

Using Networks in a Harmonic Phonology

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0. Introduction

The general goal of a theory of phonology is the development of an explicit device which can take phonological strings as its input and produce as its output a phonological grammar of some sort.¹ We will expect of this phonological grammar that it should explicitly characterize the language in question so that it will, for example, admit well-formed strings of segments and syllables, while ill-formed strings and syllables will not be admitted.² We may furthermore expect of such a device that it will explicitly determine which parts of the phonological representations are redundant and which are distinctive. The difficulty of the task lies not simply in producing an accurate phonological grammar, but in designing a device which will *itself* offer up the phonological grammar when presented with data from the language.

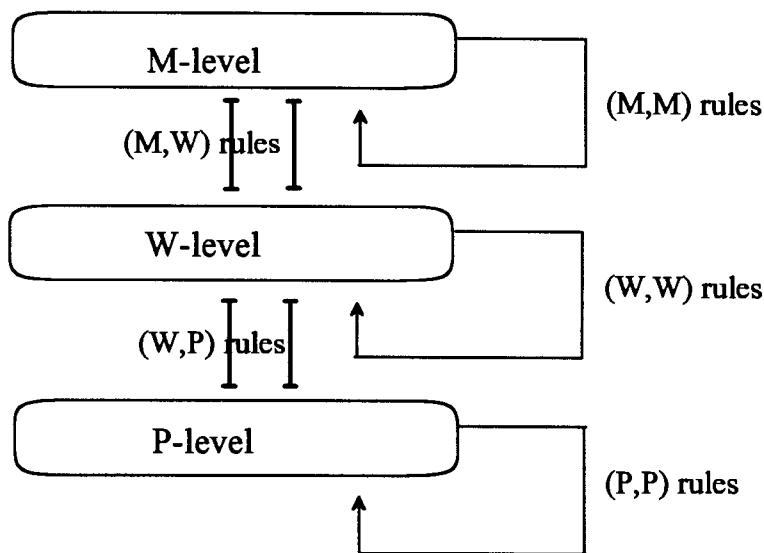
A natural hypothesis to entertain is that our language acquisition abilities are heavily indebted to our abilities to extract generalizations, which is to say, to determine patterns in data. If phonological life were extremely simple, we might then find that certain patterns — the phonotactics of the language — could be extracted from the surface data, and that the underlying forms that we assigned to particular words and morphemes, specifying only the contrastive phonological information in question, differed in trivial ways from the surface forms; the most trivial way in which the two might differ would be that contextual information would be superimposed on the underlying phonological information on the basis of the surface phonotactics. Life would indeed be simple for the phonologist if that were the case.³ But this does not appear in fact to be correct, and the kinds of phenomena that have motivated extrinsic rule ordering in the literature point to the reality of phonological generalizations drawn not from the surface data, but from representations that are already abstractions from the surface facts.

The present paper is a report on some efforts of ours to develop a computationally explicit system in which the phonological generalizations which we seek are naturally and automatically derived by the theory on the basis of data with which it is presented. In the first part of the paper, we will describe some of the features of the level-oriented harmonic phonology that we understand to be setting the stage for our work more generally. In the second part, we describe the dynamic computational network that we have developed as a particular way of implementing generalizations in phonology concerning syllabification and accentuation. The third part of the paper explores in depth the task of syllabification in Icelandic, a much-discussed problem in the phonological literature, and in the final section we discuss the nature of the cycle in phonology, and draw some general conclusions regarding the direction of our research.

1. Organization of the Model

Several recent publications have explored a model of phonology whose organization contains three phonological levels (M-level, W-level, P-level), as in (1).⁴

(1)



An important part of this proposal is the suggestion that there exist language-specific measures of well-formedness for each of these three levels, and a set of intralevel rules on each level governed by *harmonic application*, that is, by the principle that these rules apply if and only if their output is better formed than their input, according to the well-formedness measure of their level. Each level thus consists of a small factory of efforts made by the set of intralevel rules pertaining to that level, and both the function and the effect of those intralevel rules can quite definitely be said to be to improve the well-formedness of the representation on that level. Relations between representations on distinct levels are established by a set of cross-level or interface rules, rules which are specific examples of what Sadock calls interface rules, in his (1991) autolexical conception of grammar.

Both rules and measures of well-formedness are necessary, it would seem. If we have only measures of well-formedness, and no rules, then we have no idea what changes are permissible in order to improve the well-formedness of a particular representation. If we have only rules and no measures of well-formedness, then we are rather obviously back where we started.

The proposal that a rule should apply if and only if it improves the well-formedness of a representation is an attractive one, in light of the proposals by a number of linguists over the past twenty years pointing in this direction. The conspiracies that Kisseberth (1970) noted in Tonkawa illustrate this, where we see, for example, a rule of vowel deletion which fails to apply because its output would create a violation of the simple syllable structure of the language. Many phonological accounts in the 1980s appeal to general well-formedness conditions, ranging from Itô's (1986) work on syllabification to Hayes' (1986) analysis of Toba Batak. Proposals by Singh (1987), by Paradis (1988), and by Yip (1988), to cite just three, have spoken directly to the importance of linking well-formedness to rule application; Gussmann, in an issue of *Linguistic Inquiry* current as we write this, speaks in an idiom that is redolent with these concepts, when he writes, for example: "both licensing and syllabification are conditions on well-formed structures: whenever changes undermine the well-

formedness of syllables, adjustments are made to restore compliance with the regular pattern." (1992, 51). At another point he writes, "resyllabification is a process that incorporates as many of the unsyllabified consonants as possible into existing structures while observing the well-formedness constraints" (1992, 41). Any reader of contemporary phonology cannot help but be struck by the fact that the theoretical concepts that are at center stage today are precisely such notions as well-formedness and optimization subject to further conditions; it should hardly need to be said that we stand very much in need of an explicit theory that is based on these notions. That is what we are attempting to do with the framework of harmonic phonology.

What it seems to us that we want, fundamentally, is an intelligent way of speaking about the generalizations that emerge on a single level of representation: intelligent, in the sense that we should not rule out the complexities of natural language, and intelligent, in the sense that it helps us come to understand how language comes to grips with conflicts that may arise across subgeneralizations. Traditional rule formulations deal with conflict by ordering; in more recent years, trickier and more sophisticated, ways have been employed that block a later rule from applying because of the effect of an earlier rule. The conflicts that we refer to can come about in various ways; a typical example is the following. Suppose a language stresses all the odd-numbered syllables, avoids stress on consecutive syllables, and also places stress on the fourth syllable of a particular word because it contains a long vowel; the question must arise, will the third syllable be stressed or not? Suppose furthermore that in this case the answer is no. Traditional rule formulations deal with this situation in one of two ways. The third syllable may be stressed at some intermediate level of representation, only to lose that stress due to a later rule; or the stress rule that might place stress on the third syllable may, in more recent theoretical accounts, be endowed with just enough foresight to look ahead and see that its effect would create that widely despised situation, a clash of stresses, and seeing that result ahead of it, fail to apply. But even in this latter case, some part of the algorithm provides the computational device with a small chalkboard, so to speak, on which the stress leading to clash was tried out, found to be a clash-maker, and abandoned.

Much of our work comes down to developing a better way to deal with the conflict between competing generalizations, a better way than simply ordering them and thus forcing one or the other generalization to give way. David Marr, who worked on developing a computational theory of vision whose relationship to the neural wetware was to be much like what we linguists hope to find in our theories, made an interesting observation, one which he referred to as the *Principle of least commitment*:

This principle requires not doing something that may later have to be undone, and I believe that it applies to all situations in which performance is fluent. It states that algorithms that are constructed according to a hypothesize-and-test strategy should be avoided because there is probably a better method. My experience has been that if the principle of least commitment has to be disobeyed, one is either doing something wrong or something very difficult. (Marr 1982, 106)

Syllabification is something that the human brain seems to be extremely good at, something it finds easy, not difficult, and it is something it performs fluently. Marr's methodological maxim suggests that we find a better way of treating the conflict between phonological generalizations than by means of a device which first considers a possible formal move, and which can then undo that move if it notes that the move would create a conflict with information already present in the representation.

