Another Possibility of Computationally Implemented Theory of Phonology[*]

Yukio Takahashi, Morioka College
t-yukio@morioka-u.ac.jp

1 Introduction

The present paper submits an alternative to Optimality Theory (Prince and Smolensky (1993), Kager (1999)) that assumes the level of “systematic phonemes” in the sense of Halle (1964), Chomsky (1964) and Chomsky and Halle (1968) and it tries to make several steps in our struggle to move from “hand-written” to computationally implemented theories of phonology. The major milestone toward which we are traveling is verbalized as follows:

(1) The theoretical model of language based upon the ideas of Parallel Distributed Processing internalizes hierarchically organized phonological computational gadgets that give more than one articulatory strategy. The outputs of the phonology are states of equilibria among those articulatory strategies.

This paper describes the process in which this possibility is couched in a computationally implemented theory of phonology. Section 2 defines the key concepts of the theory and portrays an experimental scheme for computational implementation of phonological theory. Section 3 summarizes the points and tries to identify the status that we attain in the realm of the study of language.

2 Key Concepts of a Computationally Implemented Theory of Phonology and an Experimental Scheme for Computational Implementation of Phonological Theory

The crucial concepts in this paper are (i) parallelly distributed computational gadgets (henceforth, PDP), (ii) hierarchical organization of those gadgets (henceforth, SOC), and (iii) equilibria among articulatory strategies (henceforth, NE).[1] Those concepts interact with each other to form a new paradigm of linguistic theory, whose central cores are described as follows:

(2) Basic Concepts of PDP, SOC and NE
a. … intelligence emerges from the interactions of large numbers of agents (Cf. McClelland, Rumelhart and the PDP Research Group (1986:ix))
b. … any brain, machine, or other thing that has a mind must be composed of smaller agents that cannot think at all (Cf. Minsky (1988:323)
c. … decisions have to be made with respect to the decisions of other agents (Cf. Benz, Jäger and van Rooij (2006:8))

Under my scheme of computational implementation of phonological theory, the term *agents* refers to phonological processing units, which are (i) parallelly distributed, (ii) hierarchically organized, and (iii) optimized for equilibria among articulatory gestures.

Takahashi (2005) submitted a thesis on the theory of phonology as follows:

(3) Thesis of Equilibrium in Phonology
As the articulatory organs function, sub-modules within the phonology of speech form what we call phonological space. These phonological spaces are termed *Nash Equilibria*. The notion of *equilibrium* assumes the operation of more than one autonomous computational system, and this leads us to adopt the theorems of *Parallel Distributed Processing*. The autonomous phonological sub-modules can appropriately be termed non-terminal nodes in the feature-geometric representation.

---

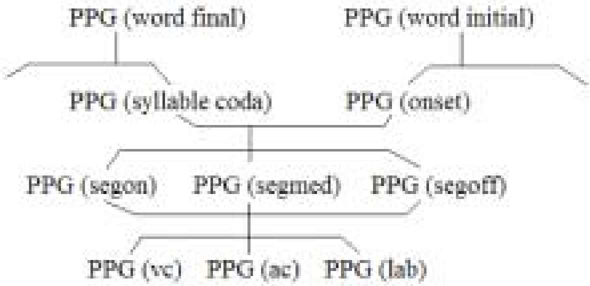
[*] The present paper is a revised version of a paper that was read at the occasion of the Thirteenth Open Seminar by The Research Center for Comparative Culture, held on December 23rd 2005, at Morioka College Library. It is supported in part by The Grant in Aid for Scientific Research by Morioka College for the year 2005. I would like to thank Shigeru Satoh for his encouragement. Thanks also go to Susan Unher for suggesting stylistic improvements. I would like to thank Ryoma Takahashi for his comments in my linguistics class at Morioka College. Remaining errors are all mine.

[1] PDP stands for “Parallel Distributed Processing,” SOC for “Society of Mind” and NE is an acronym of “Nash Equilibrium.” I would like to cordially thank those scientific giants and their academic accomplishments: David Rumelhart and James L. McClelland for PDP and Marvin Minsky for SOC, and John von Neumann, Oskar Morgenstern, and John Nash for NE.

The present section formalizes the autonomous phonological sub-modules that are identified as non-terminal nodes in feature geometry (cf. Sagey (1986)): e.g., Coronal, Labial, Dorsal, Laryngeal, Soft.

