A Dynamic Computational Theory of Accent Systems

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1.0 Introduction

The purpose of this paper is to describe the basic functioning of dynamic computational theories, and to show how this family of theories can be applied to provide a revealing typology of quantity-insensitive accentual systems.[1] To this end, we will discuss quantity-sensitive systems briefly — in part, to reveal the nature of the boundary between the two types of systems. We will illustrate how the mechanisms of this theory operate to provide linguistic accounts of systems that are familiar to phonologists working in this area, and for this reason, I have focused in the presentation on accentual systems which have been discussed at some length in the literature, and on generalizations for which considerable evidence has been amassed.

In a sense, this work is the study of an alternative account of linearity in phonology. There is a small irony to this observation: most of the important work in phonological theory over the last fifteen years or so, the work of the post-SPE period, has focused on developing an account of phonological representations that overcomes the limitations inherent in the assumption of complete linearity in phonological representations used in the classical period of generative phonology. To say that there is something more or something new to study in the structure of linear representations sounds off-beat, if not downright *rétro*.

But there is much to be done, in fact. Just as autosegmental phonology explored, and explores, the consequences of multi-linear representation for phonology, and develops the ways in which this richer conception of phonological representation provides explanations for phenomena which flow structurally out of the architecture of the representational model, so too the present dynamic theory offers a new account for some of the fundamental properties of phonological systems — first and foremost, their rhythmicity — an account in which these properties derive from the basic representational architecture, rather than a system of rules distinct and separate from the representational base.

Our view of linear representation has traditionally been that it is simply a matter of concatenation, the most simple and trivial relationship that can exist between the successive units that make up a linear sequence. The units simply *appear*, one after another, on such an account. Dynamic computational theories drop this assumption, and adopt what is, I would suggest, the next most simple assumption — though one which is, to be sure, more general than the simple concatenation assumption. Dynamic computational theories explore the premise that successive units in a phonological string enter into specific, quantitative relationships with their left- and right-hand neighbors, relationships that give rise automatically to the fundamental patterns of rhythmicity that we observe in most accentual systems.

The theory that I will present may give the impression at first glance of being a computer implementation of a familiar theory — metrical theory, in the event. That is not at all the message I wish to convey. The fact that I have used a computer to perform the calculations and present the results graphically[2] is simply a matter of convenience, since the calculations that formulas such as 0 require would be wearisome and best left to a simple calculator. We are accustomed to thinking that our phonological rules, as we formulate them on paper, are well formalized, but rarely subject that assumption to test; generative phonologists, quite rightly, do take it for granted that a formal implementation of their rule system is a necessary, not a dispensable, part of the task. The computations offered below are not an implementation of traditional metrical phonology; they are intended to be a replacement of them. Put another way, if the present theory is correct, then familiar derivational metrical theory is a finite approximation to the actual theory of accent, much as the step by step procedure of long division that we learned in school is a particular implementation of the mathematics of division.

We will explore problems of accentuation in this paper, for several reasons. First of all, it forms a well-studied subdiscipline in phonology, about which a good deal is known, and an established body of results exists which one can turn to. Second, in many languages, the principles of accentuation are arguably real from a psychological point of view, and do not have the questionable quasi-morphological status of many phonological rules. Thirdly, the present accounts of accent systems typically require complex derivational rule interactions, of the sort that dynamic computational theories disallow; they therefore serve as an instructive testing ground for the ambitions of the approach.

A few words of technical introduction. A dynamic computational theory consists of a linear string of *k* units, which we may refer to as units u_1, u_2,..., u_k; for our present purposes, these units may be thought of as syllables, and this linear string, or tier, as the metrical grid of familiar metrical theory.[3] Each unit u_i has an activation level at any given time *t*, which we will denote as u_i^t. That activation is the sum of three things: the positional activation of the unit; the internal activation of the unit; and the lateral activations passed from unit to neighboring unit. This is illustrated schematically in Figure 1. We will discuss each factor in turn in a moment. But the main point to recognize is that when given certain elementary specification of its parameters, the system will settle into (or calculate) a set of activation values for each unit (i.e., each syllable). The calculation of these activation values is (so claims the theory) how the accentual pattern of the word or phrase is established in each natural language.