The goal, then, it seems to us, is to find a way to superimpose all the generalizations pertaining to a level at once, rather than sequentially, which is to say, to find a way to avoid positing a

modification to the representation which is then undone. Putting it this way suggests a mathematical treatment in which the generalizations are expressed as linear functions of one sort or another, because it is linear functions that we know can be suitably superimposed without any significant loss or change of meaning; but even nonlinear functions can be superimposed arithmetically to produce a function for whose value we can seek maxima and minima.

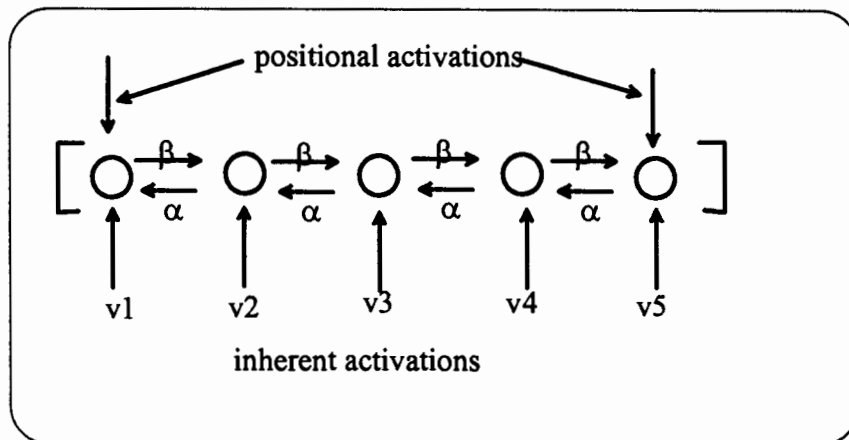
This brings us round, then, to the positive proposal which we have been exploring. We propose that all the relevant information in a phonological representation be embodied in a network, much in the style of neural network studies that have been explored over the last fifteen or twenty years. The generalizations which characterize a level of representation will be directly embodied in the connection weights among the units, while the activation values of the units express the information which we would otherwise note down on a piece of paper: such information as the value of a feature, or the formation of a syllable, or the formation of a stress foot. In terminology familiar to the linguist, we suggest that the architecture of connections corresponds to Universal Grammar, the innate composition of the device; the strength of the connections in the network corresponds to the language-particular grammar; and the activation level of units in a particular network corresponds to a representation of a particular utterance on that level. To be sure, as we try to make this notion precise, it requires considerable effort in some cases to come up with an acceptable translation of our linguistic notions into Network-Speak, and of course we want not just an *acceptable* translation of our fundamental phonological notions; we want to find that the process of translating to a neural network provides us with better analyses and deeper explanations.

In the final analysis, too, we want a system which can be implemented in real time. It seems realistic at this point to expect of our phonological theory not only to provide accurate models describing linguistic systems, but to do so in a fashion that can be implemented on the kind of neural hardware that our brains are made of. We may not succeed in that task immediately, but it seems to us highly appropriate to consider that to be part of the challenge that we undertake to meet.

2. *What does the network look like?*

Most of our work done in this area has focused on the phonological problems of stress assignment and syllabification. This dynamic computational model, as we call it, is defined by a small number of assumptions. It consists primarily of a linear sequence of units, as in (2), each endowed with an activation level at any given moment. Each of the units is also connected to its left and right hand neighbors, and each unit sends a certain proportion of its activation via these connections. This proportion, however, may be negative as well as positive; when it is negative, a unit with a high activation level will send a negative, inhibiting signal to its neighbors. This model is drawn in (2), and we can express this explicitly with the equation in (3), where the subscripts are used to indicate moments of computational time, in the sense that d^t is the activation of a unit at time t , whereas d^{t+1} is the activation of the unit at time $t+1$, i.e., the next computational moment.

(2) model of dynamic computational net



(3) $d_i^{t+1} = u_i + \alpha \cdot a_{i+1}^t + \beta \cdot a_{i-1}^t$ where u_i expresses
the *inherent activation* of unit i .

In the case of a system which is parsing individual segments into syllables, this inherent activation is the sum of two things: the inherent sonority of the segment in question, and for segments which lie near the edge of the word, a positional activation, defined in general for the two units closest to the left- and right-hand edges of the domain.⁵ Let us ignore the possibility of positional activation for the moment. When α and β are zero this model reduces simply to the now familiar sonority-oriented view of syllabification. On that old and traditional view, when a unit's activation is a peak (that is, it is greater than its neighbors' activations), it is realized as a syllable nucleus (in fact, that is what we mean by calling it a syllable nucleus), and almost all languages put strong conditions on what segment can appear in a peak position. Typically consonants may not be in a peak position, and in very few languages can any obstruents appear there. This constraint serves as a boundary condition on what kinds of sonority can be found, and the consequences are not always immediately obvious. We will explore some of these consequences in this paper. It is worth pointing out that while the immediate constituent view of syllabification was seen as a post-Bloomfieldian alternative, not a supplement, to the more traditional sonority-based view of the syllable, the two approaches have been casually mixed in most work over the past fifteen years. Currently we see in the phonological literature a universal commitment to the IC view of syllabification, despite a widespread acknowledgement that a Sonority Sequencing Principle is necessary for building up onset and coda sequences correctly.⁶ Our network models offer strong support for the view that computations of sonority are not only necessary for understanding the proper relation of successive segments in a phonological representation, they are sufficient, and we do not need to develop phonological constituents in the syntactic sense.⁷

3. Syllabification: Thresholds for peaks of derived activation

Let us consider first the case of languages whose syllabification is maximally simple. Looking across languages of the world, the most common and typical syllable structure, it appears, is the CV(C) (or possibly CVX) type, where only one consonant may appear in the onset, and no more than one consonant may appear in the coda of the syllable. In such systems, we naturally find no clusters of three consonants. On the currently familiar account of syllable structure, this is because such a cluster would have to force two of the consonants either into a coda or an onset, and neither is permitted. The dynamic computational model suggests an alternative point of view. In a language

where all consonants are treated equally, the sonority of the consonants will tend to be nearly equal, just as the sonority of the vowels will tend to be equal. For concreteness, let us assign 0.2 sonority to the consonants, and 0.8 to the vowels. But now we will drop the assumption that α and β are zero, and look at some of the consequences of the more general dynamic computational model. Let us consider some small negative assignment of values to α and β , such as -0.1.

In (4), we compare the derived activation of a V C C V pattern with that of a V C C C V pattern. In the former, neither of the Cs is a peak, while in the latter, the middle C is a peak of sonority, a result of the assumption of negative values of α and β . This results in a violation of the well-formedness condition by which a peak must have a sonority of approximately 0.6 (i.e., must be a vowel).

(4) a. V C C V $\alpha = -0.10; \beta = -0.10$

	V	C	C	V
inherent activation	0.8	0.2	0.2	0.8
derived activation	0.78	0.11	0.11	0.78

b. V C C C V $\alpha = -0.1; \beta = -0.1$

	V	C	C	C	V
inherent activation	> 0.8	0.2	0.2	0.2	0.8
derived activation	0.78	0.1	0.17	0.1	0.78

When we look at a sequence of two consonants word-finally from this point of view as in (5a), we see again that any choices of α and β that are not positive will result in the final consonant being a peak of sonority -- once again a violation of the requirement on what can appear in a peak position. However, we know that many languages do seem to relax their requirements on what may appear at their peripheries. In Arabic, for example, it has long been noted that a supernumerary consonant may appear word-finally (as noted in McCarthy 1979, Aoun 1979, Selkirk 1980, and any number of works by other linguists). In a dynamic computational model, this is the result of a position-specific activation, as noted in (5b): the word-final position has an additional negative activation, which ensures that the final consonant is not a peak, and is thus licit.

