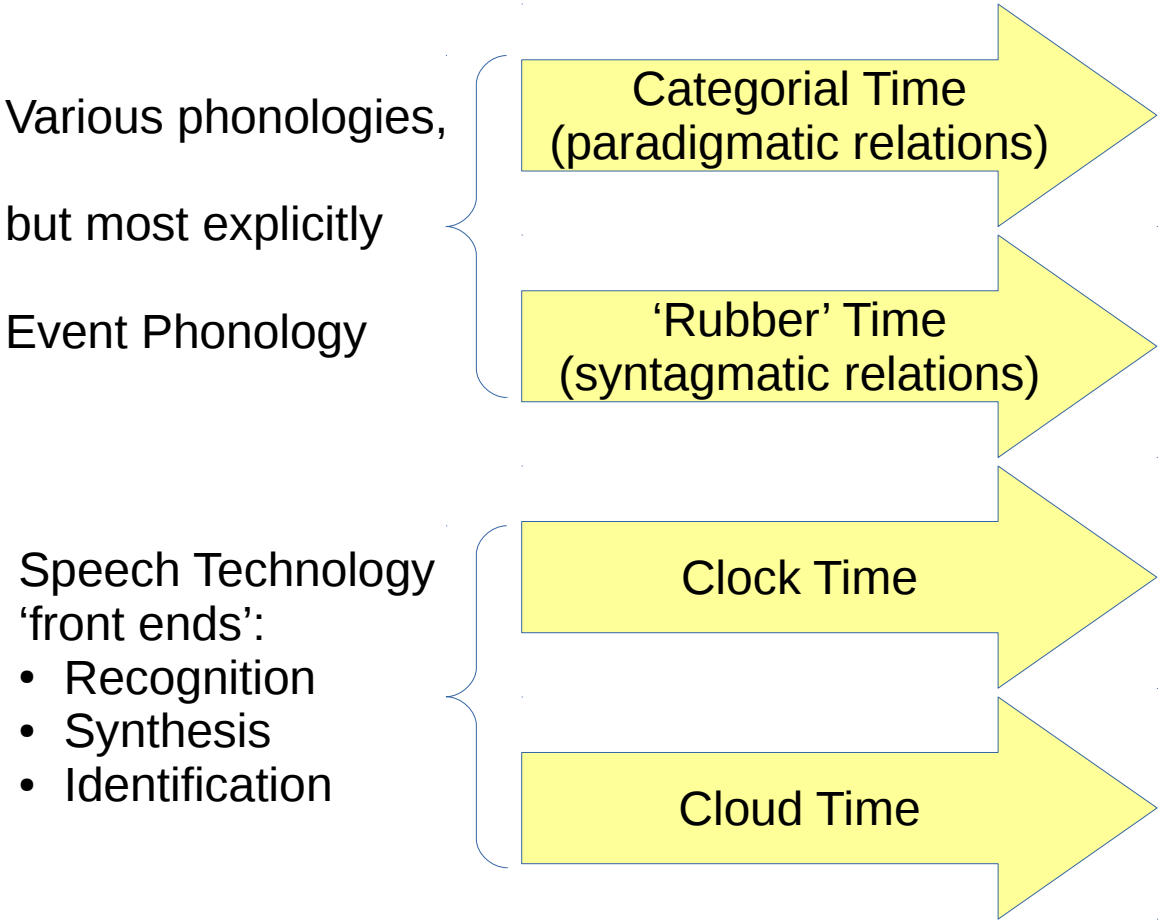

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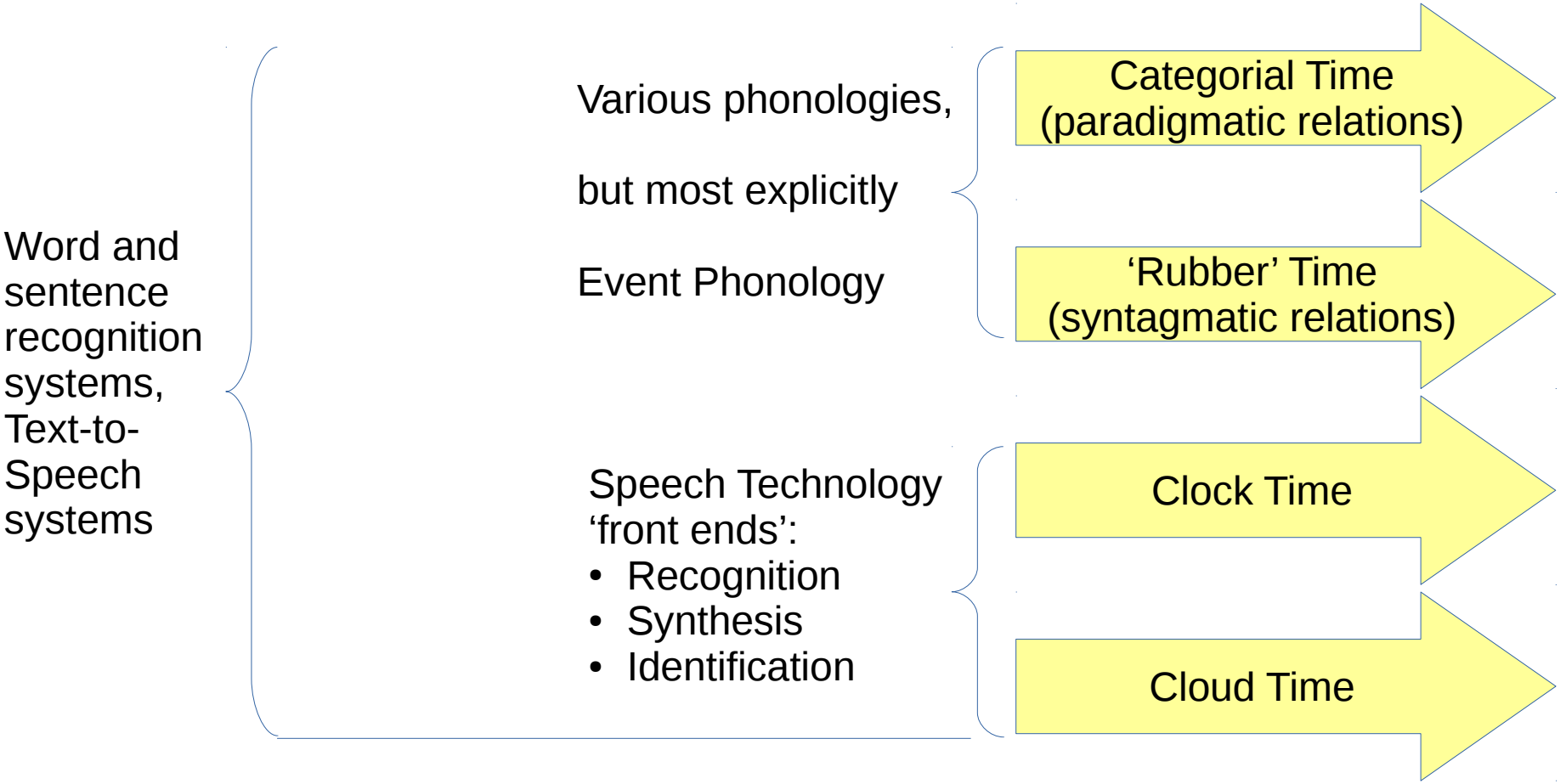

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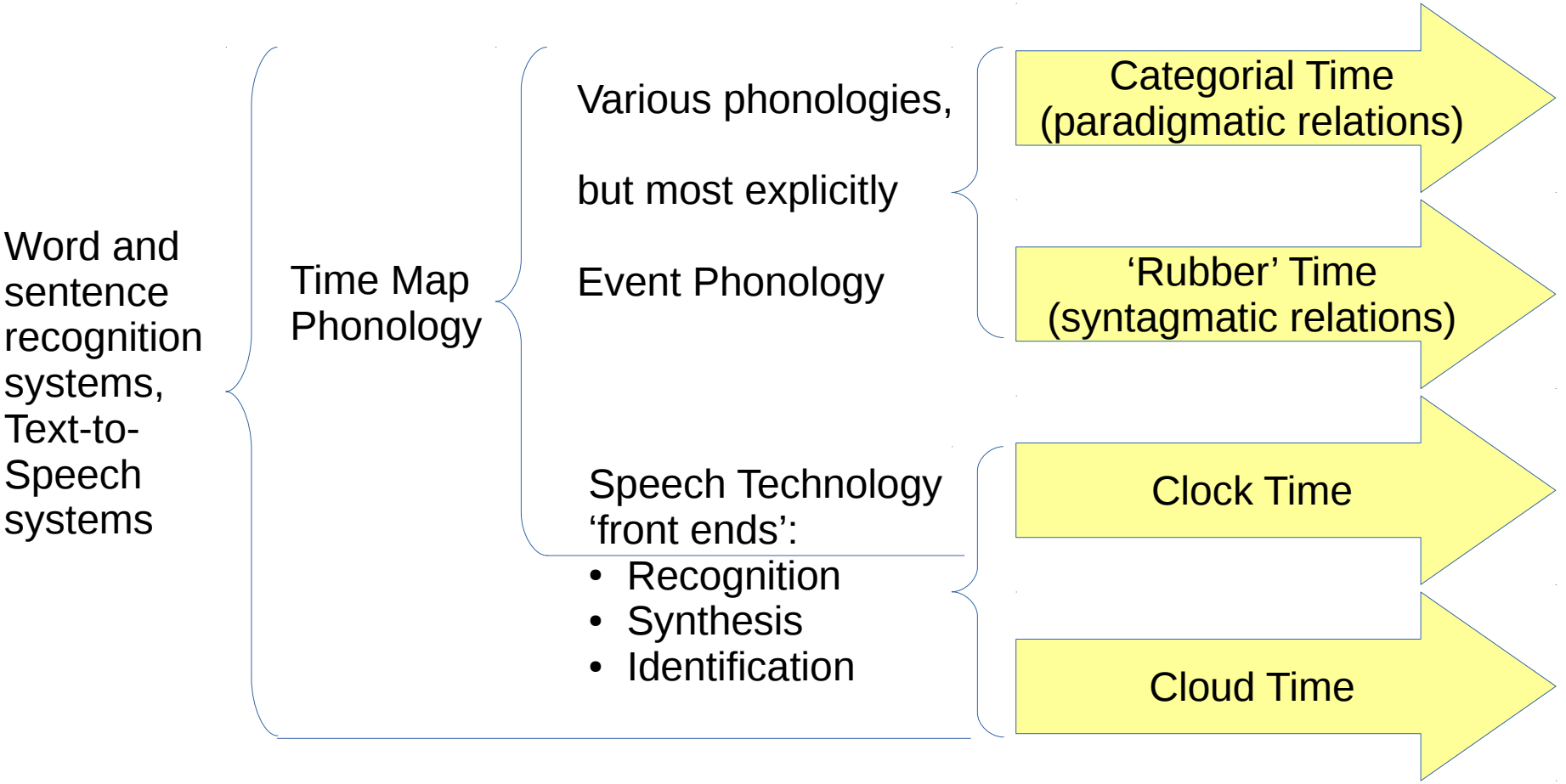

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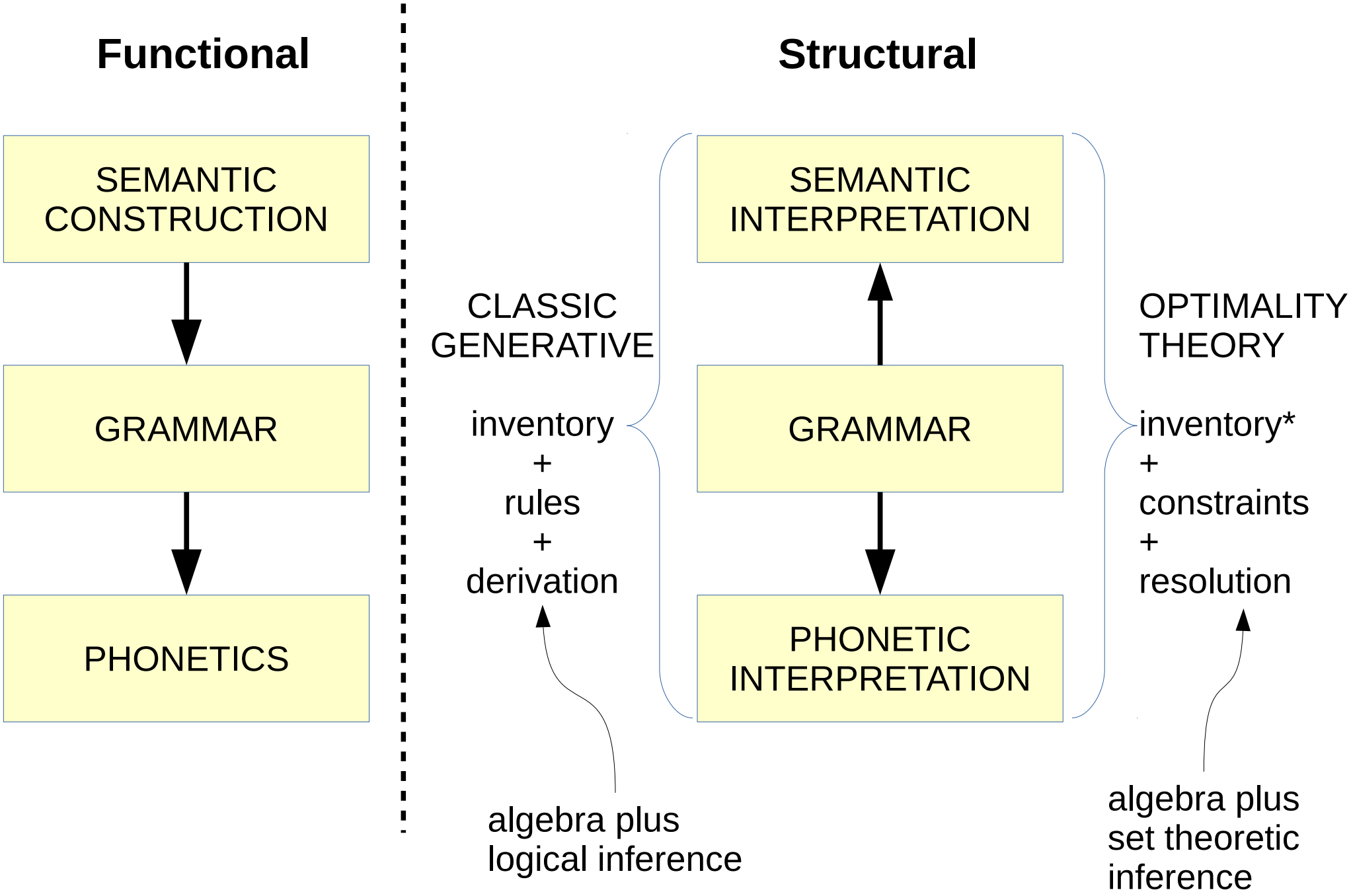
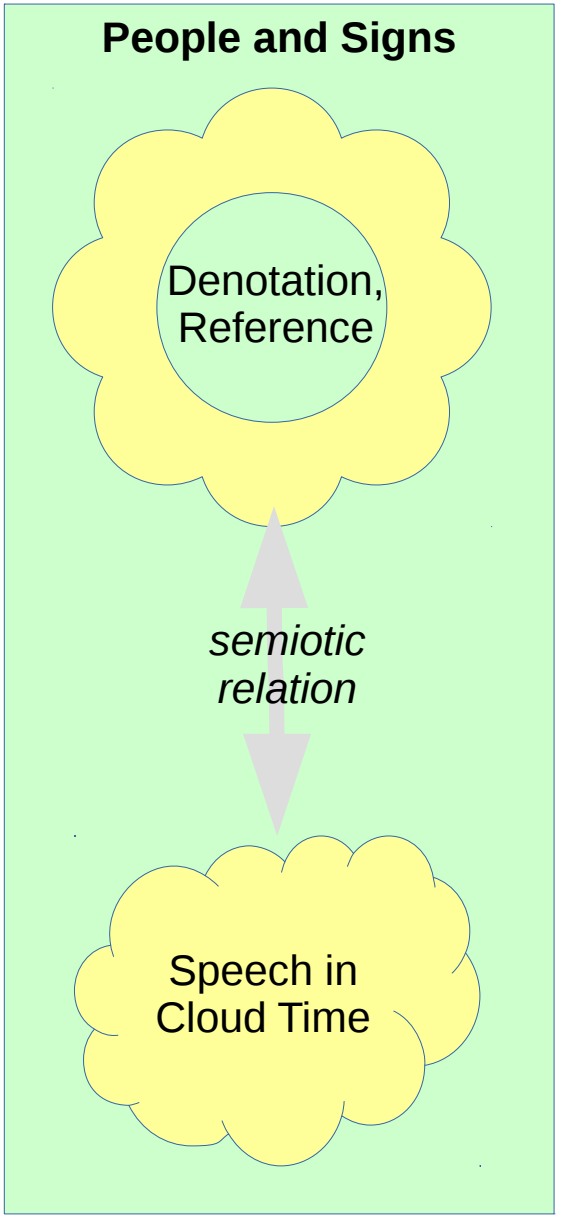
Time and Communicative Events