Let us take an example of place assimilation in English: *ten minutes*, where the /n/ is assimilated to a bilabial nasal [m]. The relevant non-terminal nodes are Coronal and Labial. Crucially we assume that the coronal place articulations are unmarked while labial place articulations are marked. The society of relevant Phonological Processing Gadgets (henceforth, PPGs) is organized as follows:[2]

(4) Networking of PPGs



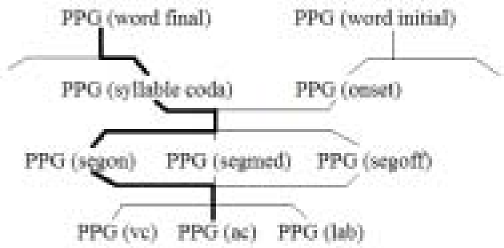
I omit reference to PPGs that are composed of, or directly and indirectly linked to, PPG (word final) and (word initial): PPG (word), PPG (clitic), PPG (phrase), PPG (intonational phrase) and PPG (utterance).[3]

The network in (4) includes temporal and atemporal linkages among PPGs. The PPGs in the lowest level can be free from linear ordering, while those in the next lowest level are intrinsically ordered. PPG (vc) may be active prior to PPG (ac), and *vice versa*, while PPG (segmed) cannot be operative prior to PPG (segon). The difference in linearity implies the difference in mutual complmentariness; PPG (segmed) cannot occupy the position where PPG (segon) is, while any of the three PPGs (vc), (ac) and (lab) can be linked with PPG (segon). In short, the PPGs at the lowest level can be either mutually conjunctive or disjunctive, while the PPGs at the next lowest level are mutually disjunctive. The mutual conjunctive and disjunctive relationships among PPGs can be captured by stipulations on the levels of threshold response and spike of the PPGs.

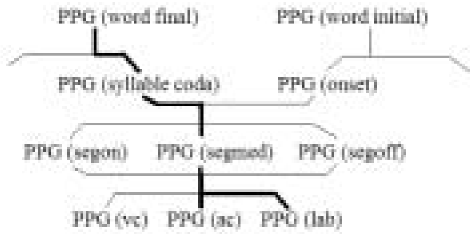
Thus, in the real time processing of *te*[n͡m] *minutes*, we have four sequential stages:

(5) Partial Assimilation in *te*[n͡m] [m]*inutes*

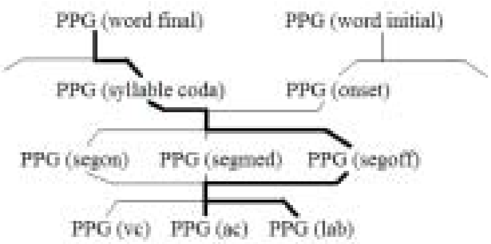
a.



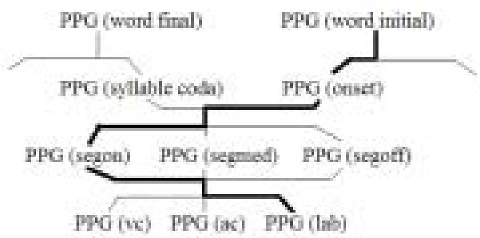
b.



c.



d.



[2] Cf. Pinker (1994). In what follows, segon stands for "segmental onset," segmed for "segmental medial," segoff for "segmental offset," vc for "velic closure, ac for "alveolar closure," lab for "labial closure."

[3] I adopt the general framework of Prosodic Phonology developed by Nespor and Vogel (1986) and Hayes (1989).

The bold lines indicate the activated linkages among PPGs.

It is remarkable that PPGs (non-terminal PPGs) other than the lowest three PPGs (terminal PPGs) function to switch the channels in which the linkages, or the electronic currents, among PPGs are active. Crucially, the non-terminal PPGs have to be operative in sync. Thus, the rather artificial, non-assimilated pronunciation of the word-final /n/ in *ten minutes* would be described as a strict synchronization of the activation of PPG (ac) with those of PPG (segoff) and PPG (syllable coda). However, we do not have to scrutinize the stages of the real time processing of the non-assimilated pronunciation.