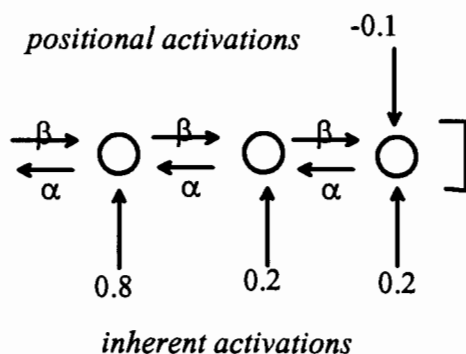
(5) $\alpha = -0.10$ $\beta = -0.10$

a. No Final Positional activation: violates peak condition, because the inherent activation of the final consonant is below threshold, even though it is a derived peak.

	V	C	C
inherent activation	0.8	0.2	0.2
derived activation	0.78	0.1	0.18

b. Final Positional Activation= -0.1

	V	C	C
inherent activation	0.8	0.2	$0.2 + (-0.1) = 0.1$
derived activation	0.78	0.11	0.08



Our hypothesis, then, is this: that with an appropriate assignment of α , β and sonority values for the segments in a language, the derived sonority values of a well-formed word will trace an envelope in such a fashion that all the peaks of this curve will coincide with the actually observed syllable nuclei. Linked to this is the hypothesis that ill-formed segment sequences will be ill-formed because they contain peaks of derived sonority for segments whose inherent sonority is beneath a language-specific threshold, a threshold that marks how sonorous a segment must be in order to serve as a syllabic nucleus. In the next section, we turn to a detailed treatment of a language much cited in the literature.

4.0 Icelandic

For the past twenty-five years, Icelandic has proven to be one of the most intransigent data sets for phonological theory. The complexities in the nominal and verbal paradigms have challenged phonologists during this period to find descriptively adequate and theoretically satisfying accounts of the phenomena. As a result, Icelandic has served as a crucial test case for nearly every theoretical innovation offered during these years. Stephen Anderson's dissertation (1969), for example, examined Icelandic within the developing paradigm of generative phonology (see also Orešnik 1972). Kiparsky (1984) argued that Icelandic demonstrates the superiority of the lexical phonology framework by calling out all of its theoretical arsenal to deal with the data. More recently, Itô (1986) has examined this data as a case study for prosodic phonology, again observing that all of the major resources of the theory are required for an adequate characterization of the data. Because of the complexity of the data, Icelandic serves as an important test case for computational theories as well (cf. Wheeler & Touretzky 1992).

We follow in the path blazed by our colleagues, and turn to Icelandic to support the dynamic computational model that we have developed.

4.1 Icelandic syllabification

In an observation that has been adopted by nearly all subsequent investigators, Venneman (1972) noted that vowel length in Icelandic is predictable from syllable structure (Orešnik 1972; Kiparsky 1984; Itô 1986, *contra* Orešnik and Pétursson 1977). Stressed vowels and diphthongs are

long in open syllables (6) and in closed monosyllables with a single final consonant (7) and short elsewhere (8).

(6) Long vowels in open syllables

hi: .ti	'heat' (data from Itô 1986)
o: .kur	'usury'
su: .pa	'to sip'
ho: .fuð	'head'
sko:	'shoe'
bu:	'homestead'

(7) Long vowels in monosyllables with single final consonant

ha:s	'hoarse'
ny:r	'new'
ski:p	'ship'

(8) Short vowels elsewhere

hit .ti	'(he) hit'
sup .tu	'sip!'
har .ður	'hard'
el .ska	'love'
hest	'horse'
björn	'bear'

4.2 Syllabification of intervocalic clusters (VCCV)

Clearly, the crucial step lies in developing a syllabification procedure that correctly parses intervocalic clusters. Icelandic differs from neighboring languages by parsing the majority of VCCV sequences as VC.CV, whether or not the consonants conform to the sonority profile of a legitimate onset, as we see in (9).

(9)	ep .li	'apple'
	es .ki	'ash'
	sig .la	'sail'
	haeg . ri	'right'
	af .laga	'out of order'
	vel .ja	'choose'
	tem .ja	'domesticate'

The preference for VC.CV syllables does not represent a universal syllable structure condition, however. Clusters formed from the union of the set $\{p, t, k, s\}$ and $\{r, v, j\}$ do prove to be tautosyllabic (V.CCV); see (10).

(10)	$\{p, t, k, s\} + \{r, v, j\}$	
	snu .pra	'chide'
	so .tra	'sweet gen. pl'
	vo .kva	'water'
	tvi .svar	'twice'
	e .sja	'a mountain'
	ve .kja	'awaken'

4.3 Acceptability of clusters as onsets

Unfortunately, the problem of identifying proper syllabification intervocalically does not reduce in any simple fashion to identifying what a possible syllable *onset* is in Icelandic. The heterosyllabic clusters in (9) prove to be well-formed tautosyllabic clusters in other environments: (a) word-initially (11), and (b) when following another consonant (12).

(11) Word-initial (#CCV)

kli .fa	'climb'	flas .ka	'bottle'
pla .ta	'plate'	fjos	'cattle'
blað	'leaf'	fru	'Mrs.'
brek .ka	'slope'	rju .ka	'smoke'
dra .ga	'to draw'	njo .ta	'enjoy'
dver .gur	'dwarf'	mjolk	'milk'
djö .full	'devil'	ljo .tur	'ugly'
skap	'temper'	sta .fa	'spell'

(12) Tri-consonantal intervocalic clusters (VC.CCV)

gil .dra	'trap'
hel .dri	'notable (compar.)'
tim .bri	'timber (dat.)'
an .dvaka	'sleepless'
af .greiða	'help, dispatch'

4.4 Itô's solution

Itô's (1986) proposal, perhaps the most interesting to date, accounts for the distribution of intervocalic clusters (V.CCV vs. VC.CV) by identifying four conditions on the syllable template of Icelandic (one universal, two set by parameter and one language-specific). Her Universal Core Syllable Condition insures that VCV sequences will be parsed as V.CV by stipulating that all CV sequences be tautosyllabic. The Icelandic template, she suggests, contains both an optional coda position and two (or more) onset positions. After assigning the obligatory onset, the assignment of remaining intervocalic consonants to onset or coda is achieved initially by setting the directionality parameter to Left-to-Right, a move that assures us that the coda position will be filled before onset positions. Consequently, VCCV sequences will be syllabified VC.CV. Itô suggests that an Icelandic Tautosyllabicity Condition overrides this default assignment when $\{p, t, k, s\}$ are followed by $\{r, j, v\}$. Additionally, while left-to-right directionality maximizes codas, Icelandic fails to have VCC.CV because of a further coda condition that limits the template to a single coda slot. Meanwhile, VC.CCV and #CCV are further limited by the general Sonority Sequencing Principle that requires that all onsets conform to the sonority hierarchy and a Minimum Sonority Distance Principle that rules out sequences such $*bn$ or $*tm$ that conform to the Sonority Sequencing Principle but are not a sufficient distance apart on the sonority hierarchy.

(13) Summary of Syllable Types and conditions that lead to syllabification (Itô)

- | | |
|-----------|---|
| a. V.CV | Universal Core Syllable Condition |
| b. VC.CV | Universal Core Syllable Condition
L-R Directionality (maximizes coda) |
| c. V.trV | Universal Core Syllable Condition
Icelandic Tautosyllabicity Condition (overrides L-R Directionality) |
| d. VC.CCV | Universal Core Syllable Condition
L-R Directionality (maximizes coda)
Coda condition (single coda slot) |

(Sonority Sequencing Principle and Minimum Sonority Distance active throughout b,c,d.)

4.5 Discussion

While Itô's set of templatic constraints correctly parses intervocalic clusters and thereby accounts for the distribution of long and short vowels, several considerations weigh against it. First, Itô argues that Icelandic generally conforms to universal principles, requiring only one language-specific constraint, the tautosyllabicity condition which requires clusters like *pr*, *tr*, etc., to be (tautosyllabic) onset clusters. This would suggest that the oddity in Icelandic is in (14a) rather than (14b).