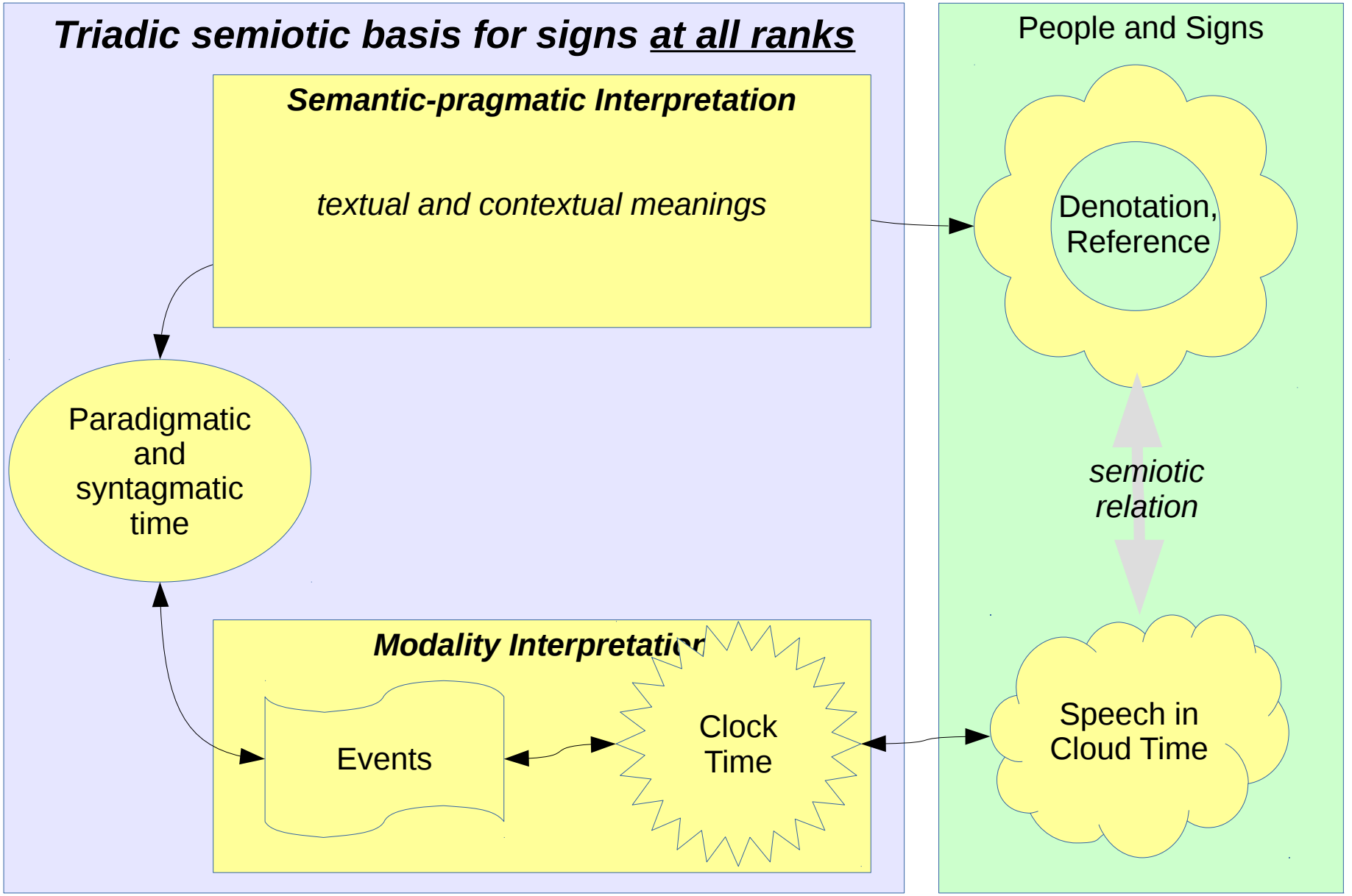
Two Well-known Architectures



Dyadic Semiotic Relation: Sounds and Meanings



Rank Interpretation Architecture



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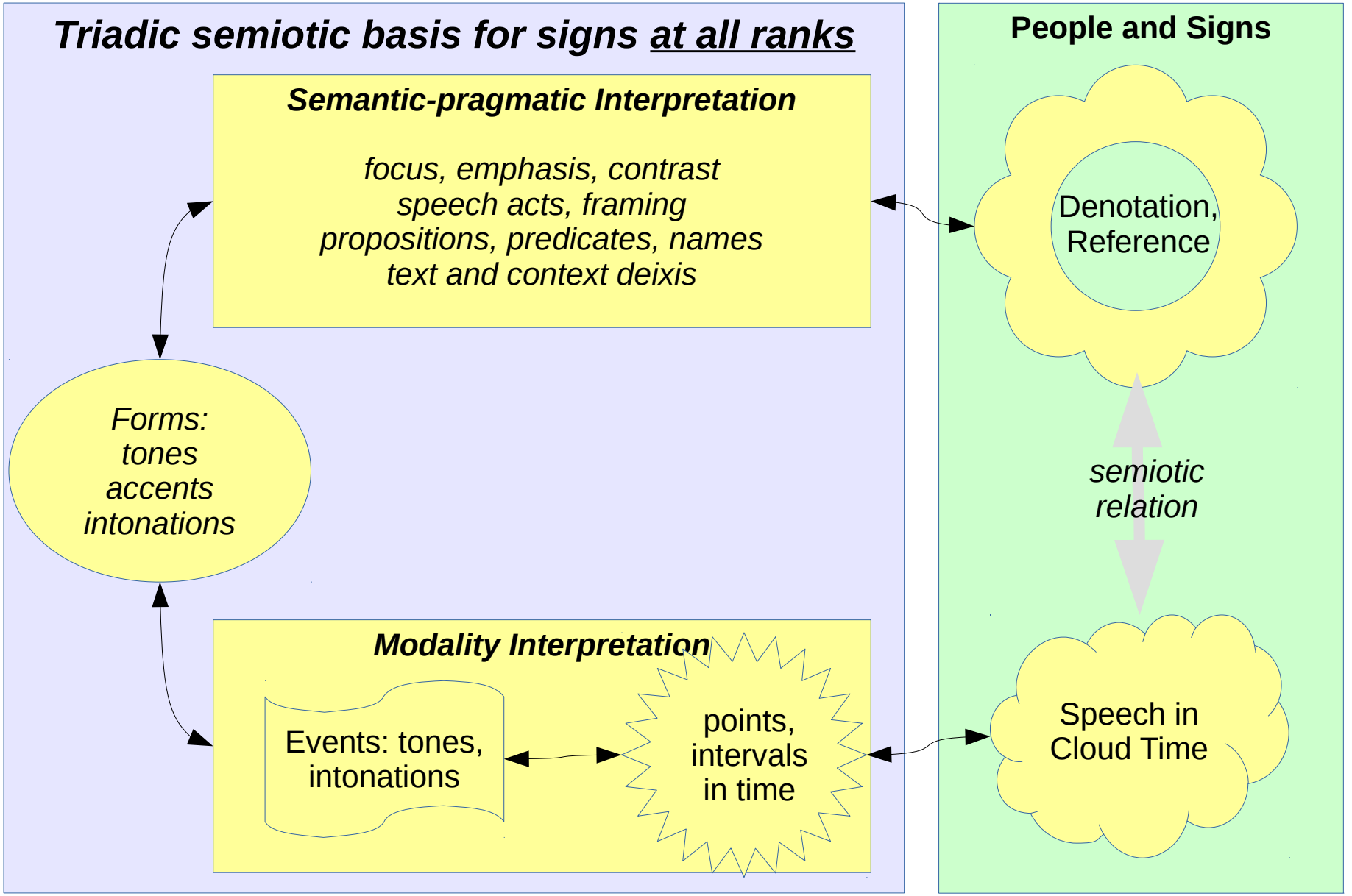


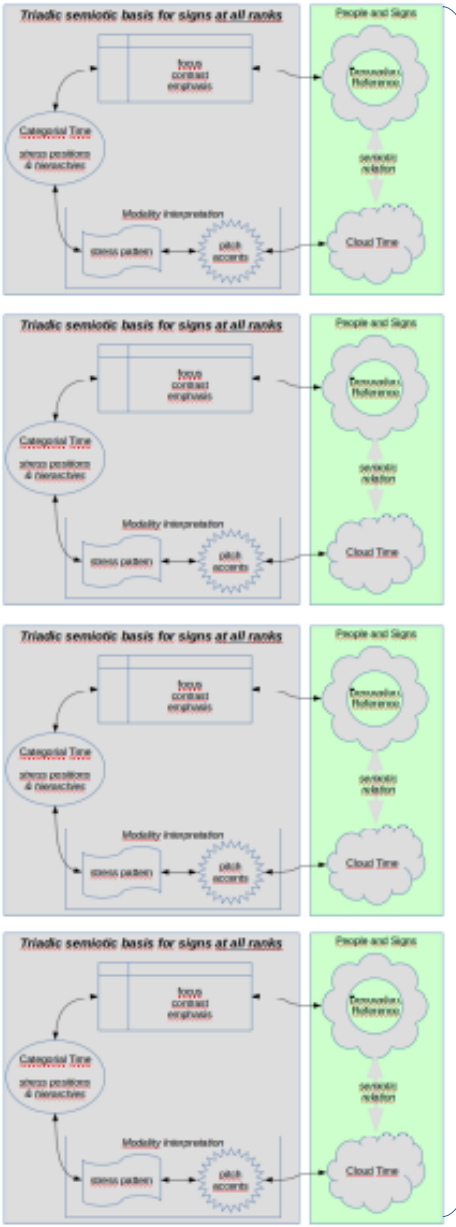
Rank – Interpretation Model: a Consistent Semiotic Architecture

Discourse: Utterance, Exchange

Utterance: turn, IPU, ...

Sentence, phrase, clause

Word: simple, derived, inflected, compound



Dual Semiotic Interpretation at every Rank

Interpretations

- mappings of sign events to two kinds of reality
  - prosodic-phonetic interpretation (modality interpretation)
  - pragmatic-semantic interpretation

Ranks

- signs of different sizes / functions / forms / types
  - discourse (utterance, exchange)
  - sentence (clause, phrase)
  - word (inflected, derived, compound)
  - phonematic unit (morphophoneme, archiphoneme, phoneme, feature)

The Phonology of Prosody

So, what is Prosody, again?

Let's get back to Prosody

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The 'Proto-Phonology' of Prosody:

Intonation Models in Pronunciation Teaching

Older textbook approaches: 'iconic' transcription

- Intonation vocabulary items represented iconically in graphic transcriptions:
  - dots or dashes for 'stressed' syllables
  - smaller dots for 'unstressed' syllables
- Intonation Group represented iconically:
  - sequence of vocabulary items
  - declination as sloping sequence
  - reset or 'break' to re-start Intonation Group
  - final 'nuclear' stress/accent/tone

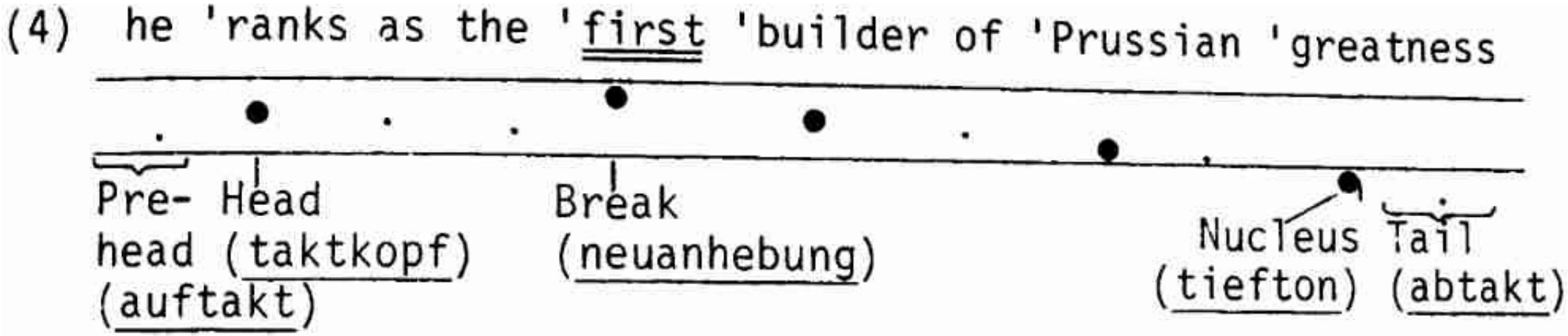
One-dimensional notations:

- Pronunciation textbook notations:
  - informal stylised melodic shapes
  - iconic ‘tadpole’ notations
  - text with ‘wavy typesetting’

/JOHNny /SAW the \MILKman
JOHNny SAW the MILKman
L*H L*H H*L

- Dictionary notations:
  - partly iconic diacritic notations
  - capitalisation
- Linguistic notations:
  - numerical notations: intonation levels, Mandarin tone numbers
  - symbolic notations (Pierrehumbert, ToBI)
- Phonetic notations:
  - IntSint (Hirst)

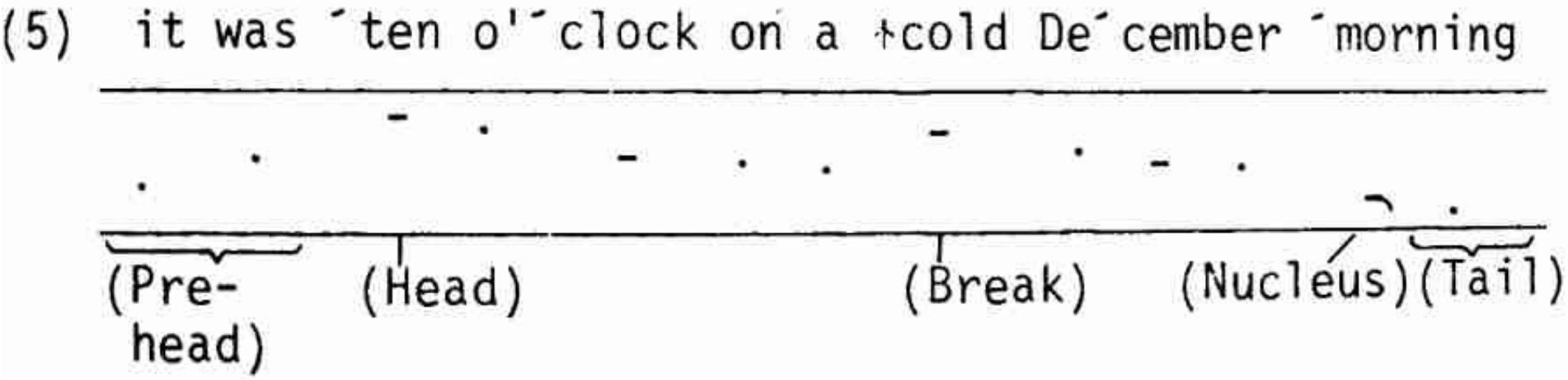
Graphical 'iconic' transcription: Proto-Phonology



Top: Klinghardt & Klemm (1920)
Bottom: Armstrong & Ward (1926)

Assign boundaries – e.g. foot, intermediate phrase, ...