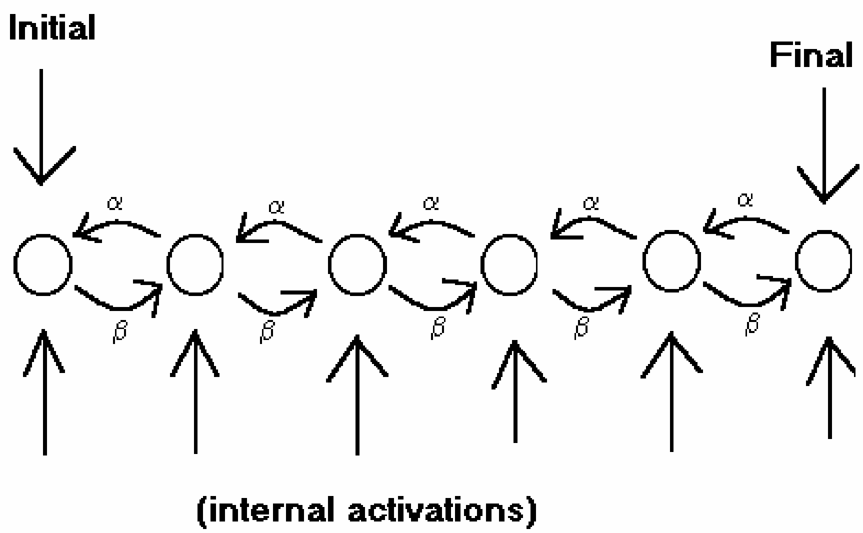


Figure 1
Dynamic computational network

In certain representational respects, this is not radically different from the familiar metrical grid of Liberman 1975, Liberman and Prince 1977, Prince 1983, and others. In metrical grid theory, we find a grid in which a column of x's — grid-marks — is placed over each syllable, in such a fashion that the number of grid marks corresponds to the accentual prominence of the syllable in question, as in 0.

(1)

```
      x
x     x
x  x  x  x
A la ba ma
```

Each syllable in the traditional metrical grid is assigned a number, the height of its particular column; we might for the moment call that its "metrical height". In the present dynamic computational theory, each syllable is assigned a number, which differs from its metrical height in three ways: first, the metrical height can only be a positive number, while its activation level can be positive or negative; second, the metrical height can only be an integral value, and its activation level can be any rational number; third, what is phonologically relevant in traditional metrical theory is absolute height, while in dynamic computational models, it is the identification of peaks that is phonologically interpreted, not the absolute height.[4] The important difference, to which we return in a moment, is just how the metrical grid-marks, and the activation levels, are formally arrived at. Let us consider the three sources of activation within the dynamic computational system.

First, there is *positional* activation, which is specific to, and relevant to, only the first and last units of the sequence, units u_1 and u_k. They will be assigned a positional activation equal to *I* (for "initial") and *F* ("final"), respectively, in a language-particular fashion. These numbers, like all the numbers in the model, can be negative as well as positive.

The *internal* activation of a unit on the metrical grid is the measure of the syllable's weight, determined, as we know, in a language particular fashion. When all units on the metrical grid are assigned the same internal activation regardless of the internal structure of the syllable in question, we have a quantity-insensitive accentual system, the topic of our extended discussion below.[5] When the internal activation of the syllables varies from syllable to syllable, the result is a quantity-sensitive accentual system.