- | | | | | |
|------|----|--------|--------|--------------------------------|
| (14) | a. | V.prV | *Vp.rV | |
| | | V.kjV | *Vk.jV | |
| | b. | *V.brV | Vb.rV | Conforms to sonority hierarchy |
| | | *V.plV | Vp.lV | Maximal Onset Principle |

But the syllabifications in (14b) conform to the sonority hierarchy, to the maximal onset principle, and they are the ones found in related languages. If an idiosyncratic condition is to be established for Icelandic, it seems more appropriate that it should account for those forms which are unexpected rather than those which are not. Yet postulating a tautosyllabicity condition is forced by the more radical and more general proposal of left-to-right directionality, a move which then overgenerates codas; this leads us to an unhappy violation of Marr's Principle of Least Commitment, so that the tautosyllabicity condition must come in to override those effects.

The proposal that Icelandic is properly characterized as having left-to-right (rather than right-to-left) scanning raises a number of questions. Granted, one can say that the syllabification algorithm is applied with a directionality opposite to the direction used by the other Germanic languages, but to make this account plausible, one would like to know what linguistic principle it was, combined with what data, that motivated the major shift in the syllabification algorithm in the speakers, viewing the problem from a diachronic point of view. If what we found were that the coda in Icelandic, unlike its linguistic neighbors, was the site to which most intervocalic consonants associated, we could imagine this fact serving as the basis for the qualitative shift that Itô proposes. But there is no such shift; the Icelandic coda continues to be restricted to a maximum of one consonant.

The heart of the problem in Itô's account, though, and its most important difficulty, is that it appears to miss the crucial generalization concerning the relationship between the abstractly defined sets $\{p, t, k, s\}$ and $\{r, v, j\}$, the consonants which must be tautosyllabic. The former set represents the four lowest sonority consonants in Icelandic while the latter set represents the three highest sonority consonants (*v* is the Icelandic reflex of the back glide). Icelandic places a condition on intervocalic onsets that requires them to be maximally separated with respect to sonority. Harris (1983), Levin

(1985) and others have noted that onsets are frequently subject to a Minimum Sonority Distance Principle that excludes onsets such as English **pn* and **ml*. Levin (1985) further observes that this Minimum Sonority Distance varies among languages and frequently between onsets and codas as well. What is special about the Icelandic case is that even within onsets, the Minimum Sonority Distance is contextually dependent, being greater in biconsonantal intervocalic clusters than in other environments (VCCV vs. #CCV or CCCV). In short, *pr* clusters and others like it are found in the onset when they are strictly intervocalic because their large sonority difference permits it, while other clusters are not permitted in an onset when in strict intervocalic position. But the notion of "strict intervocalic position", which excludes word-initial position and also following a consonant, shows us that the notion of minimal sonority distance must be context dependent. This brings us to the next aspect of our discussion.

4.6 Computational alternative

Larson (1990) provides a computational alternative that accounts for the Minimum Sonority Distance Principle using lateral inhibition within a dynamic computational network. Using Harris' (1983) account of Spanish syllabification as a point of departure, it accounts not only for the distribution of onset clusters, but also coda constraints and glide formation as well. While the function of lateral inhibition within the network is similar to that of the Minimum Sonority Distance Principle both in process and effect, it differs in one crucial respect. The Minimum Sonority Distance principle serves as a static condition between two segments (i.e. the sonority of the second segment in an onset cluster must exceed the sonority of the first by a fixed amount). In the network account, however, the distance constraint depends not only on the sonority difference between the two segments but also on their context. In the paradigm Minimum Sonority Distance case (e.g. English **mla*, negative α), the cluster is deviant because the high sonority vowel inhibits the segment to its left to such a degree that the second consonant is left with lower derived sonority than the first, and hence the *m* is a peak, a violation of the sonority threshold. In other words, this minimal sonority distance constraint is due to the fact that the onset consonants are too close in sonority in the environment where they precede a vowel (or other high sonority segment). As a result, the dynamic model predicts that the environment of preceding and following segments should affect the well-formedness of onset clusters. Icelandic provides precisely the phenomena that will allow us to choose between the static and the dynamic sonority models. The well-formedness of onset clusters in Icelandic is dependent on the preceding environment (V— vs. #— vs. VC—). Just as a negative α can dictate the permissible distance between the consonants that precede a vowel, a positive β can determine the degree of affinity the initial consonant has to its preceding vowel. As β becomes more positive, the post-vocalic consonant increases in derived sonority, thereby becoming more likely to be realized as a coda rather than as initial onset segment (i.e., it is less likely to be a trough in the sonority wave). Since α , β , and the sonority coefficients for each segment interact dynamically, the empirical question is whether or not a descriptively adequate set of coefficients can be discovered.

4.7 Architecture of the network and testing procedure

Once inherent sonority values are input into the syllable network, a variety of processing alternatives are available to account for left and right inhibition. Beginning with Larson (1990) and Goldsmith & Larson (1990), we have typically adopted a recurrent network architecture (as in (2) above) where units influence their left and right neighbors iteratively within the same layer. It has been demonstrated that such a network rapidly converges as long as α and β are relatively small ($\alpha, \beta < .50$; cf. Prince 1992, Goldsmith 1992).

Larson (this volume) demonstrates that a feedforward architecture which permits an additional inhibitory/excitatory connection to the left and right neighbors on the input layer can provide an excellent first-order approximation to the recurrent net. The feedforward network not only achieves the same experimental results for syllabification, but also processes forms much more quickly due to the elimination of iterative computations (approximately 15% as long). As a result, we will use the feedforward architecture for our simulations in this section.

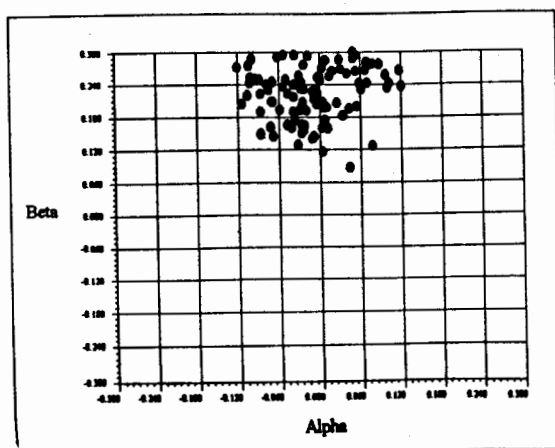
While a principal goal of ours was to determine whether a descriptively adequate set of sonority values and α, β coefficients exists, rather than to determine whether they can be learned by the network, the latter procedure has proven to be the best way to establish the former. We therefore used the following learning simulation to discover appropriate coefficients. For a test corpus we used the 65 Icelandic forms cited in Itô (1986), coded both with the broad phonetic transcription provided by Itô and the syllabification predicted by her analysis. At the beginning of the simulation, the network was seeded with random values (0.00 to 10.00) for each of the segments in the phonological inventory and random values (-.25 to +.25) for α and β . The words in the corpus were presented in random order to the network with the coefficients randomly modified in the event of an error (an error being defined as any discrepancy between the experimental and the target syllabification) using a modified simulated annealing algorithm (cf. Larson (this volume)).⁸ After each of the 65 words were presented, they were re-randomized, thereby insuring that the order of presentation did not influence performance. Once the network either successfully learned to correctly parse all 65 forms, or the network froze (temperature equal to 0), the results were tabulated, and the final values of each of the coefficients were recorded. To insure the replicability of the results with a variety of initial weights, the entire procedure was repeated 175 times, beginning each time with randomized values and ending when the network froze in an energy minimum/harmony maximum.