Graphical 'iconic' transcription: Proto-Phonology



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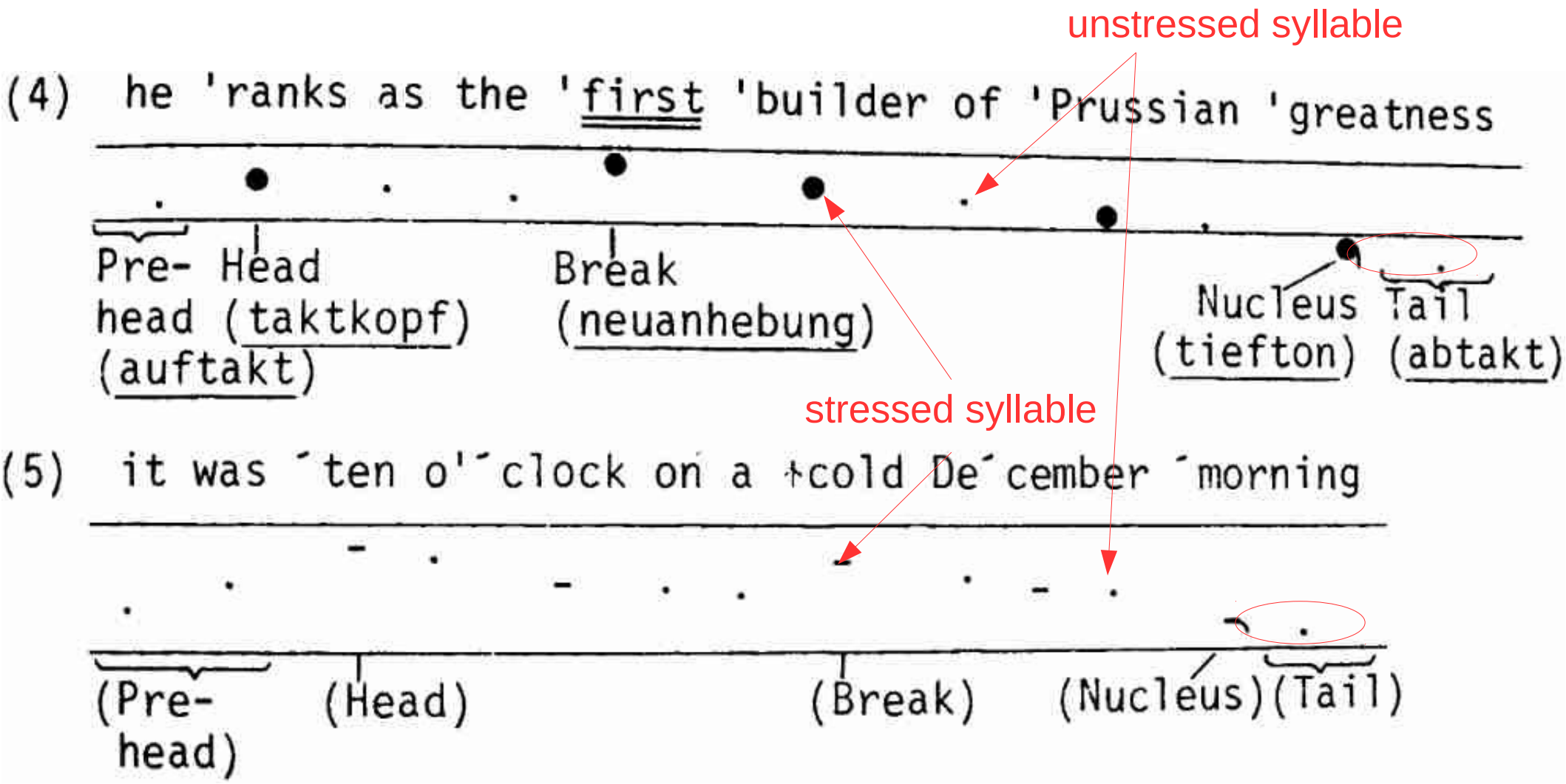

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Bottom: Armstrong & Ward (1926)

Grammar for 'Proto-Phonologies'

IG → NonFinal* Final
NonFinal → Bk Ana* Accent (Str)* Unstr
Final → Ana* Nucleus Unstr*

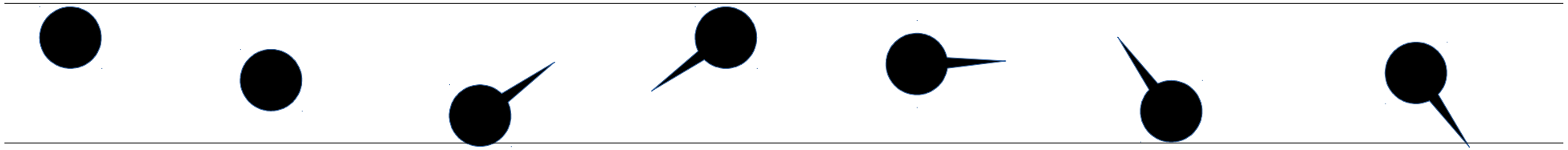
Moving on from 'proto-phonology'

Big John wanted a nice honey and cheese sandwich.

A ToBI type tonal notation:

H* **L*** **L*H** **LH*** **H*H** **HL*** **H*L**

A Tadpole notation:



An Attribute-Value notation:

shape=point
place=H

shape=rise
anchor=start
place=L

shape=level
anchor=start
place=H

shape=fall
anchor=start
place=H

shape=point
place=H

shape=rise
anchor=end
place=L

shape=fall
anchor=end
place=L

Graphical 'iconic' transcription: Proto-Phonology

Contour notations for pitch accents can represent four kinds of information:

- Global and local shapes of pitch accent contour
- Main pitch accent tone associated with a stressed syllable
- Height of pitch accent on a frequency scale
- Size of pitch accent in terms of prominence
- Length of pitch accent
- Location of pitch accent

Symbolic and level notations for pitch accents can represent

- Relative height of the pitch accent
- Location of the pitch accent

Processing Prosody: a Computational Perspective

Traditional Domain Properties for Prosody

- Phrasing (boundary placement)
  - Halliday's 'tonality'
- Accentuation (stress/accent placement)
  - Halliday's 'tonicity'
- Shape (sequence of levels/contours)
  - Halliday's 'tone':
    - global intonation contour
    - shape of pitch accents and boundary tones

Types of structure to be described

Classificatory (paradigmatic) items in prosody:

- lexicon of tones, durations, syllable types, ...

Compositional (syntagmatic) operations in prosody:

- Sequencing:
  - concatenation of phonemes, syllables, words, phrases, ...
- Parallelism:
  - synchronisation of features, prosodic and paralinguistic items
- Grouping:
  - hierarchies; generalisations; rule application domains

Formalisation: Steven Bird: Event phonology

- Julie Carson-Berndsen: Time-Map phonology

Prosody as a Formal Language

- The elements of a formal language are described by a formal grammar.
- The components of a formal grammar:

  Vocabulary (Lexicon, Dictionary, Inventory)

  - List of items (phonemes, morphemes, words, idioms, …)
  - Set of paradigmatic (classificatory, similarity) relations

  Grammar (Rule system, Constraint system)

  - Generator / Parser (creation and analysis of structures)
  - Set of syntagmatic (compositional) relations

Like word and sentence structure, prosodic structures are also described by a vocabulary and a grammar.

Processing Prosody: a Computational Perspective

The Prosodic / Phonological Hierarchy:

- sentential domains:
  - Utterance
  - Intonation Phrase
  - Phonological Phrase
- lexical domains:
  - Phonological word
  - Foot
  - Syllable
  - Mora
  - Phonematic Unit

Key computational question:

Is this hierarchy too complex to process in real time?

Processing Prosody: a Computational Perspective

Computational requirements for real time processing (the recursion issue):

- finite memory space
- finite or linear processing time

Fulfilment of real time processing requirements:

- iterative grammars have linear processing requirements
- right-branching, or left-branching grammars have linear processing time
- finite-depth grammars have constant finite processing time

Nonfulfilment of real time processing requirements:

- non-deterministic grammars (e.g. grammars like A → a b | a c
- centre-embedding phrase structure grammars

Processing Time and Processing Space: a Note on Recursion

Food for thought:

- recursion is not just about a node dominating another node with the same name – that name may be ill-defined and ambiguous, or a generalisation, or vague; this criterion is necessary but not sufficient
- recursion is about describing an infinite number of objects (sentences, words, numbers, …)
- a recursive theory of language and speech must also be realistic:
  - the Linear Processing Time Constraint:

    The time required for processing speech must be linear in relation to the length of the input.
  - the Finite Processing Space Constraint:

    The memory required for processing speech must be finite.

Processing Time and Processing Space: a Note on Recursion

In the many discussions of recursion over the past 20 years or so, this crucial distinction between two types of recursion with different processing time and space properties has been neglected:

- linear recursion:
  - left & right branching (computationally equivalent to iteration)
  - linear recursion is realistic, requiring finite working memory, and processing time which is a linear function of the size of the input
- non-linear recursion:
  - centre-embedding, cross-serial dependencies
  - non-linear recursion is unrealistic, requiring unrestricted memory and at least quadratic processing time, thus implausible for speech

Processing Time and Processing Space: a Note on Recursion

Non-linear recursion is unproblematic: the basic principle of creativity in language.

But speakers fail at producing and understanding centre-embedding in spontaneous speech. How can this then be a feature of language?

In rehearsed speech, writing and read speech, a small amount of centre-embedding is possible, due to the additional time and memory space provided by this kind of register.

Processing Time and Processing Space: a Note on Recursion

Where did centre-embedding come from?

Speakers were trying to be clever: generalising *linearly recursive* sentence-final nominal clauses (e.g. relative clauses, that clauses) to *centre-embedding* non-final positions.

So centre-embedding is

- derived from right or left recursion
- *plus* a generalisation:

"Use right (or left) branching anywhere"

Unfortunately, processing capacity is too limited to permit more than one application of this generalisation, unless rehearsal or writing are involved. And speakers fail.

Where did centre-embedding come from?

Speakers were trying to be clever: generalising *linearly recursive* sentence-final nominal clauses (e.g. relative clauses, that clauses) to *centre-embedding* non-final positions.

1. Linear (right-branching):
   - Jim saw the man who found the boy
2. Centre-embedding experiment – tough to process:
   - the man who found the boy saw Jim
3. **Linear right-branching solution – use the passive:**
   - Jim was seen by the man who found the boy

Processing Time and Processing Space: a Note on Recursion

Try pronouncing this:

> I met the lady who the girl who the teacher who my friend saw was teaching was visiting had in fact left town.

Processing Time and Processing Space: a Note on Recursion

Try pronouncing this:

> I met the lady who the girl who the teacher who my friend saw was teaching was visiting had in fact left town.

Now try pronouncing this:

> I met the lady who was being visited by the girl who was being taught by the teacher who was seen by my friend.

Back to the Prosodic Hierarchy

Computing the Prosodic / Phonological Hierarchy:

- sentential domains: ok, total depth is finite
  - Utterance: ok if only iterative or right/left branching
  - Intonation Phrase: ok if only iterative or right/left branching
  - Phonological Phrase: ok if only iterative or right/left branching
- lexical domains: ok, total depth is finite
  - Phonological word: ok if finite depth or right/left branching
  - Foot: ok because finite depth and finite maximum length
  - Syllable: ok because finite depth and finite maximum length
  - Mora: ok because finite depth and finite maximum length
  - Phonematic Unit: ok because just one (features change nothing)

Answer to the previous question:

Not too complex IF the above conditions are fulfilled.

Categorial Time and Rubber Time

A Prosodic Hierarchy which goes higher than the utterance

- phonological segment – vowels, consonants; distinctive features
- syllable – stress, accent, tone
- foot – basic unit of rhythm in stress languages
- prosodic word – domain of lexical phonological rules
- prosodic phrase – domain of intonation: onset – body - nucleus
- paratone – (larger intonation domain, analogous to ‘paragraph’)
- dialogue exchange

In the Rank Interpretation Architecture,

the Prosodic Hierarchy is part of Modality Interpretation.

The Prosodic Hierarchy: an integrative view

Utterance (Utt): constituent of turn-taking, Q&A etc.

Intonational Phrase (IP): boundary tones, association with grammatical phrase

Phonological phrase (PhP), Intermediate Phrase (ip): phrase boundary tone, domain of phrase stress

Phonological word, Prosodic Word (PW, PrWd, ω): domain of word stress, prosodic morphology, clitics

Foot (φ): Domain of primary, secondary, fixed stress, prosodic morphology

Syllable (σ): phonotactic patterns, stress-bearing unit, (phonetically: local sonority peak)

Mora (μ): tone placement, phonotactic patterns

Segment: smallest 'leaf' element in prosodic hierarchy

Subsegment: affricates, diphthongs; (phonetic: stop closure-pause-release)

The grammar of the Prosodic Hierarchy

Prosodic Category inventory:

PC = {Utt, IP, PhP, PrWd, omega, Ft phi, syll, mora, segment}

Prosodic Hierarchy ordering:

L = <Utt, IP, PhP, PrWd, omega, Ft phi, syll, mora, segment>

l1 = Utt, l2 = IP, … l9 = segment

Structural constraints on Prosodic Hierarchy

Strict Layering Hypothesis:

PC at L_i dominates only PCs at L_{i+1}i

- Fixed depth (no recursivity): No PC at L_i dominates a PC at L_{i+1}
- Exhaustivity: All PCs at L_i are dominated by a single PC at L_{i-1}

Headedness:

- Every PC at L_i immediately dominates a PC at L_{i+1}

Computing: the Grammar of the Prosodic Hierarchy

Prosodic Category inventory:

PC = {Utt, IP, PhP, PrWd, omega, Ft phi, syll, mora, segment}

Prosodic Hierarchy ordering:

L = <Utt, IP, PhP, PrWd, omega, Ft phi, syll, mora, segment>

l1 = Utt, l2 = IP, … l9 = segment

Structural constraints on Prosod

Strict Layering Hypothesis:

PC at L_i dominates only PCs at L_{i+1}i

- Fixed depth (no recursion): No PC at L_i dominates a PC at L_{i+1}
- Exhaustivity: All PCs at L_i are dominated by a single PC at L_{i-1}

Headedness:

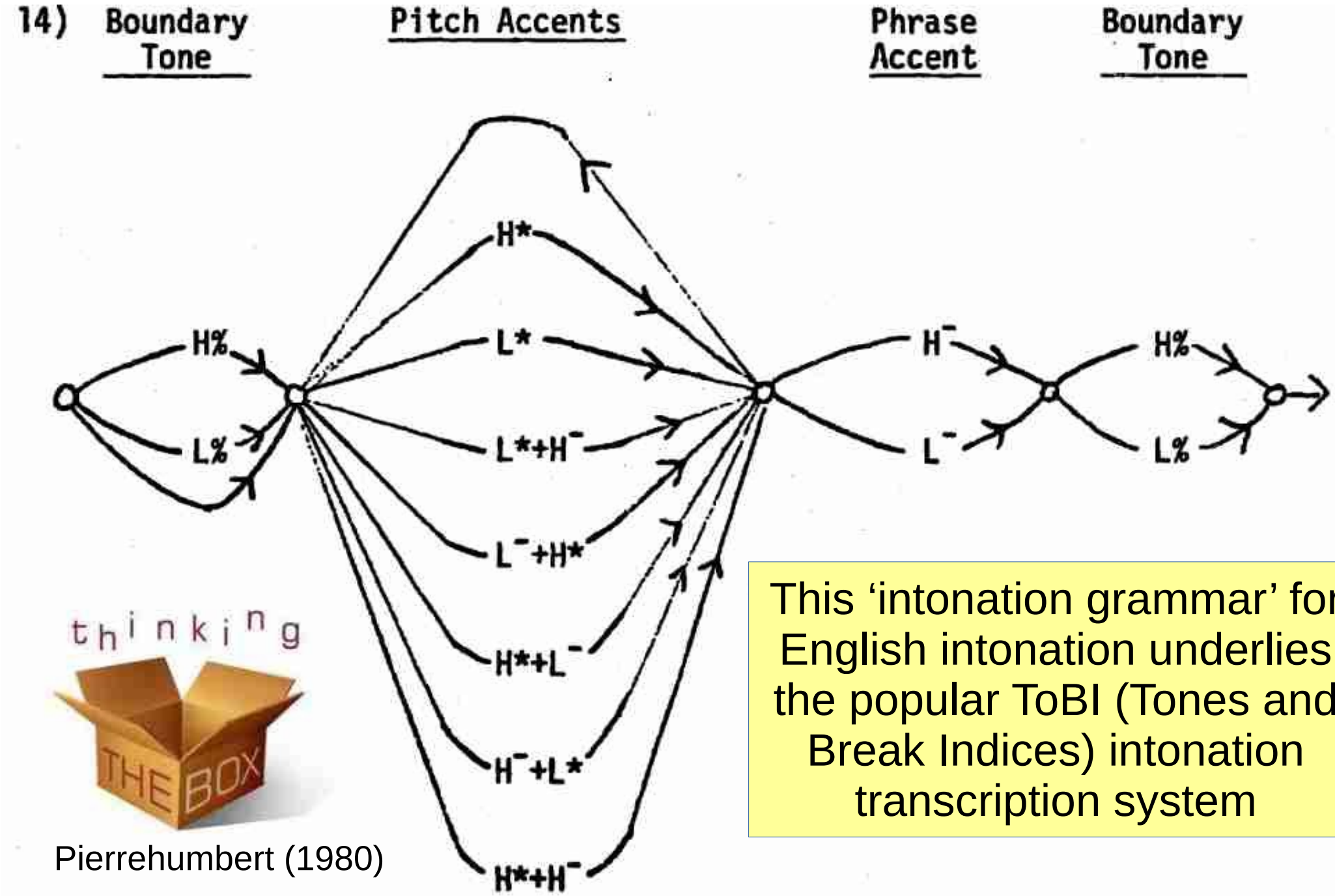
- Every PC at L_i immediately dominates a PC at L_{i+1}

But 'flat' recursion at the same rank is ok.