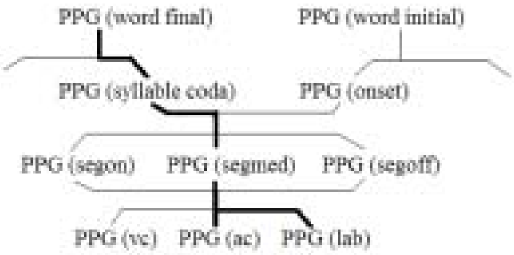
The effective operation applied by the whole network to achieve this result (te[n] [m]inutes) would be to make the activation of PPG (lab) delayed so that the system may avoid the dual linkage on PPG (segmed) and PPG (segoff) as diagrammed in (5) b and c. As Jun (2004:63) observes rightly, the velocity of what we call terminal PPGs is not uniform:

(6) Typically, the underlying gesture with which coronals are realised is articulated more rapidly. That is, tongue tip gestures are rapid and thus have rapid transition cues; whereas tongue dorsum and lip gestures are more sluggish and thus give rise to long transitions.

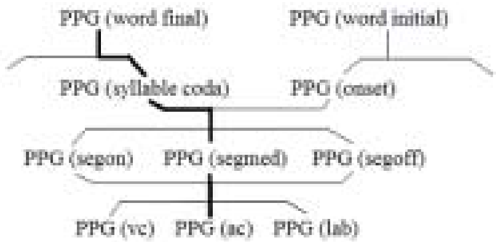
Thus, by default, the rate of activity of PPG (lab) is higher than that of PPG (ac), which implies that PPG (ac) and PPG (lab) are doubly linked onto the non-terminal PPG (segmed) and PPG (segoff). Therefore the non-assimilated /n/ in *ten minutes* lowers the naturalness of the pronunciation.

Let us examine the payoff relations that hold for *te*[n͡m] *minutes* and *te*[n] *minutes*, assuming (i) that PPG (ac) are OFF by default and (ii) that PPG (lab) and PPG (vc) always ON and are parasitic on neighboring segments. Payoff matrices are described as for evaluation of the neural activity networking in (5b) and (7):[4]

(5b) [n͡mm]



(7) [nm]



Payoff matrices for (5b) and (7) are described as follows:

(8) Sub-matrix for PPG (segmed), PPG (ac) and PPG (lab) [n͡mm]

	PPG (ac) **ON**	PPG (ac) **OFF**	PPG (ac) **ON** PPG (lab) **ON**	PPG (ac) **OFF** PPG (lab) **OFF**
PPG (lab) **ON**	(1, –1)	(1, Ø)	(1, –1, 1) ¶	(1, Ø, –1)
PPG (lab) **OFF**	(–1, –1)	(–1, Ø)	(–1, –1, 1)	(–1, Ø, –1)

(9) Sub-matrix for PPG (lab) and PPG (ac) [nm]

	PPG (ac) **ON**	PPG (ac) **OFF**
PPG (lab) **ON**	(1, –1) ¶	(1, Ø)
PPG (lab) **OFF**	(–1, –1)	(–1, Ø)

Note that the combination of PPG activations in (9) is NOT identical with the state in which a phonological equilibrium is achieved. It is remarkable that the totally assimilated instantiation of /n/ in *ten minutes* is highly evaluated at the state of equilibrium:[5]

[4] Cf. Archangeli (1984)

[5] Our argument is applicable to the phenomena of coarticulation, as discussed in Farnetani (1990), Kühnert and Nolan (1999) and Fletcher and Harrington (1999): /ibi/ *vs.* /aba/ and [k̟iː] *vs.* [k̠^{w}ɔː].

(10) Sub-matrix for PPG (lab) and PPG (ac) [m͡mm]

	PPG (ac) **ON** PPG (lab) **ON**	PPG (ac) **OFF** PPG (lab) **OFF**	PPG (ac) **OFF** PPG (lab) **ON**
PPG (lab) **ON**	(1, –1, 1)	(1, Ø, –1)	(1, Ø, 1) ¶
PPG (lab) **OFF**	(–1, –1, 1)	(–1, Ø, –1)	(–1, Ø, 1)

Our assumptions on the neural network captures the naturalness of the total assimilation in the sequence *te*[m] *minutes*.