4.8 Results

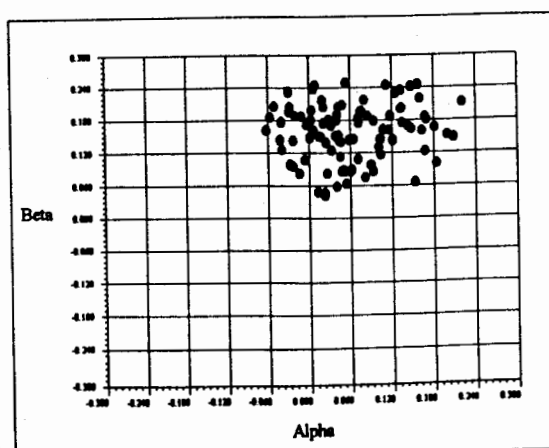
The network proved to be very successful in correctly parsing all of the Icelandic data, which is to say, in finding the peaks and the troughs in the right places. In 172 of the 175 replications, the network achieved 100% performance. In the other three tests the network correctly syllabified 64 of the 65 words. Over the course of the entire experiment, the network achieved 99.97% performance. The network also reached its solution very efficiently. Over the course of 175 replications, the network required an average of 96.72 training epochs, where an epoch consists of the presentation of each of the words in the training corpus. In the best case the network reached its solution in 16 epochs (1040 total words) and in the worst case, 378 epochs.

If the final values of α and β for each replication are plotted in a two-dimensional space, the scatter plot in (15) is generated.

(15) Icelandic



(16) English



The plots of the α/β solution space reveal a fairly broad range of values for α and β where the network performs well. More importantly, as we noted above, the crucial predictor of success is the positive β . α appears to be able to take a range of both positive and negative values as long as β is sufficiently positive for the vowel to attract the appropriate coda consonants (i.e. all but the lowest sonority p, t, k, s).

It is also instructive to compare the plot of the α/β solution space for Icelandic with the solution space for English (16). While the two displays are different, they are not nearly as different as Itô's characterization of the syllable template for the two languages would suggest. The computational network more appropriately accounts for the evolutionary differences between historically related languages. Relatively small changes in α , β and/or the sonority coefficients can result in apparently significant paradigmatic differences. Viewing the differences among Germanic languages in terms of a variable leftward affinity to vowel (in our terms, a positive β) offers insight into how a language could change in the way that we find it has.

4.9 Icelandic length revisited

Thus far we have proceeded on the assumption that the appropriate syllabification of intervocalic clusters is essential to the correct description of Icelandic phonology. Based on Venneman's (1972) observation that it is in open syllables that vowels are lengthened, syllabification seems to provide an appropriate *explanation* for length, so much so that to many phonologists today, the step from noticing where vowels lengthen in Icelandic to the inference that Icelandic has syllables is virtually automatic. Itô makes this correlation more natural by describing the correlation as a templatic condition that marks the coda position in the syllable template as obligatory. If the position is not filled by a consonantal segment (due to the Universal Core Syllable Condition (V.CV) or the Icelandic Tautosyllabicity Condition ($V.trV$)), the vowel is lengthened (cf. Maddieson 1985). But is syllabification, a process breaking up the segments into the constituents we call syllables, truly motivated empirically in Icelandic? Apart from the mandate to assign segments to onsets or codas in order to account for length, there is little *independent* evidence for the proposed parsing of intervocalic clusters (cf. Orešnik & Pétursson 1978).

The same computational network that allows us to correctly parse intervocalic clusters in Icelandic provides additional information that may allow us to predict vowel length in initial stressed syllables directly, without recourse to the constituency of the following consonant (i.e., without determining whether it is in the onset or the coda). The reader will recall that we have focused our attention in the networks on which units are local peaks and which are local troughs of activation. The actual derived sonority values have played no role, however, except in cases where segments must meet a threshold in order to be licensed as a syllable nucleus (e.g. English does not license the sonority peak in /pnp/ as a nucleus because *m*'s inherent sonority is not great enough). Segments do take different derived sonority values, however, depending on their environment. For instance, if $\alpha < 0$, a segment will have a higher derived sonority if followed by a low sonority segment than if followed by a high sonority segment. In a recurrent network, a segment would also be sensitive to the sonority of its more distant neighbors. In a less dramatic fashion, in a recurrent network a segment will have a higher derived sonority if the segment two segments to its right has high sonority than if it has low sonority.

(17) If $\alpha < 0$, in $V X_1 X_2$, derived sonority of V is inversely proportional to X_1 and directly proportional to X_2

If the derived sonority of a vowel is roughly correlated with its length, the distribution of facts described in (17) precisely describes the distribution of long vowels in Icelandic. In those solutions in (15) where $\alpha < 0$, the network generally assigns higher sonority to vowels in "open" syllables than it does to the same vowel in closed syllables. The correlation between derived sonority and length is not a linear one, however. It is certainly not the case that long vowels are 50% or even 10% more sonorous than short vowels. We rather observe a threshold above which a vowel can be interpreted as long and below which a vowel is interpreted as short. Alternatively, we could view the "excess" derived sonority as licensing a vowel length feature.

4.10 Test #1 (end of test 175 above) $\alpha = -.172$ $\beta = .243$

In order to test the possibility of predicting length directly from the network without intermediate reference to constituency, we conducted two tests on an artificial corpus of twenty-eight forms that reflect the crucial consonantal contrasts. In addition to the twelve V.CCV forms representing the intersection of $\{p, t, k, s\}$ and $\{r, v, j\}$, sixteen VC.CV forms with clusters having a slighter smaller sonority difference were included in a test corpus. In the first test, we simply used the values for α, β and all of the sonority coefficients that had been trained at the end of the 175th replication of the syllabification task in 4.8 above. Without modifying weights, each of the 28 forms in the test corpus were presented to the network. The output sonority values for each form are below in (18a,b).

(18)		Derived activation			
(a) V: .CCV forms:					
	<i>e: .pra</i>	9.95	3.01	3.77	11.26
	<i>e: .pja</i>	9.98	2.86	4.60	11.47
	<i>e: .pva</i>	9.94	3.09	3.29	11.15
	<i>e: .tra</i>	10.10	2.15	3.56	11.26
	<i>e: .tja</i>	10.12	2.01	4.40	11.47
	<i>e: .tva</i>	10.08	2.24	3.08	11.15
	<i>e: .kra</i>	9.98	2.86	3.73	11.26
	<i>e: .kja</i>	10.00	2.72	4.57	11.47
	<i>e: .kva</i>	9.96	2.94	3.25	11.15
	<i>e: .sra</i>	10.08	2.24	3.58	11.26
	<i>e: .sja</i>	10.11	2.09	4.42	11.47
	<i>e: .sva</i>	10.07	2.32	3.10	11.15
(b) VC.CV forms					
	<i>ep.la</i>	9.91	3.22	2.50	10.96
	<i>et.la</i>	10.06	2.37	2.30	10.96
	<i>ek.la</i>	9.94	3.08	2.47	10.96
	<i>es.la</i>	10.05	2.46	2.32	10.96
	<i>eb.ra</i>	9.52	5.49	4.37	11.26
	<i>eb.ja</i>	9.55	5.35	5.21	11.47
	<i>eb.va</i>	9.51	5.58	3.89	11.15
	<i>ed.ra</i>	9.50	5.66	4.41	11.26
	<i>ed.ja</i>	9.52	5.51	5.25	11.47
	<i>ed.va</i>	9.48	5.74	3.93	11.15
	<i>eg.ra</i>	9.20	7.35	4.83	11.26

<i>eg.ja</i>	9.23	7.21	5.66	11.47
<i>eg.va</i>	9.19	7.44	4.34	11.15
<i>eb.la</i>	9.49	5.71	3.11	10.96
<i>ed.la</i>	9.46	5.88	3.15	10.96
<i>eg.la</i>	9.17	7.57	3.56	10.96

Two observations can be made concerning the output of the network. First, each of the forms are correctly syllabified (the onset of the second syllable begins at the sonority minimum). Second, without any attempt to train the network to generate a length distinction, a general distinction can be observed. If all of the forms are listed in descending order based on the derived sonority value of the first vowel, the V.CCV forms would be at the top of the list, as shown below.