Linear Phrasal Grammar of English Sentence Prosody:

A Computational Perspective

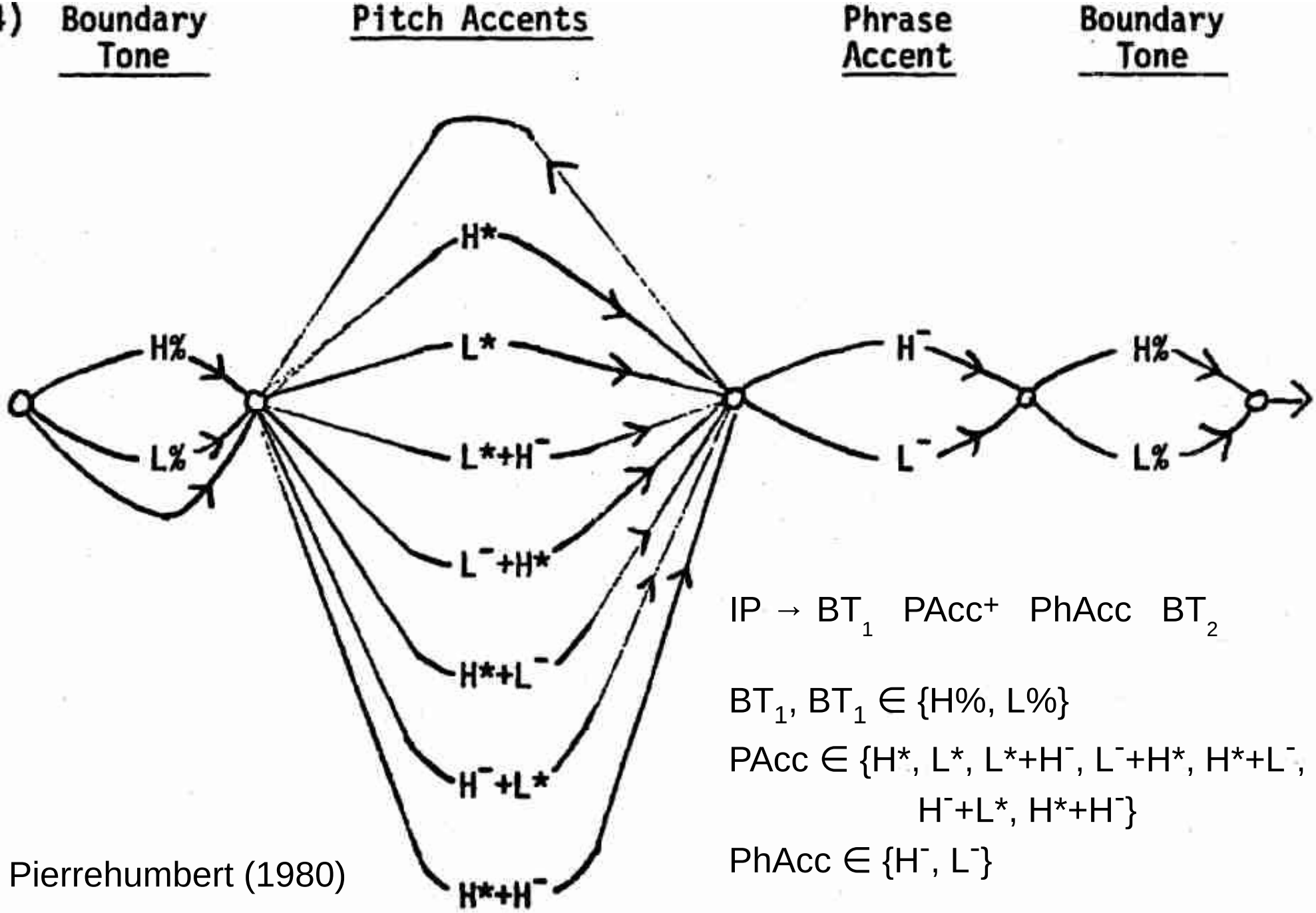
Phrasal Grammar: Pierrehumbert's Finite Machine Model



Pierrehumbert (1980)

This 'intonation grammar' for English intonation underlies the popular ToBI (Tones and Break Indices) intonation transcription system

Phrasal Grammar: Pierrehumbert's Finite Machine Model



IP → BT_1 $PAcc^+$ PhAcc BT_2

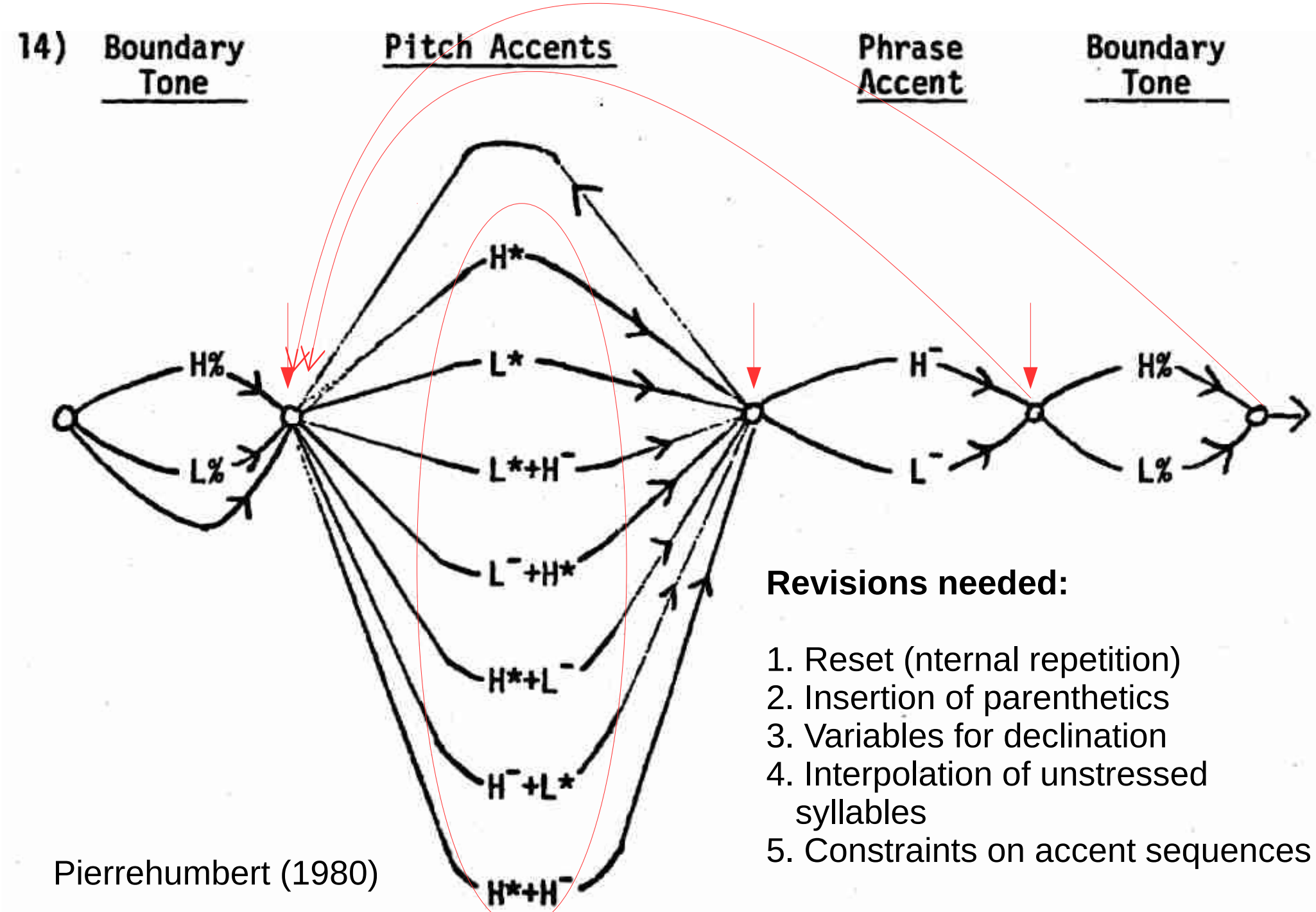
BT_1, $BT_1 \in$ {H%, L%}

PAcc ∈ {H*, L*, L*+H⁻, L⁻+H*, H*+L⁻, H⁻+L*, H*+H⁻}

PhAcc ∈ {H⁻, L⁻}

Pierrehumbert (1980)

Iterative Finite Machine as Abstract Oscillator

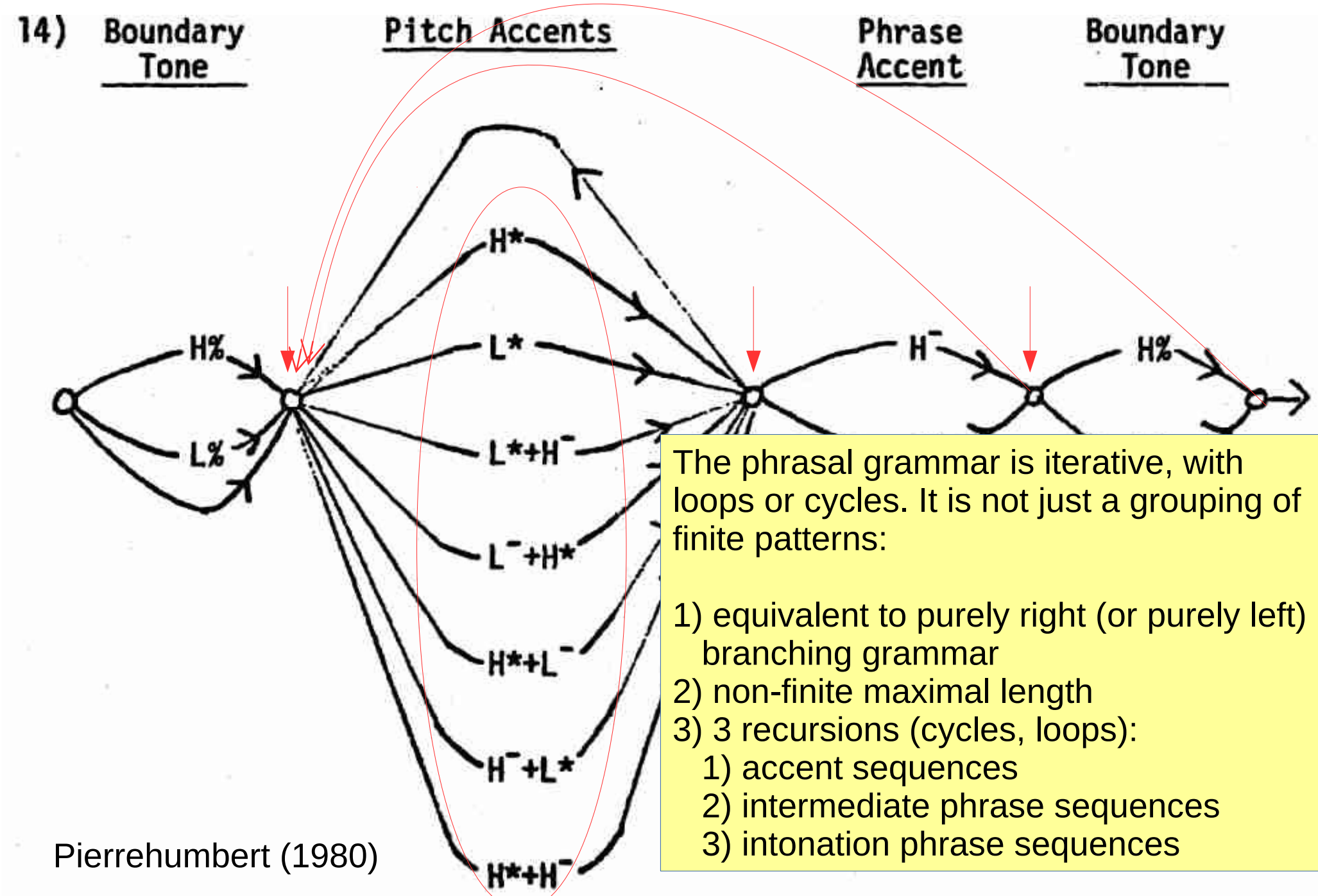


Revisions needed:

1. Reset (nternal repetition)
2. Insertion of parenthetics
3. Variables for declination
4. Interpolation of unstressed syllables
5. Constraints on accent sequences

Pierrehumbert (1980)

Iterative Finite Machine as Abstract Oscillator



The phrasal grammar is iterative, with loops or cycles. It is not just a grouping of finite patterns:

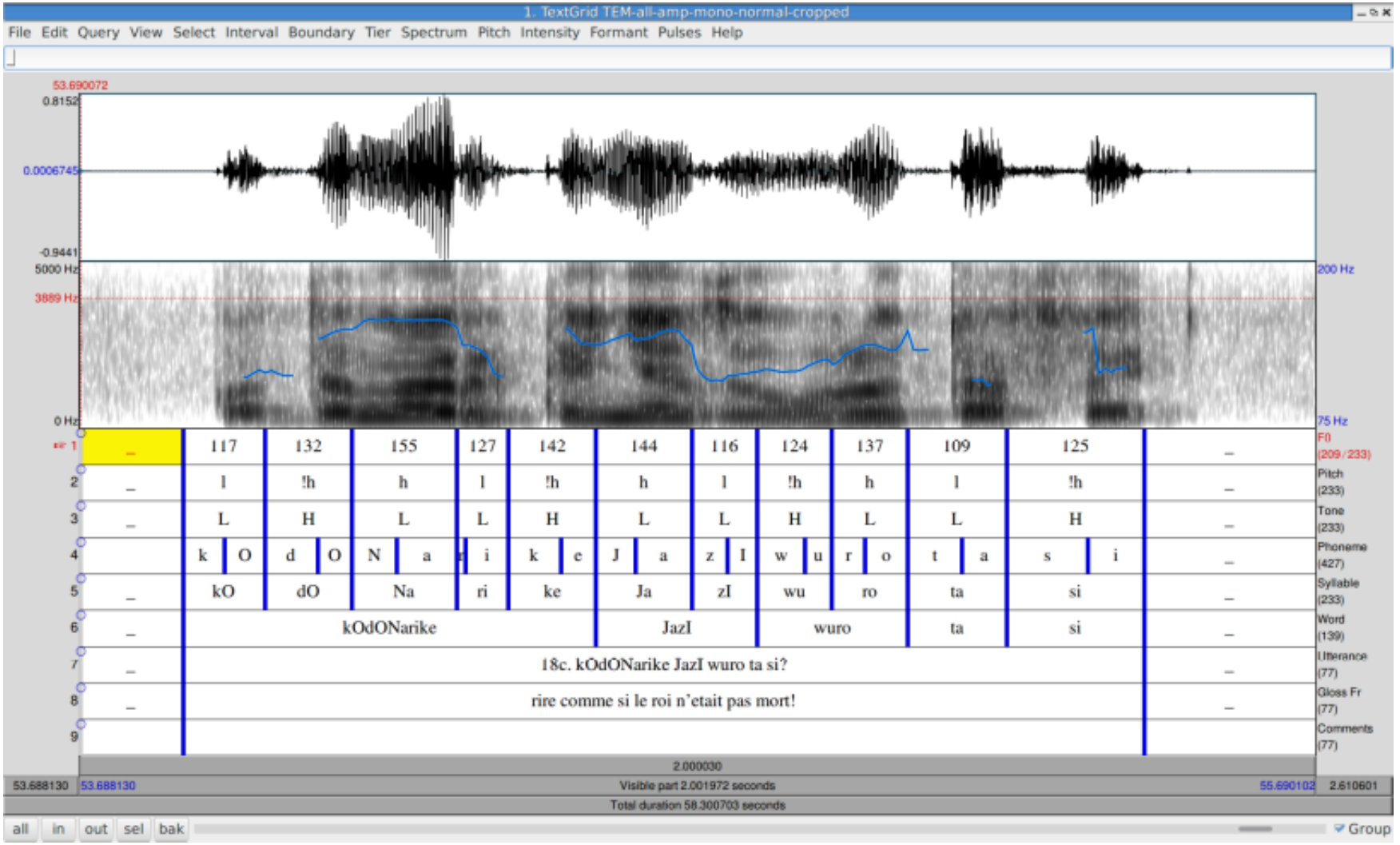
1) equivalent to purely right (or purely left) branching grammar
2) non-finite maximal length
3) 3 recursions (cycles, loops):
   1) accent sequences
   2) intermediate phrase sequences
   3) intonation phrase sequences

Pierrehumbert (1980)

Linear Phrasal Grammar of Niger-Congo Phrasal Tonotactics (Tone Sandhi):

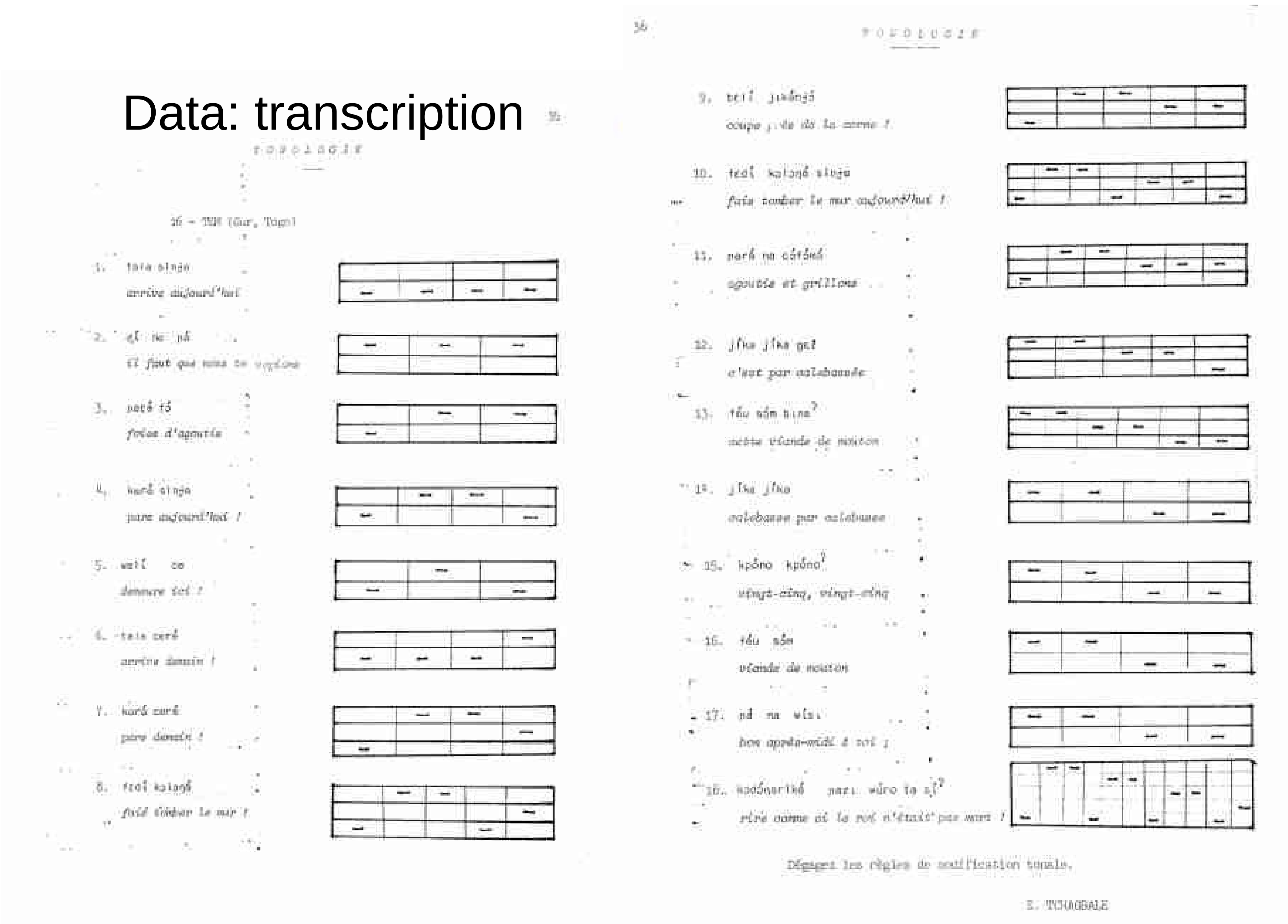
A Computational Perspective

Tem (Togo; (Gur; ISO 639-2 kth)



Tem (Togo; (Gur; ISO 639-2 kth)

Data: transcription



36 – TEM (Gur, Togo)

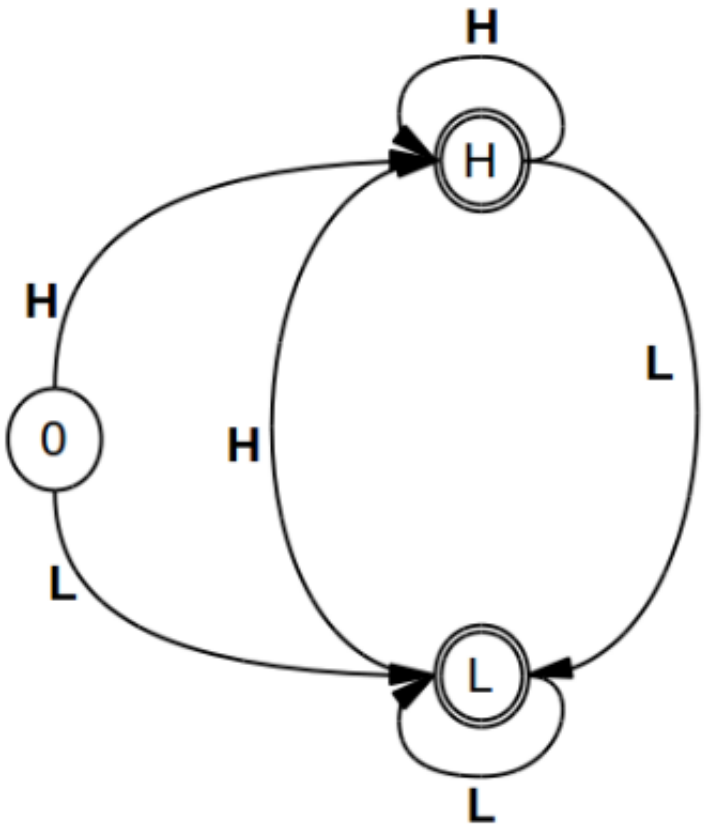
1. taia singa
   arrive aujourd'hui
2. ɛ́ɛ ne pá
   il faut que nous te voyions
3. peté tó
   forces d'agoutis
4. kará singa
   pars aujourd'hui !
5. weiɛ́ ce
   demeure ici !
6. taia ceré
   arrive demain !
7. kará ceré
   pars demain !
8. tcaɛ́ kalaŋá
   fais tomber le mur !
9. tcɛ́ jikáŋá
   coupe ... de la corne !
10. tcaɛ́ kalaŋá singa
    fais tomber le mur aujourd'hui !
11. pará na córóná
    agoutis et grillons
12. jíka jíka gɛɛ́
    c'est par calebasse
13. téu sóm tina?
    cette viande de mouton
14. jíka jíka
    calebasse par calebasse
15. kpóno kpóno?
    vingt-cinq, vingt-cinq
16. téu sóm
    viande de mouton
17. ná na wisi
    bon après-midi à toi !
18. kpaɖɔɔrikɛ́ pari wúro ta sɛ́?
    rire comme si le roi n'était pas mort !

Dégagez les règles de modification tonale.

E. TCHAGBALE

Finite Machine for Niger-Congo Languages with 2 Lexical Tones

1-tape (1-level) transition network



Finite Machine for Niger-Congo Languages with 2 Lexical Tones

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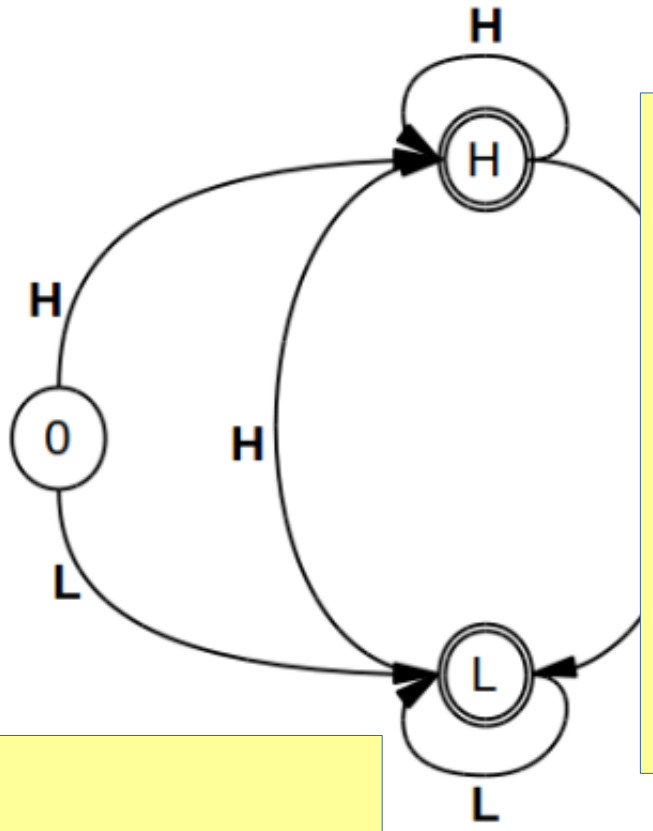


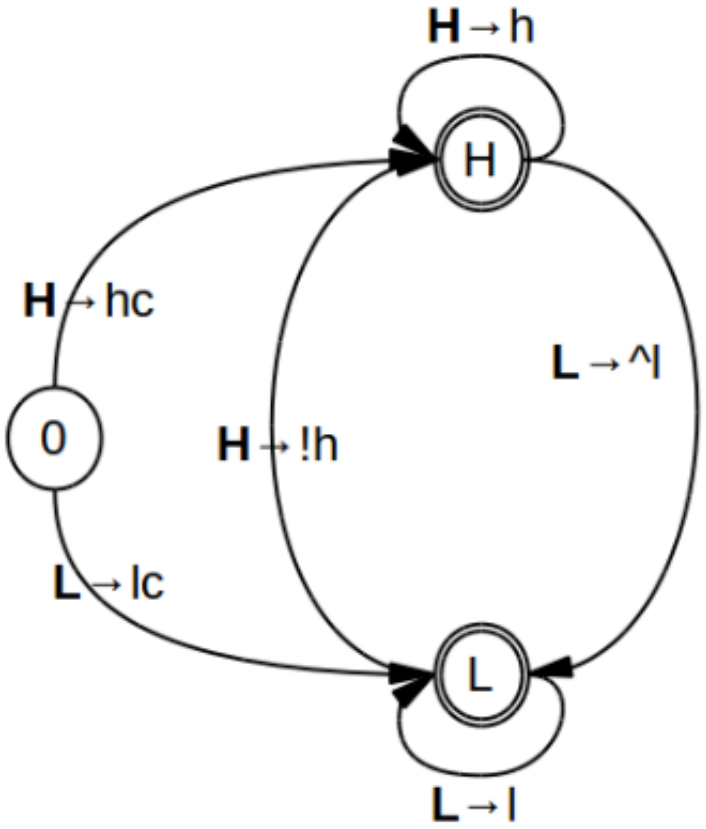
The phrasal tone-sandhi grammar is iterative, with loops or cycles. It is not just a grouping of finite patterns:

1) equivalent to purely right (or purely left) branching grammar
2) non-finite maximal length
3) 3 recursions (cycles, loops):
   1) accent sequences
   2) intermediate phrase sequences
   3) intonation phrase sequences

Note:
'post-lexical' means phrasal.