3 Concluding Remarks

We have tried to re-construct the principles of the derivational aspects of the theory of phonology, resorting to the theory of decision making (Game Theory) and the theory of cognitive structure of the brain (PDP Connectionist Theory). We assumed what we may call "the society of phonological mind" after Minsky (1988), which internalizes a hierarchically organized system of phonological processing gadgets. The possible instances of the electronic channel among the gadgets as drawn in (5b) and (7) are evaluated with reference to the payoff matrices, in which at least one instance of the electronic channel forms what we may call "equilibrium in phonological space," after Nash Equilibrium by John Nash.

The present paper has submitted an alternative to Optimality Theory: OT resorts to the idea that a set of ranked, violable constraints evaluates a virtually infinite number of outputs from GEN to select an optimal candidate, and OT argues that it successfully discarded the traditional notion of ordered applications of grammatical rules. The framework of phonology laid out in this paper assumes a network of phonological processing gadgets, whose operations are stipulated individually. In our framework the number of the outputs from phonology is in principle specifiable: the whole set of the possible outputs CAN be evaluated, and the whole theoretical system is verifiable. The advantage over OT is that it can be computationally implemented. The possibility of computational implementation is guaranteed by the stipulation to the effect that the phonological processing gadgets (PPGs) can only be either ON or OFF.

References

Archangeli, Diana (1984) *Underspecification in Yawelmani Phonology and Morphology*, Doctoral Dissertation, MIT.

Benz, Anton, Gerhard Jäger and Robert van Rooij (2006) "An Introduction to Game Theory for Linguistics," *Game Theory and Pragmatics*, Palgrave, Macmillan, Hampshire.

Chomsky, Noam (1964) "Current Issues in Linguistic Theory," J.A. Fodor and J.J. Katz (eds.) *The Structure of Language: Readings in the philosophy of language*, Prentice-Hall, New Jersey, 50-118.

Chomsky, Noam and Morris Halle (1968) *The Sound Pattern of English*, Harper & Row, New York.

Farnetani, Edda (1990) "V-C-V Lingual Coarticulation and its Spatiotemporal Domain," W.J. Hardcastle and A. Marchal (eds.) *Speech Production and Speech Modelling*, Kluwer Academic Publishers, Dordrecht.

Fletcher, Janet and Jonathan Harrington (1999) "Lip and Jaw Coarticulation," W.J. Hardcastle and N. Hewlett (eds.) *Coarticulation: Theory, data and techniques*, Cambridge University Press, Cambridge, 164-1175.

Halle, Morris (1964) "Phonology in Generative Grammar," J.A. Fodor and J.J. Katz (eds.) *The Structure of Language: Readings in the philosophy of language*, Prentice-Hall, New Jersey, 334-354.

Hayes, Bruce (1989) "The Prosodic Hierarchy in Meter," *Phonetics and Phonology I: Rhythm and Meter*, 201-260.

Jun, Jongho (2004) "Place Assimilation," B. Hayes, R. Kirchner and D. Steriade (eds.) *Phonetically Based Phonology*, Cambridge University Press, Cambridge, 58-86.

Kager, René (1999) *Optimality Theory*, Cambridge University Press, Cambridge.

Kühnert, Barbara and Francis Nolan (1999) "The Origin of Coarticulation," W.J. Hardcastle and N. Hewlett (eds.) *Coarticulation: Theory, data and techniques*, Cambridge University Press, Cambridge, 7-30.

McClelland, James, David E. Rumelhart and the PDP Research Group (1986) *Parallel Distributed Processing: Explorations in the microstructure of cognition*, Vol. 1: Foundations, MIT Press, Cambridge, Massachusetts.

Minsky, Marvin (1988) *The Society of Mind*, Touchstone Book, Published by Simon & Shuster, New York.

Nespor, Marina and Irene Vogel (1986) *Prosodic Phonology*, Foris, Dordrecht, Holland.

Pinker, Steven (1994) *The Language Instinct*, William Morrow and Company, New York.

Prince, Alan and Paul Smolensky (1993) *Optimality Theory: Constraint Interaction in Generative Grammar*, MS, Rutgers University and University of Colorado, Boulder.

Sagey, Elizabeth (1986) *The Representation of Features and Relations in Non-Linear Phonology*, Doctoral Dissertation, MIT.

Takahashi, Yukio (2006) "On the Nash Equilibrium in Phonological Space," *The Journal of Morioka College*.