4.11 Test #2 $a = -.25$ $b = 0.0$

In the previous test, the derived sonority distinctions between vowels in open syllables and vowels in closed syllables were simply observed as the accidental byproduct of the previous syllabification experiment. In our second test, we attempted to study the correlation more explicitly. This was done by performing a learning simulation on the 28 constructed forms. Beginning with random values for the sonority coefficients, we used the learning algorithm to train descriptively adequate values. While the sonority coefficients were modifiable, we clamped the values of α and β in order to test the hypothesis that the length distinction is sensitive to a negative α ($\alpha = -0.25$, $\beta = 0$). The following results indicate the network's success both in predicting length and syllable structure:

(19)	<i>e: .pra</i>	10.02	0.53	2.70	10.00
	<i>e: .pja</i>	10.05	0.44	3.07	10.00
	<i>e: .pva</i>	9.99	0.65	2.22	10.00
	<i>e: .tra</i>	10.18	-0.11	2.70	10.00
	<i>e: .tja</i>	10.21	-0.20	3.07	10.00
	<i>e: .tva</i>	10.15	0.01	2.22	10.00
	<i>e: .kra</i>	10.05	0.41	2.70	10.00
	<i>e: .kja</i>	10.08	0.32	3.07	10.00
	<i>e: .kva</i>	10.02	0.53	2.22	10.00
	<i>e: .sra</i>	10.13	0.10	2.70	10.00
	<i>e: .sja</i>	10.15	0.01	3.07	10.00
	<i>e: .sva</i>	10.10	0.22	2.22	10.00
	<i>ep.la</i>	9.87	1.15	0.23	10.00
	<i>et.la</i>	10.03	0.51	0.23	10.00
	<i>ek.la</i>	9.90	1.03	0.23	10.00
	<i>es.la</i>	9.98	0.72	0.23	10.00
	<i>eb.ra</i>	9.33	3.29	2.70	10.00
	<i>eb.ja</i>	9.36	3.19	3.07	10.00
	<i>eb.va</i>	9.30	3.41	2.22	10.00
	<i>ed.ra</i>	9.31	3.40	2.70	10.00
	<i>ed.ja</i>	9.33	3.31	3.07	10.00
	<i>ed.va</i>	9.28	3.52	2.22	10.00
	<i>eg.ra</i>	8.94	4.85	2.70	10.00

From CLS 28(1992): see last page for complete citation.

<i>eg.ja</i>	8.97	4.75	3.07	10.00
<i>eg.va</i>	8.91	4.97	2.22	10.00
<i>eb.la</i>	9.18	3.90	0.23	10.00
<i>ed.la</i>	9.15	4.02	0.23	10.00
<i>eg.la</i>	8.79	5.46	0.23	10.00

In this second test, the only exceptional form is *et.la*, which has a higher value than some of the forms in (19a). While this may be troublesome, the cluster *tl* proves to be unusual in several languages. For instance, in Harris' analysis of Spanish syllable structure constraints, *tl* must be excluded even though it satisfies the Minimum Sonority Distance Principles (presumably because *t* and *l* share the same point of articulation). Larson (1990) accounts for this constraint by suggesting that this *t* has a higher inherent sonority because it is underspecified for point of articulation, sharing this specification with the following segment. In addition to accounting for the syllable structure constraints in Spanish (and English as well), the same observation would eliminate the exceptional character of *et.la* in this test.

4.12 Discussion

While it might be claimed that the network can predict vowel length without recourse to syllable constituency, the analysis that we have presented above can be taken to show that the two can be correlated. In all of the forms in (19a,b), the network produced the syllabifications predicted by traditional analyses in addition to predicting vowel length. Perhaps a more compelling demonstration would be to train the network to recognize vowel length without concern for syllabification and then see what syllabifications would result. Alternatively, we could attempt to correlate predictions of vowel length with syllable structures that uniformly conform to the Maximal Onset Principle. Without independent evidence concerning Icelandic syllable structure, however, it is more critical to demonstrate that the network can generate traditional syllabification.

There are, in fact, additional environments where length and traditional syllabifications do not line up, environments that demonstrate the superiority of the network analysis. Orešnik and Pétursson (1978) note four classes of exceptions to Icelandic length assignment, as in (20).

(20)	CV:CC	CV:C.CV	CV:Cr	CVCr
	<i>ski:ps</i>	<i>li:t .ka</i>	<i>pu:kr</i>	<i>klifr</i>
	<i>lei:ks</i>	<i>no:t .kun</i>	<i>snu:pr</i>	<i>grenj</i>
	<i>bá:ts</i>			

In each of the first two environments, we would expect short rather than long vowels. While final extrametricality can account for the appearance of long vowels in closed monosyllables, the forms in the first column have two final consonants. While the forms are bimorphemic, an analysis that assigns vowel length before adding the *s* would contradict the analysis of inflectional morphology that forms the rationale for either Itô's or Kiparsky's discussion of Icelandic. Even if the forms in the first column were rationalized as morphologically complex, the forms in the second column are not amenable to such an analysis. In both columns, the relevant observation appears to be that the consonant that follows the vowel is from the class $\{p, t, k, s\}$ which typically follow a long vowel. Since the principal determinant of length in the network is the sonority of the following segment, the seeming exceptions are consistent with the network's predictions.

In the final two columns, the gross structure of the forms is identical (*CVCr*) but the length is variable. Kiparsky (1984) correctly notes that though the forms are analyzed as monosyllables, the clusters that follow long vowels are precisely those that would be well-formed onsets in bisyllabic forms. He accounts for the distribution by noting that the forms are derived from verbs ending in *a*. Length assignment must precede derivation, after which resyllabification takes place. While possible, perhaps, such a solution relies on post-lexical derivational morphology, a theoretical move that violates much of the spirit of lexical phonology. The network accounts for the contrast in a straightforward fashion since length is dependent on the sonority profile of the cluster following the vowel rather than syllable structure.

Whether or not the exceptional forms in (20) are admitted into the discussion, the network provides a more direct explanation both for the distribution of long vowels and the syllabification of intervocalic clusters. Rather than positing extra machinery and large-scale differences in directionality to account for Icelandic's unique syllabification phenomena, the network simply assigns marginally different parameters for lateral inhibition.

5. Stress systems, final positional activation, and the cycle

We turn now briefly to our final topic, the cycle in linguistic analysis. The key insight involved in cyclic analyses is that in some linguistic forms, we find one structure nested inside another of the same type — typically in phonology, we find one phonological word nested inside another. Compounds are the most obvious example of this sort: a word like *handstand* has a syllable structure which is not to be found in a simple monomorphemic form; the sequence ...*ndst*... is a sequence which is normally found only in the juxtaposition of two phonological words. But we also know that from a prosodic point of view, where we focus on the timing, the stress and the pitch pattern — not to mention the semantics — *handstand* is a single word, and hence we assign to it a nested bracketing: *[[hand][stand]]*. Forms other than compounds illustrate a similar point, to be sure: there are certain sequences of segments that are simply not found inside a simple phonological word but which can be found in certain morphological formations. Well-known examples include the apparent geminate consonants found in adverbs ending in *-ly* followed by *-ly*, as in *coolly* or *wholly*, and the sequence of schwa plus vowel in a nonce-form such as *Indiana-ism*. These words evidently have the structure *[[cool]ly]* and *[[indiana]ism]*.

The traditional derivational account of these patterns of structure is that the internal word constituent undergoes the effects of the language's phonological rules first, and only then do the rules of the language apply to the larger, more inclusive word constituent. But the fundamental and guiding principle of the dynamic computational model is the notion that superposition is the key means for dealing with the relationship between distinct and even contradictory influences. Any linguistic relationship between elements can be expressed as an arithmetic relationship, and sets of these arithmetic relations can simply be added to determine the resultant effect of these relationships.

In the case of a cyclic analysis, this means that we can in effect perform the computations on the outer cycle and the inner cycle simultaneously, in the same computation. One way of expressing this in familiar terms is that cyclicity becomes, on this view, a matter of representation rather than of derivation. We will turn now to two cases of cyclic assignment that emerge from the present model concerning stress assignment.