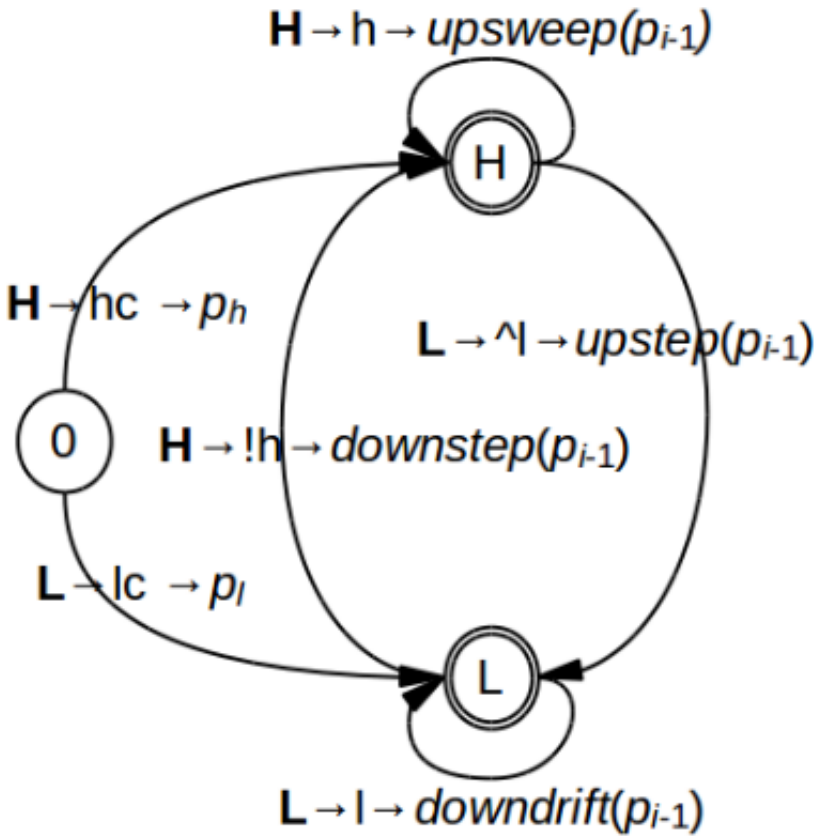
Generalised Two-tone Machine with Two-level Phonetic Mapping

2-tape (2-level) transition network



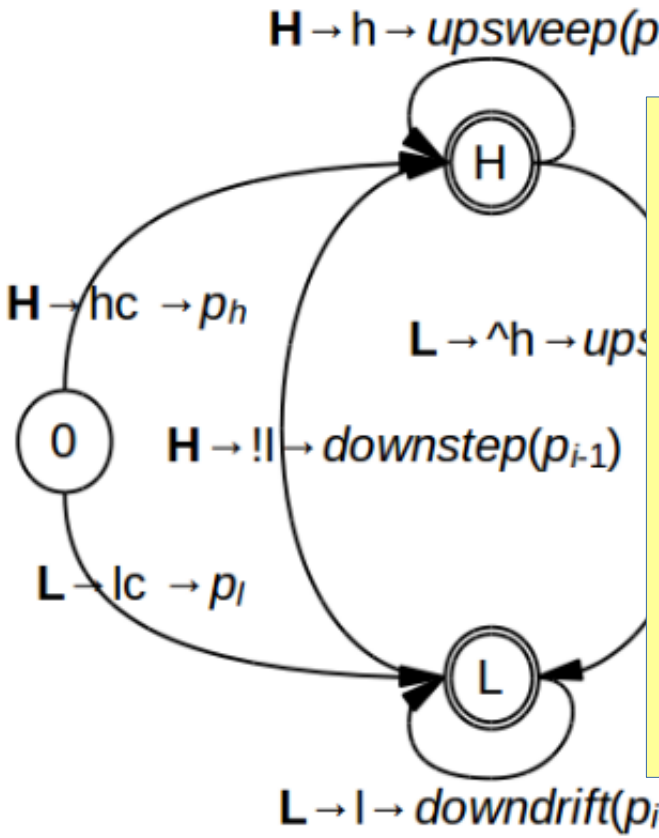
Generalised Two-tone Machine with Three-level Phonetic Mapping

3-tape (3-level) transition network



Generalised Two-tone Machine with Three-level Phonetic Mapping

3-tape (3-level) transition network



The functions on the third level can easily be assigned numerical values:

1) initial 'start-up' high or low fuzzy pitch constant
2) multiplication of previous value by an *upsweep*, *downdrift*, *upstep*, or *downstep* value
3) addition of a baseline value

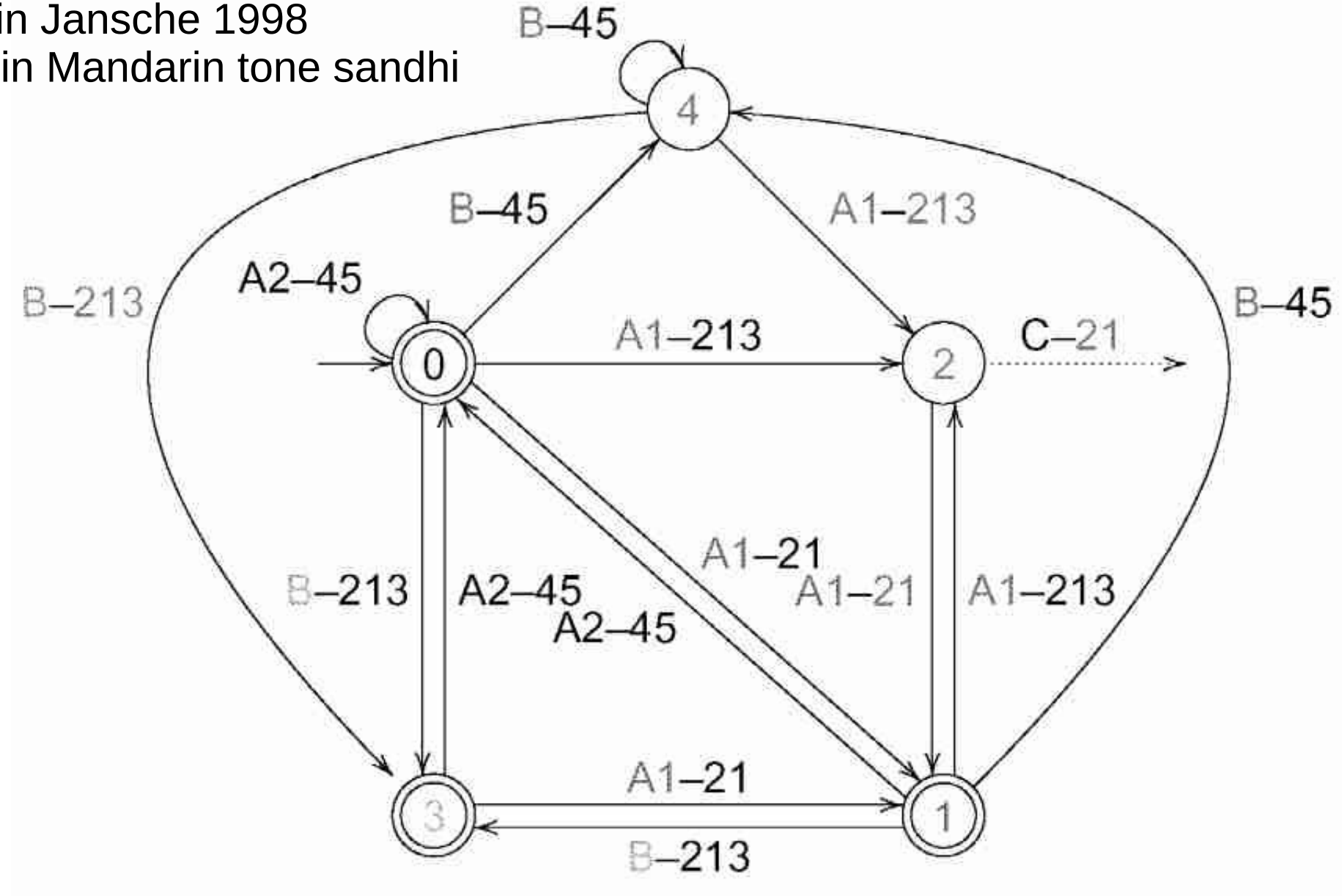
cf. Liberman & Pierrehumbert (e.g. 1984)

Linear Phrasal Grammar of Tianjin Mandarin Phrasal Tonotactics (Tone Sandhi):

A Computational Perspective

Generalised Two-tone Machine Three-level Machine for Mandarin

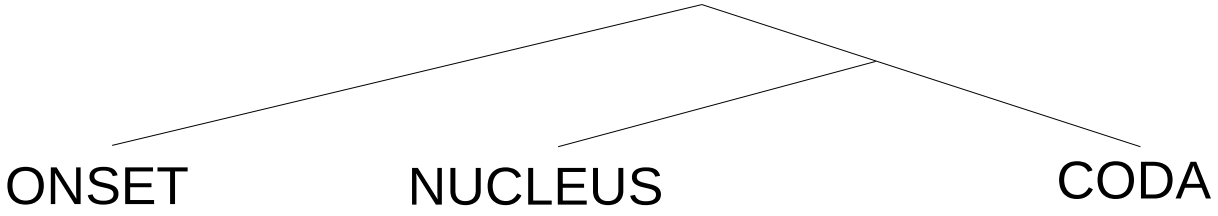
Martin Jansche 1998
Tianjin Mandarin tone sandhi



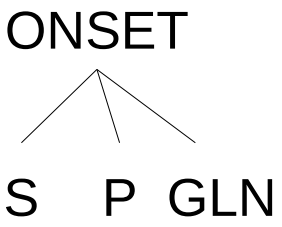
Linear phrasal Grammar of English Syllable Phonotactics:

A Computational Perspective

Linear Syllable Grammar (English)



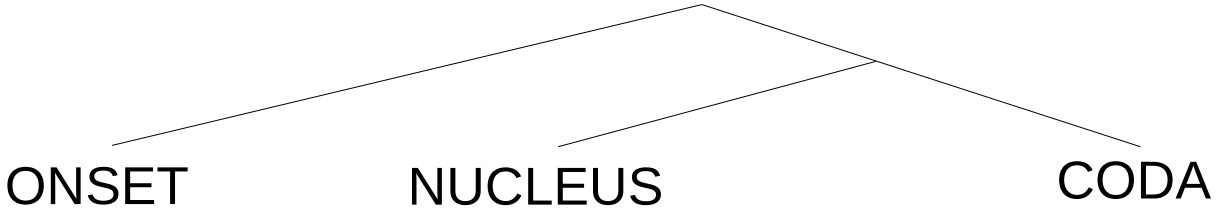
How many terminal elements does the longest monosyllabic word in have?



ONSET:

Sibilant – Plosive – Glide/Liquid/Nasal

Linear Syllable Grammar (English)



How many terminal elements does the longest monosyllabic word in have?

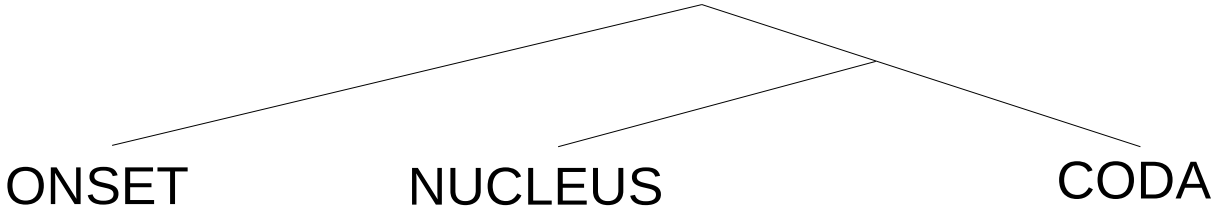
ONSET

S	P	GLN
s	p	r
s	t	r
s	k	l
s	k	w

Pam
pram
Sam
tram
spit
split
straps
strapped

stray
strains
strange

Linear Syllable Grammar (English)



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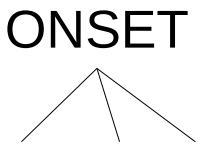


	S	P	GLN
	s	p	r
	s	t	r
	s	k	l
	s	k	w
*	s	p	w
*	s	t	w
*	s	t	l

Pam
pram
Sam
tram
spit
split
straps
strapped

stray
strains
strange

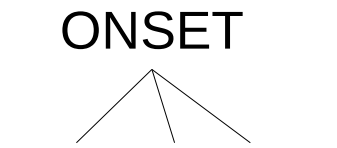
Clearly, the tree notation over-generalises and has to be constrained.
Is this kind of hybrid notation necessary?

Linear Syllable Grammar (English)

Clearly, the tree notation over-generalises and has to be constrained: a hybrid system is necessary:

1. Generate too many combinations (with the trees).
2. Limit the set (with constraints).

Is this kind of hybrid system necessary? In principle, no.



	S	P	GLN
	s	p	r
	s	t	r
	s	k	l
	s	k	w
*	s	p	w
*	s	t	w
*	s	t	l

Pam
pram
Sam
tram
spit
split
straps
strapped

stray
strains
strange

Benjamin Lee Whorf's solutions

To show the full formula for this law or pattern—a so-called "morphophonemic structural formula"—I should need a large piece of paper. I can however set up a condensed form of it as:

$$O,\ C - ng,\ C_1C_2,\ C_3C_4,\ \text{etc.} \ldots .$$
$$s \pm C_mC_n + V + (V_1)\ O, \pm (r, w, y);$$
$$C - h,\ C'_1C'_2,\ C'_3C'_4,\ \text{etc.} \ldots .$$
$$C'_mC'_n \pm (t/d,\ s/z,\ st/zd).^3$$

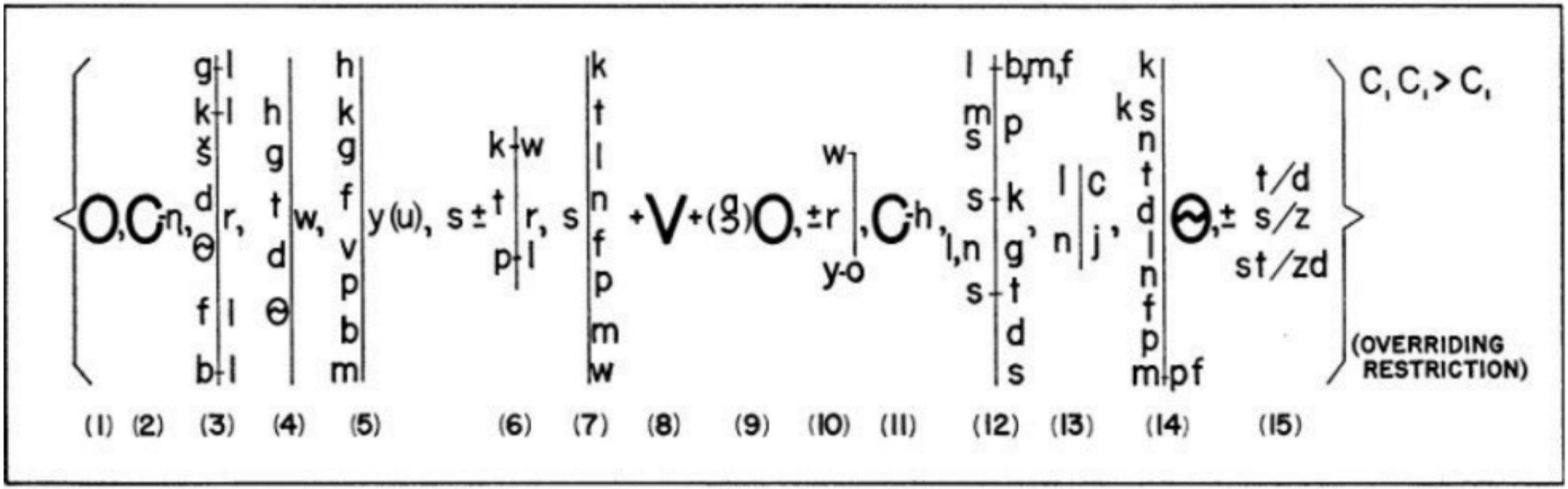
This formula requires that the English words be symbolized or "spelt" accord-

[3] The full formula from which this is abbreviated is printed and explained in my paper "Linguistics as an Exact Science" in *Technology Review*, December 1940, Massachusetts Institute of Technology, Cambridge, Mass.