5.1 Cyclicity in Greek and Menem stress

We will assume here negative values (or rather, non-positive) in general for α and β ; these values play the same mathematical role that they did in the treatment of sonority, but in the case of accent systems in quantity-insensitive languages, the primary function of α and β is to induce a

pattern of alternating rhythm, rather than to emphasize inherent differences between successive units. To put the same point another way, while we find rhythmic, alternating patterns both in the case of sonority and in the case of accent (this latter in a large number, though by no means all languages), the origin of the rhythmicity is different in the two cases, for in the case of sonority, it is the inherent featural content of each successive segment that plays the most important role in determining the degree of that element's activation, while in the case of accentual patterns, the inherent character of the syllable *may* play a role (a state of affairs that we call "quantity sensitivity", of course), but in general it is a syllable's position in a word that plays an even greater role in determining the syllable's degree of accentual prominence, and this characteristic is determined jointly by the positional activation attached to near-edge syllables, and to the lateral effects of the α and the β connections.

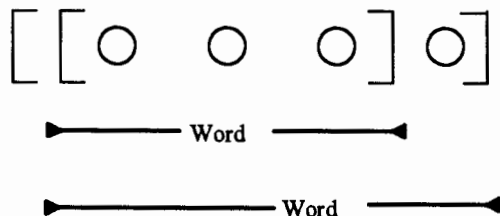
Let us consider a language which assigns a positional activation of -1.0 to its final syllable. In a simple monomorphemic word, we will find a pattern of stress on the penultimate, then, and on every other syllable to its left, as in (21).

(21) Monomorpheme stress on penult and to the left ($\alpha = -.50$, $\beta = 0$)

	σ	σ	σ	σ	σ	σ	σ	σ	σ	σ	σ	σ
inherent activation	0	0	-1	0	0	0	-1	0	0	0	0	-1
derived activation	-0.2	0.5	-1.0	0.12	-0.2	0.5	-1.0	-0.06	0.12	-0.20	0.50	-1

Let us consider next a cyclic structure, formed from a three syllable base and a monosyllabic cyclic suffix, as in (22). Here we do not compute the activation on the inner cycle first, and then submit that to computation on the outer cycle, as we would under the assumptions of a traditional derivational theory; rather, we perform all of the computation in exactly the same steps as we would for the non-cyclic case. The only difference is that two syllables, the third and the fourth, *both* receive inherent positional activation for being in word-final position

(22)



Let us compare three cases: a monomorphemic (and, hence, a word with one cycle) of 3 syllables; a monomorphemic word with four syllables; and a bicyclic word with four syllables, as in (23a, b,c), respectively (again, we have given numbers based on the simple assumption that $\alpha = -0.5$ and $\beta = 0$).

(23)	a.	[	σ_1	σ_2	σ_3]	
Inherent			0	0	-1		
Derived			-0.2	0.5	-1		
	b.	[	σ_1	σ_2	σ_3	σ_4]
Inherent			0	0	0	-1	
Derived			0.06	-0.2	0.5	-1	
	c.	[[σ_1	σ_2	σ_3]	σ_4]
Inherent				0	0	-1	-1
Derived				-0.12	0.25	-0.5	-1

In cases (23a,b), as we see, stress is assigned to the penultimate syllable, whereas in the cyclic case, (23c), it is σ_2 that is the peak of activation, the stressed syllable. This result holds over a wide range of initial assumptions regarding the network's parameters.⁹ From the linguist's point of view, this means that a cyclic suffix in this language will appear to leave the stress pattern of the base largely unchanged, and this is, of course, one of the central ideas in the original notion of a cyclic suffix. But a cyclic suffix is not a *neutral* suffix. We would expect it to have *some* effects on the word to which it attaches. And indeed, when we look at forms with two cyclic suffixes, as in (24), we find that a stress shift has indeed occurred, and the rightmost stress falls on the penultimate syllable, i.e., the first cyclic suffix. This syllable (σ_4) is a peak of activation (that is, its activation is greater than that of its neighbors, regardless of the fact that its activation is negative). Again, this behavior is found over a wide range of choices of α and β .

(24)	[	[	[	σ_1	σ_2	σ_3]	σ_4]	σ_5]
Inherent				0	0	-1	-1	-1
Derived				-0.18	0.37	-0.7	-0.5	-1

Do we find stress patterns such as these in natural languages? Indeed we do, and not at all uncommonly. We can summarize this pattern as having regular penultimate stress, with antepenultimate stress occurring only in the case of a base followed by exactly one suffix (or more generally, an odd number of suffixes, according to our predictions). We observe this pattern in (25), in examples chosen from Modern Greek, a regular pattern of word stress with imperative enclitics.¹⁰

(25) Modern Greek

a.	δώσε	'give!'
b.	δώσε μου	'give me!'
c.	δώσε μου το	'give me it!'

The published literature concerning Menem (Lichtenberk 1983, Chasky 1986, and L. Itô 1989) contains another example of much the same accentual behavior, as illustrated in (26). Lucille Itô provides a concise summary of a core set of stress facts in Manam, which we have summarized in (26). This is precisely the behavior that we expect for cyclically formed words with negative positional activation on the final syllable, for the reasons we have just seen.

- (26) a. Regular stress falls on the penult: pátu 'stone'.
 b. Monosyllables are stressed.
 c. A heavy syllable in one of the last three syllables will attract stress.
- | | |
|---------|----------------|
| malabón | 'flying fox' |
| dámwa | 'forehead' |
| émbeʔi | 'sacred flute' |
- d. Some suffixes attract stress to them:
- | | |
|-----------|--------|
| ana-gu-má | 'mine' |
|-----------|--------|
- e. The case that concerns us here: when one of a particular class of suffixes is attached to a base, stress falls on the penult of the base, i.e., on the antepenult of the resultant word:

súru-be	'soup and'
---------	------------

However, when two suffixes from this class appear on a word, stress falls on the penult of the entire word, that is, on the leftmost of the two suffixes:

ɲa.u-lá-be	'only I and'
ɲáu-la	'only I'

This final property is the critical one, and the one which puts its cyclic character into the same category as the Greek clitic case, and which suggests a dynamic treatment of the sort indicated in (23c) and (24).

5.2 Greek vs. Indonesian style of cyclicity

There is, however, a second pattern of cyclic stress found in other languages with penultimate stress, and this is the pattern found, for example, in Indonesian, discussed in Cohn (1988) and Goldsmith (1992). In this second pattern, stress falls on the penult syllable of the outer word, regardless of how many cyclic suffixes are added. The cyclic nature of the process emerges not in the placement of the rightmost stress, but in the placement of secondary stresses. The forms in (27) illustrate this. Note, for example, how the stress pattern of a 2-cycle word of 6 syllables is different from that of a 1-cycle word of 6 syllables. The monocyclic form has a secondary stress on the third syllable, whereas the bicyclic form does not, because of the effect of the hidden stress on the fourth syllable, which is the penultimate syllable (and hence the stressed syllable) of the inner word.

- (27) a. $\left[\begin{array}{cccccc} \sigma & \sigma & \sigma & \sigma & \sigma & \sigma \\ * & & * & & * & \end{array} \right]$ e.g., [òtobiográfi]
- b. $\left[\left[\begin{array}{ccccc} \sigma & \sigma & \sigma & \sigma & \sigma \\ * & & & & * \end{array} \right] \sigma \right]$ e.g., [[kòntinuasi]ña]

In a detailed analysis of this data (Goldsmith 1992), it was assumed that there was a positive positional activation on the first syllable and the penultimate syllable (0.65 and -1.0, respectively), rather than on the first and the final.

A brief inspection of the mathematics will show that these assumptions were necessary, and no choice of α and β along with a positional activation on the final syllable will lead to stress on the penultimate syllable in the case of a word with a cyclic suffix. This is illustrated in (28). No choice of α and β will make the penultimate a local maximum. This is not surprising; it is what we saw in the preceding discussion of Greek and Menem. The existence of systems of this present sort --

where accent appears on the penultimate, regardless of the number of cyclic suffixes -- leads us to the second type of positional activation, which is activation assigned to the penultimate syllable.

$$\begin{array}{rcl}
 (28) & [[& \sigma & \sigma & \sigma & \sigma] & \sigma] & F = \text{final activation} \\
 & & & & & F & F & \alpha = -.4 \\
 & & & & & & & \beta = -.2 \\
 & & & & & & & \dots & .31 & -.72 & -.85
 \end{array}$$

As we have noted, the straightforward conclusion from this calculation is that both the ultima and the penult are positions which can be assigned positional activation. In simple monomorphemic words, it will generally be impossible to see the difference between the two (and indeed, a language may choose either device, or both, in the ambiguous cases). In the case of cyclic structures, however, the choice of a positive penultimate activation versus a negative ultimate activation gives rise to the qualitative difference that we have seen in the contrast between languages like Indonesian and those like Modern Greek or Manam.