Benjamin Lee Whorf's solutions

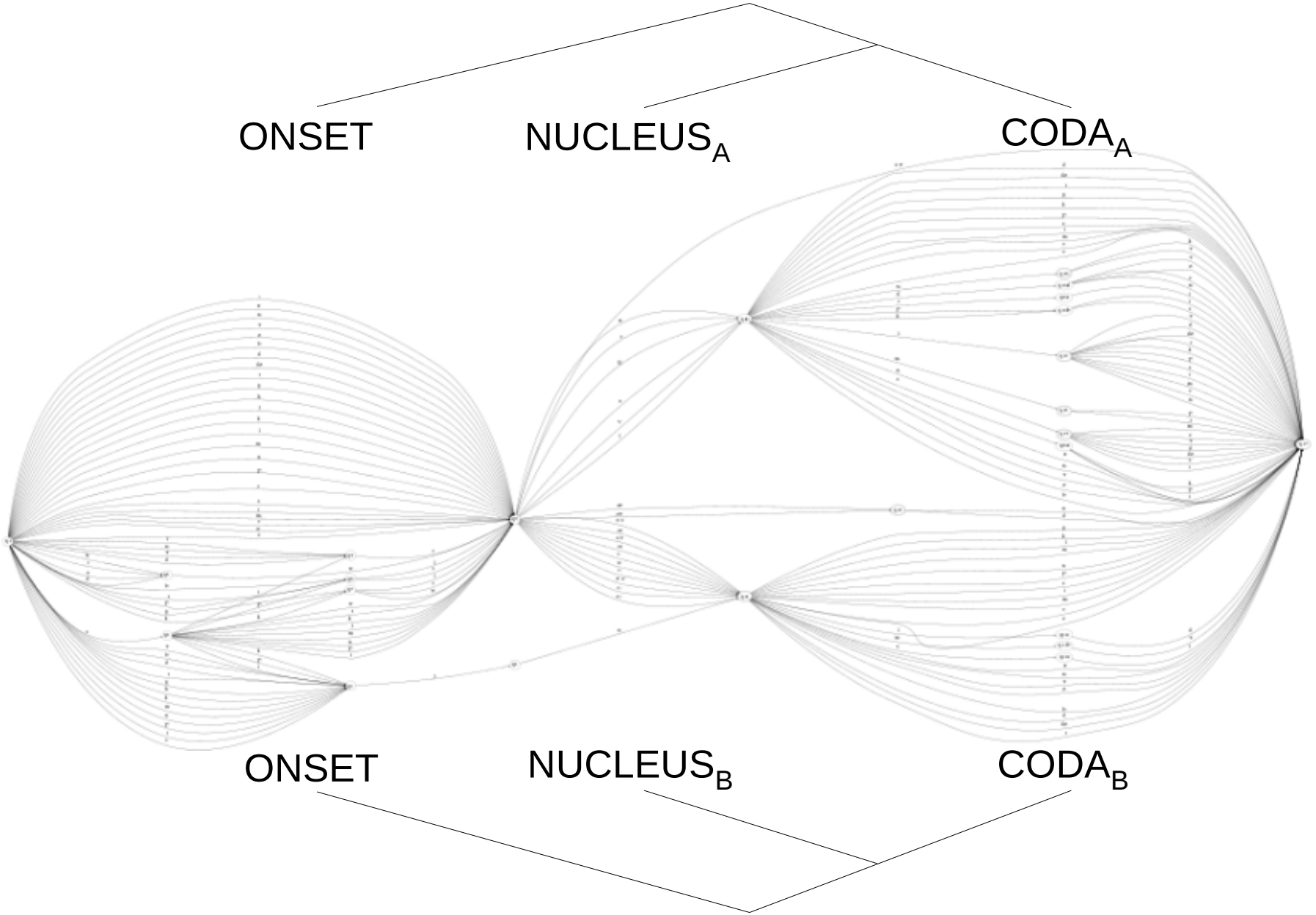
To show the full formula for this law or pattern—a so-called "morpho-phonemic structural formula"—I should need a large piece of paper. I can however set up a condensed form of it as:

$$\begin{aligned} &O,\ C - ng,\ C_1C_2,\ C_3C_4, \text{ etc. } . . . \\ &s\pm C_mC_n + V + (V_1)\ O, \pm (r, w, y); \\ &\quad C - h,\ C'_1C'_2,\ C'_3C'_4, \text{ etc. } . . . \\ &\quad C'_mC'_n \pm (t/d,\ s/z,\ st/zd).^3 \end{aligned}$$



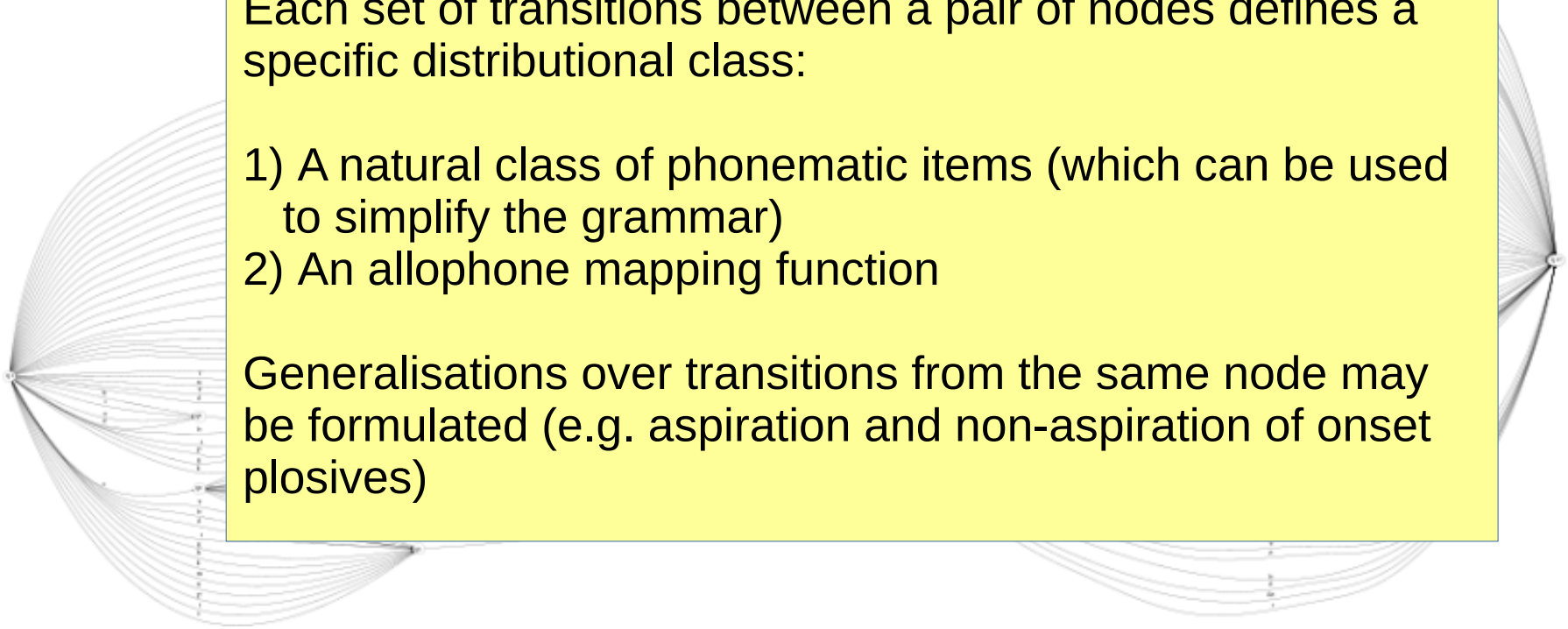
Carroll, John B. (ed.) (1956). Language, Thought, and Reality: Selected Writings of Benjamin Lee Whorf. Cambridge, Mass.: MIT Press, p. 284.

Linear Syllable Grammar (English)



English Monosyllabic Words

Linear Syllable Grammar (English)



The grammar defines all monosyllabic words in English

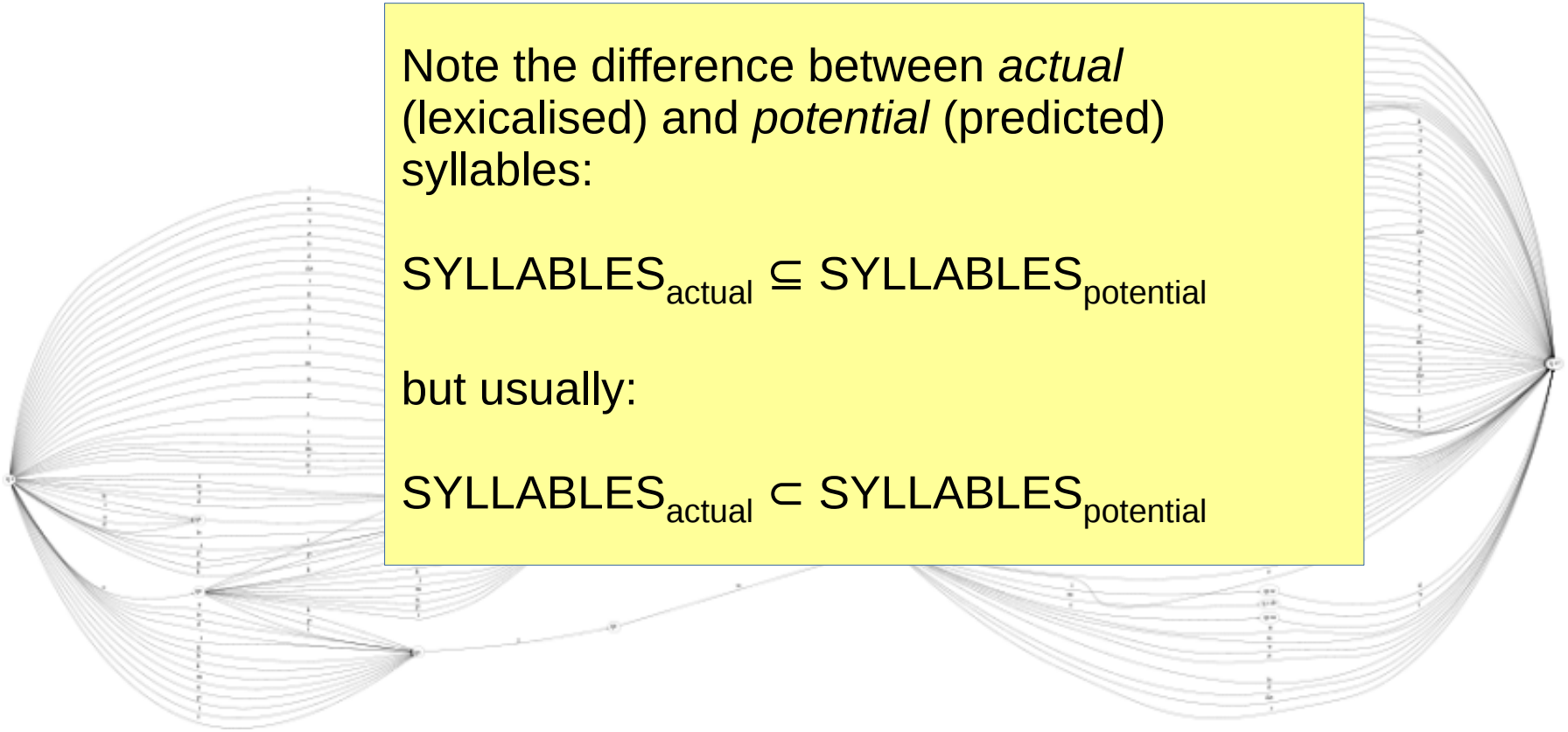
Each set of transitions between a pair of nodes defines a specific distributional class:

1) A natural class of phonematic items (which can be used to simplify the grammar)
2) An allophone mapping function

Generalisations over transitions from the same node may be formulated (e.g. aspiration and non-aspiration of onset plosives)

English Monosyllabic Words

Linear Syllable Grammar (English)



Note the difference between *actual* (lexicalised) and *potential* (predicted) syllables:

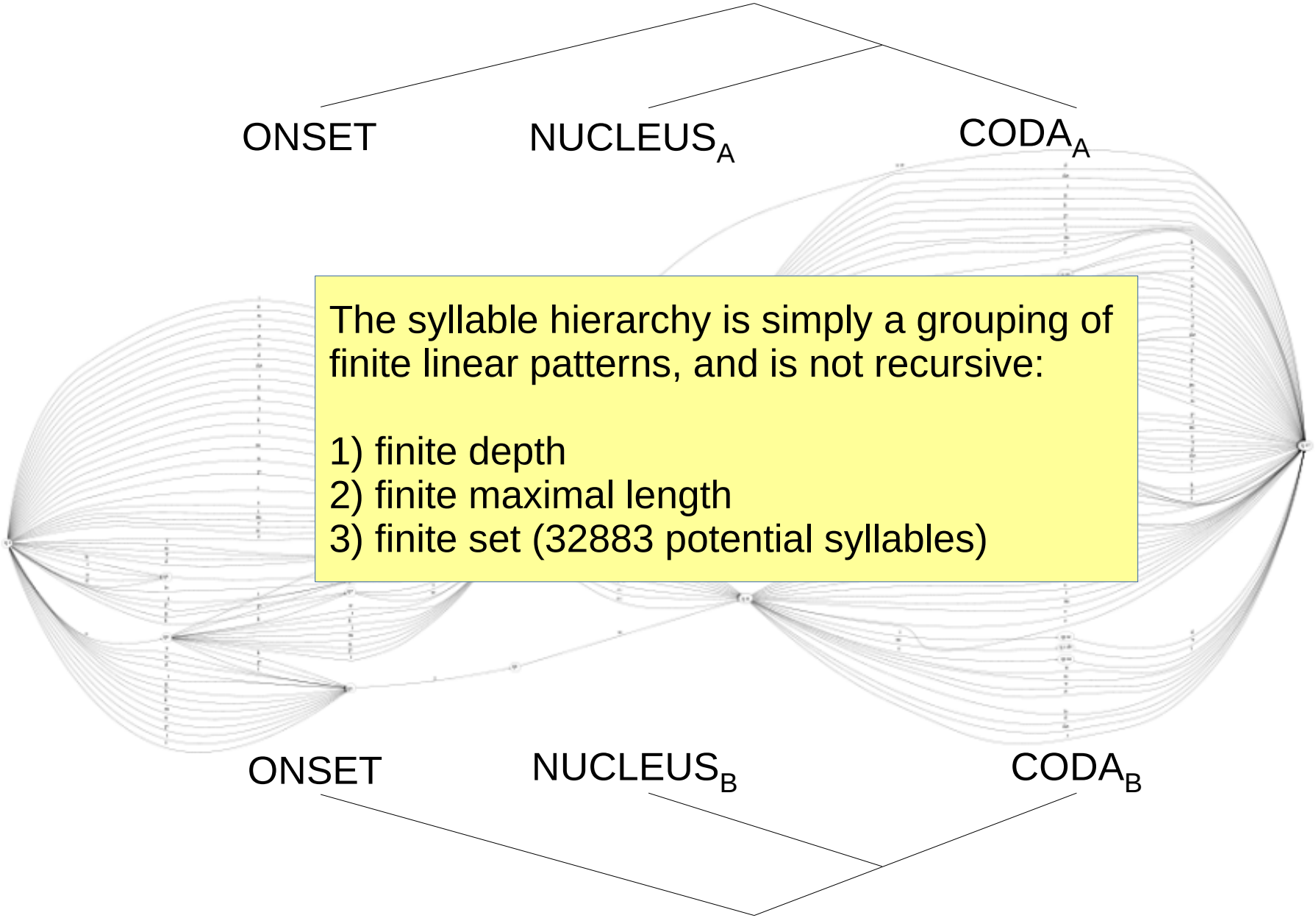
$SYLLABLES_{actual} \subseteq SYLLABLES_{potential}$

but usually:

$SYLLABLES_{actual} \subset SYLLABLES_{potential}$

English Monosyllabic Words

Linear Syllable Grammar (English)



The syllable hierarchy is simply a grouping of finite linear patterns, and is not recursive:

1) finite depth
2) finite maximal length
3) finite set (32883 potential syllables)

English Monosyllabic Words

Linear Phrasal Grammar of Mandarin Syllable Phonotactics:

A Computational Perspective

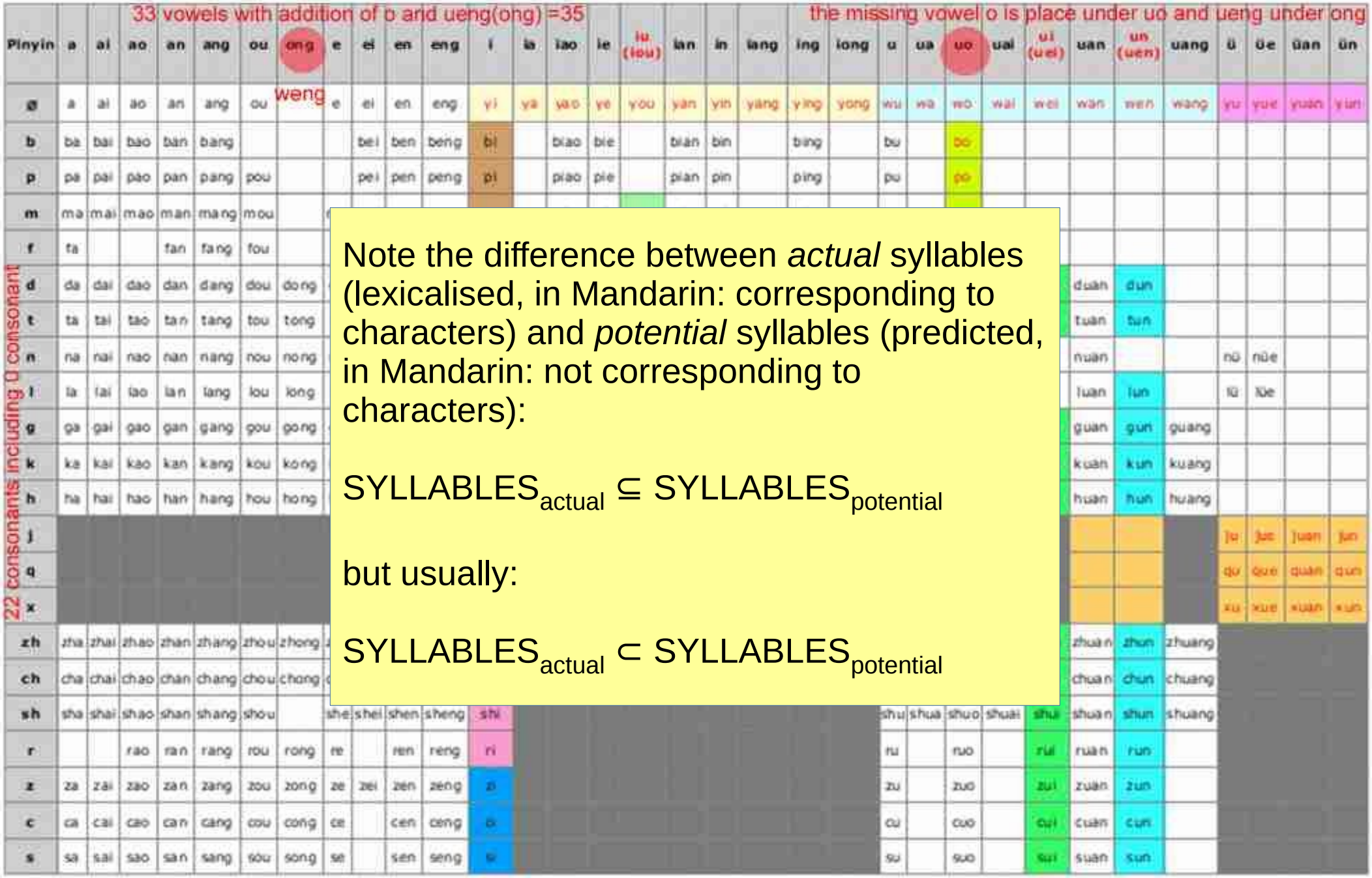
Diphone Linear Syllable Grammar (Mandarin)

33 vowels with addition of o and ueng(ong) =35 — the missing vowel o is place under uo and ueng under ong

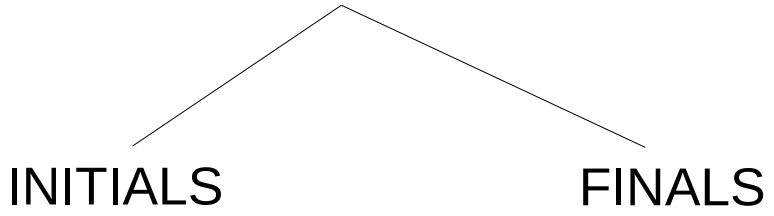
Pinyin	a	ai	ao	an	ang	ou	ong	e	ei	en	eng	i	ia	iao	ie	iu (iou)	ian	in	iang	ing	iong	u	ua	uo	uai	ui (uei)	uan	un (uen)	uang	ü	üe	üan	ün
ø	a	ai	ao	an	ang	ou	weng	e	ei	en	eng	yi	ya	yao	ye	you	yan	yin	yang	ying	yong	wu	wa	wo	wai	wei	wan	wen	wang	yu	yue	yuan	yin
b	ba	bai	bao	ban	bang				bei	ben	beng	bi		biao	bie		bian	bin		bing		bu		bo									
p	pa	pai	pao	pan	pang	pou			pei	pen	peng	pi		piao	pie		pian	pin		ping		pu		po									
m	ma	mai	mao	man	mang	mou		me	mei	men	meng	mi		miao	mie	miu	mian	min		ming		mu		mo									
f	fa			fan	fang	fou			fei	fen	feng											fu		fo									
d	da	dai	dao	dan	dang	dou	dong	de	dei		deng	di		diao	die	diu	dian			ding		du		duo		dui	duan	dun					
t	ta	tai	tao	tan	tang	tou	tong	te			teng	ti		tiao	tie		tian			ting		tu		tuo		tui	tuan	tun					
n	na	nai	nao	nan	nang	nou	nong	ne	nei	nen	neng	ni		niao	nie	niu	nian	nin	niang	ning		nu		nuo			nuan			nü	nüe		
l	la	lai	lao	lan	lang	lou	long	le	lei		leng	li	lia	liao	lie	liu	lian	lin	liang	ling		lu		luo			luan	lun		lü	lüe		
g	ga	gai	gao	gan	gang	gou	gong	ge	gei	gen	geng											gu	gua	guo	guai	gui	guan	gun	guang				
k	ka	kai	kao	kan	kang	kou	kong	ke	kei	ken	keng											ku	kua	kuo	kuai	kui	kuan	kun	kuang				
h	ha	hai	hao	han	hang	hou	hong	he	hei	hen	heng											hu	hua	huo	huai	hui	huan	hun	huang				
j												ji	jia	jiao	jie	jiu	jian	jin	jiang	jing	jiong									ju	jue	juan	jun
q												qi	qia	qiao	qie	qiu	qian	qin	qiang	qing	qiong									qu	que	quan	qun
x												xi	xia	xiao	xie	xiu	xian	xin	xiang	xing	xiong									xu	xue	xuan	xun
zh	zha	zhai	zhao	zhan	zhang	zhou	zhong	zhe	zhei	zhen	zheng	zhi										zhu	zhua	zhuo	zhuai	zhui	zhuan	zhun	zhuang				
ch	cha	chai	chao	chan	chang	chou	chong	che		chen	cheng	chi										chu	chua	chuo	chuai	chui	chuan	chun	chuang				
sh	sha	shai	shao	shan	shang	shou		she	shei	shen	sheng	shi										shu	shua	shuo	shuai	shui	shuan	shun	shuang				
r			rao	ran	rang	rou	rong	re		ren	reng	ri										ru		ruo		rui	ruan	run					
z	za	zai	zao	zan	zang	zou	zong	ze	zei	zen	zeng	zi										zu		zuo		zui	zuan	zun					
c	ca	cai	cao	can	cang	cou	cong	ce		cen	ceng	ci										cu		cuo		cui	cuan	cun					
s	sa	sai	sao	san	sang	sou	song	se		sen	seng	si										su		suo		sui	suan	sun					

22 consonants including 0 consonant

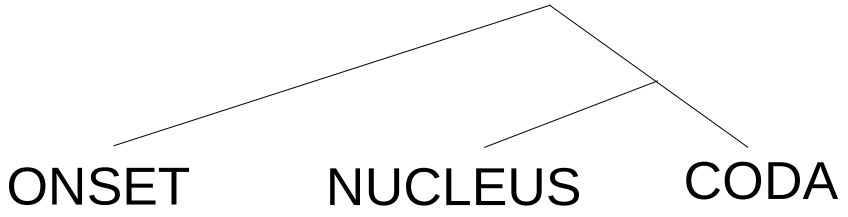
Diphone Linear Syllable Grammar (Mandarin)



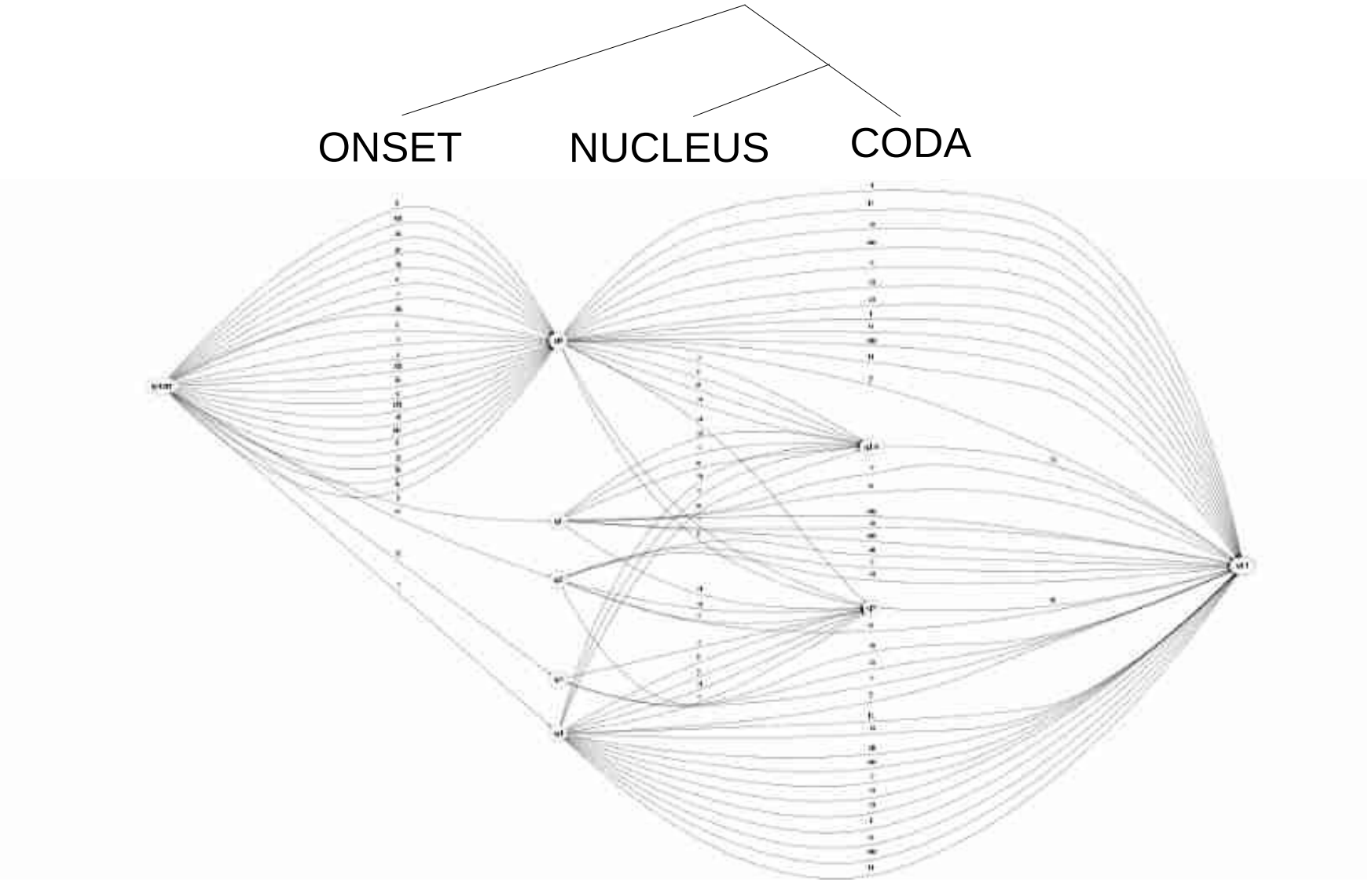
Linear Syllable Grammar (Mandarin)



Linear Syllable Grammar (Mandarin)

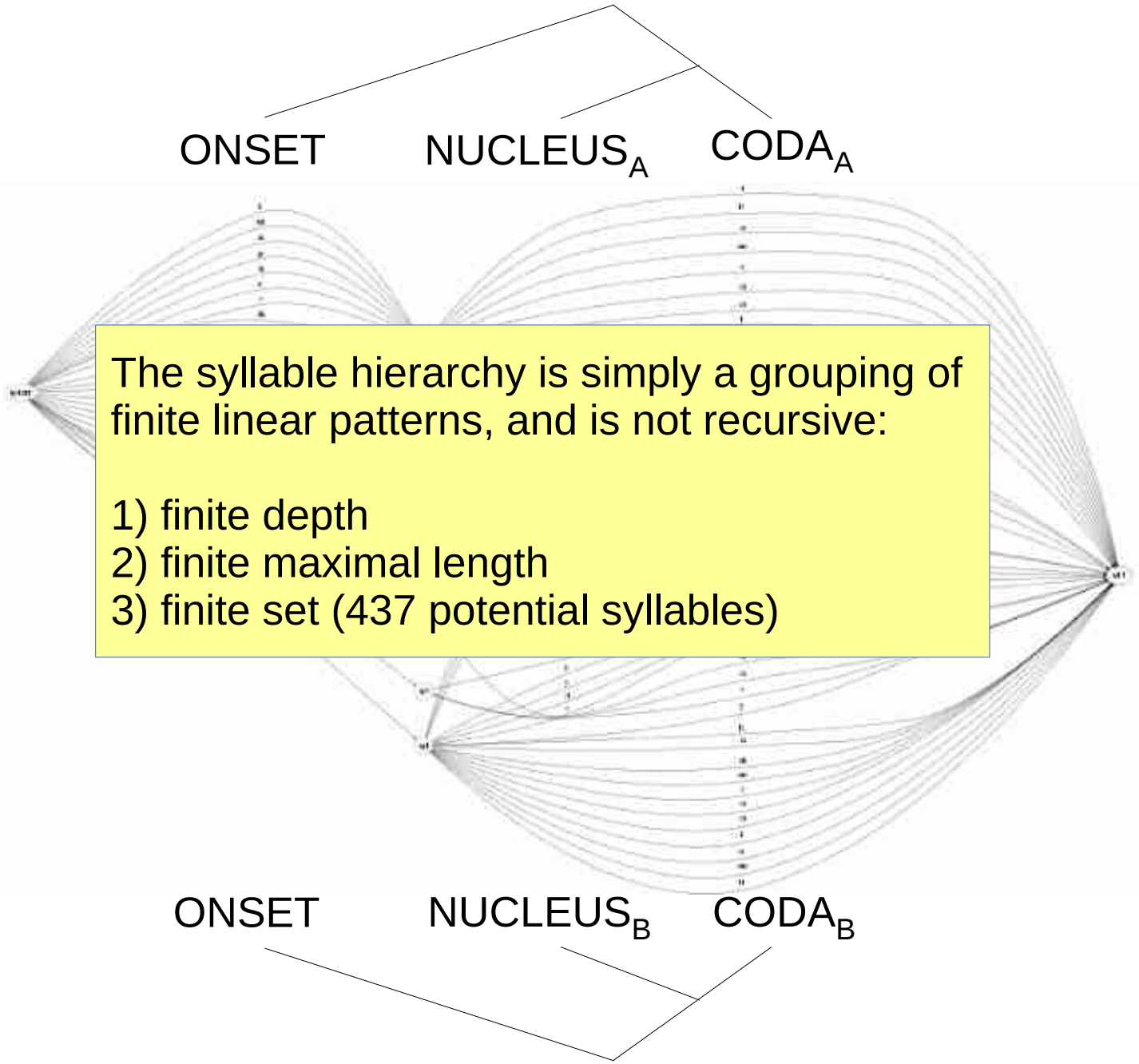


Linear Syllable Grammar (Mandarin)



Linear Syllable Grammar for Mandarin

Linear Syllable Grammar (Mandarin)



The syllable hierarchy is simply a grouping of finite linear patterns, and is not recursive:

1) finite depth
2) finite maximal length
3) finite set (437 potential syllables)

Linear Syllable Grammar for Mandarin

Looking Ahead: from Deduction to Induction

Next lecture: Time and Rhythm

Phonetic mode (signal analysis):
- Domains:
  - time functions (articulatory, acoustic, auditory)
- Analysis:
  - time domain
  - frequency domain (spectrum)

Tonal tokenisation (e.g. Tobi):
BoundaryTone PitchAccentTone PitchAccentTone* BoundaryTone
Boundary tone: { **H%**, **%L%** }
PitchAccentTone: { **H***, **L***, **L*H**, **LH***, **H*L**, **HL***, **H*H** }

Contour parsing (Tonetics):
prehead head body nucleus tail

Categorial interpretation (prosodic phonologies):
- Configurative: Initial/final boundary; ip, IP boundary
- Contrastive: accents
- Culminative: accent placement

Summary:

Aspects of Prosody and Time

The architecture of language:
Ranks
Interpretations

The Phonology of Prosody:
A Computational Perspective

Summary:

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Next lecture:

Time and Rhythm

Conclusion:

… thinking outside the box

Thank you!

谢谢！