6. Conclusion

A number of linguists have begun exploring the mathematical and linguistic properties of the dynamic computational model discussed here (in addition to the papers referred to in note 7, one may see now Prince 1991 and Bailey 1992, for example).

We are struck by three characteristics of these models: first, the essential identity of the architectures of the theory of accent and that of syllabification; second, the ease with which a computationally explicit learning algorithm can be designed and implemented; and third, the way in which the notion of a cyclic analysis can be reanalyzed in a fashion that ensures that cyclic analyses are not computationally more complex than noncyclic analyses, a thoroughly surprising result.

The results that we have had in designing a learning algorithm for these phonological models has led us to a position of skepticism concerning the intrinsic importance for linguistics of efforts to develop a highly constrained linguistic theory. Virtually all of the motivation for focusing on developing constrained theories of language was the hope and belief that with enough limitations on what a possible human grammar was, we would be able to find someday a model of acquisition that would account for how the child is able to input data and arrive at the adult grammar. Work on dynamic computational models suggest, however, that learning algorithms are close at hand, and simply do not depend on prior efforts to constrain the class of possible grammars.

There are two ways in which it seems to be necessary to improve the dynamic computational network that we have looked at in this paper. First of all, while we are able to superimpose by the simple process of addition different sets of constraints relating to stress or syllabification, we have not yet seen a natural way to add together in a similar way other non-prosodic constraints. We have alluded to this already, without going into any detail. Suppose we have a process that deletes a particular consonant -- a γ , let us say; and suppose, as is typically the case, that this rule will fail to apply if its output cannot be properly syllabified. A case of precisely this form is argued for in a recent paper by Andrew Black on Axininca Campa (1991). In the Campa case, γ -deletion is blocked if its output would contain a sequence of three vowels, a result which would include, in our terms, a vowel which was a local minimum of sonority, a result which is typically not permitted in languages. Precisely how, we may ask, is the γ -deletion rule then blocked from applying? In principle, there would seem to be two ways to approach the problem, and which course we take depends on specifically which constraints will be taken into account in determining whether a rule may apply or not.

The first way is to construct a mathematical function which allows us to compare well-formedness and ill-formedness from various different sources, including both the presence of γ s, say, in the Campa case, and various assignments of sonority. The sum total of the well-formedness would then be maximized by the grammar. This is the general perspective suggested by Smolensky's (1986) harmony theory, for example. The second way, the alternative way, is to construct the phonological machine in such a way that the space of possible states that it explores is precisely limited and bounded by those values of sonority that yield well-formed representations in the sense that we have been looking at them in this paper. This appears to us to be a more likely and promising approach, and it involves (by definition) a search through a smaller subspace of possible phonological representations.

A second area for research in the short run involves the thorough-going linearity of the system that we are exploring. While it is true that restricting our systems to purely linear functions greatly simplifies the mathematics involved, it is also true that it limits the kinds of feedback or recurrent network design that we can allow ourselves. It seems likely that we will want to improve the model in such a way that linearity will be found only in a part of the response of the units. That would be the case if our units responded in a more or less linear fashion at low activations, but leveled off asymptotically to 1 as the activation increased; this kind of response bespeaks the presence of what is known as a logistic function.

Let us briefly imagine what would force this kind of modification. Suppose we find in a language that there is a strong causal relationship between stress and length in both directions: a stressed vowel must be in a heavy syllable (i.e., either the syllable is closed, or the vowel is long), and a heavy syllable must be stressed. Burzio (ms) has argued that English is such a case. It is natural to model this kind of relationship with a recurrent network, i.e., one involving feedback, but in a network of the form studied here, α and β — the coefficients marking the strength of the linking between the two systems, for stress and for length — would have to be quite small, no greater than about 0.3, for the system would explode computationally if they were any larger. This limitation on the strength of the coupling vanishes, however, if the units are non-linear, because the non-linearity removes the malevolent effects of positive feedback.

In conclusion, then, it seems to us that neural network style modeling will play an increasingly useful and valuable role in our linguistic theorizing in years to come, and we have sketched one way in which these networks can help us better realize the general notion of harmonic rule application.

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² The intent behind this statement is not at all controversial, and the view it expresses is taken by phonologists whose position is otherwise greatly at variance with the proposals we present here. Dresher and Kaye, for example, suggest that "[a] central goal of modern linguistic theory is to explain how, on the basis of limited data, a person is able to attain the grammar of his or her language....Acquisition of grammar...becomes a matter of correctly fixing the parameters for the grammar one is acquiring....[Our] learning theory is instantiated in a computer program capable of taking appropriate data from any language as input, and which then attempts to 'learn' the grammar of stress which generates the data it has been exposed to. By 'learn', we mean that, given input data and a model of universal grammar (UG) which includes a set of open parameters, the program contains a procedure which can correctly fix the parameters, and can then apply the system so as to generate well-formed strings." (1990, 138).

³ Things would still be a good deal more abstract in such a system than was ever envisaged by theories of phonemics. In particular, neutralizations would be perfectly acceptable (and would often be found) in a system of the sort mentioned in the text, though they would not in general be accepted in a phonemicist system. The devoicing of a word-final obstruent, for example, is a procedure that is consistent with the view of phonology described immediately above in the text but which is not, in many traditional structuralist views, considered an allophonic, because of the contrast between voiced and voiceless obstruents in other positions.

⁴ See Goldsmith 1990, 1991, and the papers by Goldsmith, Lakoff, and Wheeler and Touretzky in Goldsmith, ed. (1993); see also Bosch 1991, Brentari 1990, Wiltshire 1992.

⁵ Such a system will settle into equilibrium after approximately five recalculations, provided that the product of α and β is less than approximately 0.5.

⁶ Itô observes, for example, that "[n]umerous proposals have been made concerning the role of sonority in syllable structure...and all researchers agree that syllables generally conform to some principle of sonority sequencing: 'in any syllable, there is a segment constituting a sonority peak that is preceded and/or followed by a sequence of segments with progressively decreasing sonority values (Selkirk 1984, p. 116). The exact implementation of this generalization in syllable theory, however, is still a matter of debate.'" (1989, 221-222).

⁷ This model is explored in other places as well; see, for example, Goldsmith and Larson 1990, Larson 1990, 1992, Goldsmith in press a, b, Prince 1992.

⁸ The model learns essentially as follows. It begins with random values assigned to the variables in question, and assigns itself a high "temperature" (100). The temperature plays the role of measuring how close the system is to settling down and learning no more; the higher the temperature, the less satisfied the system will act with its current hypothesis. With the presentation of each piece of data, the system tests its predictions against reality. If its prediction is correct, it decreases the temperature slightly (by a fixed percentage, that is). If its prediction is incorrect, it cannot determine what aspect of its current hypothesis is incorrect, so it changes all of the values of its current hypothesis, in an amount which is randomly chosen, but using a bell-shaped curve of random numbers (so to speak) in such a fashion that the width of the bell-shaped curve is proportional to the current temperature. Thus, as the temperature decreases, due to the improvement in the system's performance, the average change in each of the parameters will decrease, until the temperature has sunk low enough that the system freezes and learns no more.

⁹ If we assume $\beta=0$, for example, then σ_4 's derivated activation will be I, σ_3 's derived activation will be $(1-\alpha)*I$, and σ_2 's activation will be $(\alpha-\alpha^2)$. Thus σ_3 is a peak for any choice of α between -1 and 0. A nonzero choice of β affects this conclusion, but not greatly.

¹⁰ I am grateful to Kostas Kazazis for these forms.

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