The *lateral* activations which pass from a unit to its left- and right-hand neighbors form the heart of the present system. Each unit u_i, whose activation is x_i, passes a quantity of activation (sometimes negative, sometimes positive) to its left-and right-hand neighbors, a quantity which is a fixed proportion of its own total activation. In particular, we establish once and for all for a given language two important coefficients — fixed numbers — on each given network-tier; we will call these coefficients α and β. α is the coefficient that expresses the strength of the activation signal that a given unit sends to its lefthand neighbor, and β is the coefficient that expresses the strength of the activation signal that a unit sends to its righthand neighbor. Thus a unit with an activation level of x_i^t at time *t* will send a signal of strength $\alpha \cdot x_i^t$ to its left hand neighbor (u_{i-1}) which that unit (u_{i-1}) will use in recomputing its own level of activation at the next instant, i.e., at time *t+1*. Similarly, that same unit u_i^t will send a signal of strength $\beta \cdot u_i^t$ to its right hand neighbor (u_{i+1}) which is used in the recomputation of u_{i+1}'s activation level at time *t+1*. All of the units of the system continue to recompute their activation levels, simultaneously, until the system reaches a steady state, or equilibrium (this steady state may be approached asymptotically, to be sure).

Technically, then, each unit in a network composed of *k* units computes its activation value according to the following equation:

(2) $x_i^{t+1} = P(i) + \alpha \cdot x_{i+1}^t + \beta \cdot x_{i-1}^t + N(i)$

where P(i) indicates positional activation:

P(1) = I, P(k)=F, and P(j) = 0 for all other j.[6]

and N(i) indicates internal activation; N(i)=0 for all i, in our initial discussions.

In sum, then, such a network is the basis of the behavior of the metrical grid that we have explored over the past fifteen years. No longer will we have or need, I would suggest, a derivational account of the behavior of the relative prominence of each member of the metrical grid, a derivational account in which structure is assigned step by step, in which rules exist in a fashion distinct from the representation, in which rules are extrinsically ordered, and in which this extrinsic ordering is the means necessary to express the fact that generalizations (such as alternating stress and stress clash avoidance) can be in conflict, and the only apparent fact that one of the principles will necessarily appear to win out over the other. The goal of the dynamic computational is to retain what is valid about our representational theories, and to dispense with the weaknesses of derivational manipulations of those representations, without losing sight of the richnesses and complexities found in naturally occuring phonological systems.

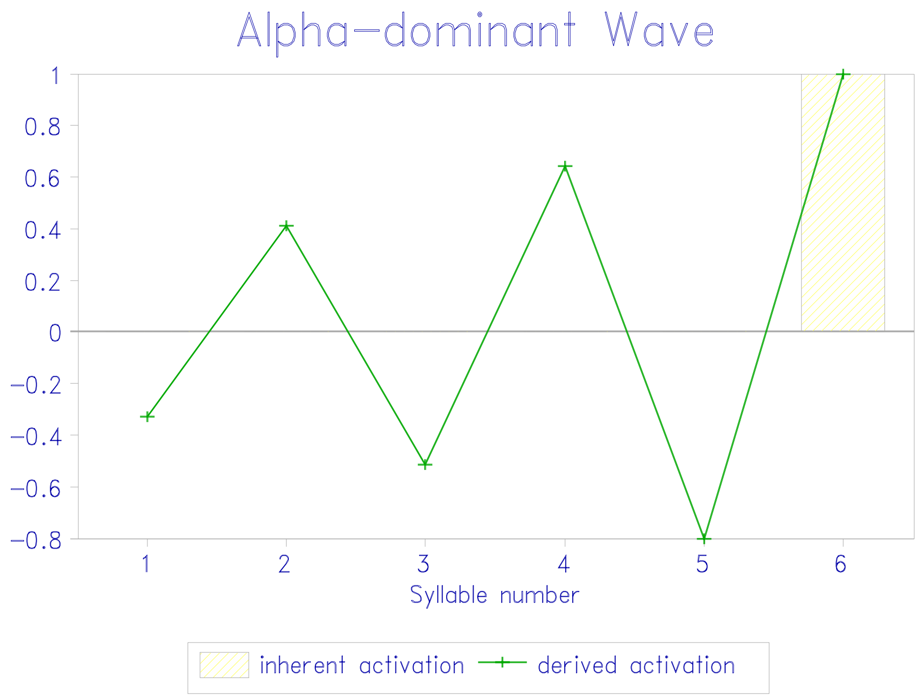
These basic observations are summarized in the following table:

(3)

Network notions	Familiar concepts
Internal activation	syllable weight
Positional activation	End Rule effects
Contextual activation	rhythm/perfect grid; culminative accent

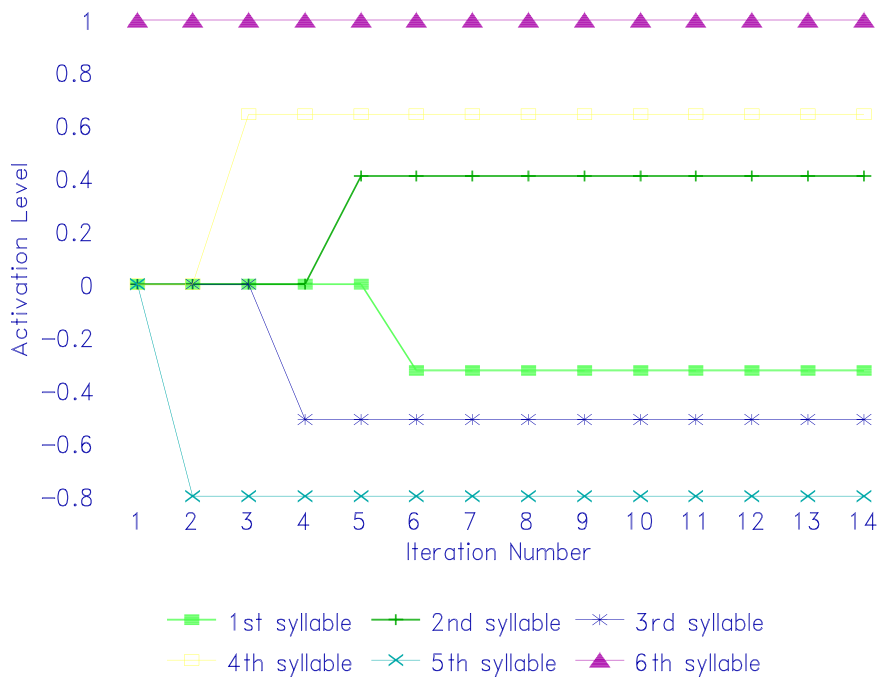
Let us consider a simple example, to illustrate the effects of these local connections. Let us suppose that α=-.8 and β=0, for simplicity's sake, and that the final unit has a positional activation of 1.0. No other activations are present at the initial state of the system: there is no initial activation (I) on the first unit, and no internal activation. The initial state (represented with the bar graph) and final state (represented by a line graph) are given in 0; the evolution of this system is illustrated in 0, iteration by iteration. We see that a wave of positive and negative activation passes leftward from the end to the beginning of the network; we see that, with a negative value of α, there is an essential rhythmicity built into the architecture of this system.

(4) Wave from Right to left, Final High:



α=-0.8
β=0
I=0
F=1

(5) Evolution



α=-0.8
β=0
I=0
F=1

By the same token, we can also see that the rhythmic effects of the system are in large measure independent of the exact choices of the numbers involved. We have chosen in 0 to specify α as -0.8, but any value for α that is between -1.0 and 0.0 will give the same "qualititative" result — a wave with peaks on odd numbered syllables, counting from the end of the word, and troughs on the even numbered syllables. The qualitative character of the system will be an important characteristic of dynamic computational systems.

In this simple example, the rhythmic character seems to be the direct result of a pulse that begins at one end of the word, either the left or the right end. We should observe, however, that much the same rhythmic effect is achieved by assigning to *each* of the units the same degree of internal activation (1.0, say); we shall refer to this common activation as a *bias*. Such a system is still quantity-insensitive, in the sense that all units receive the same (here, non-zero) activation regardless of their internal structure. We shall return to this characteristic, important for our understanding of the system, in section 3; for now, we shall assume that bias is zero.

Let us turn now to a consideration of quantity-insensitive accent systems from the point of view of this system.

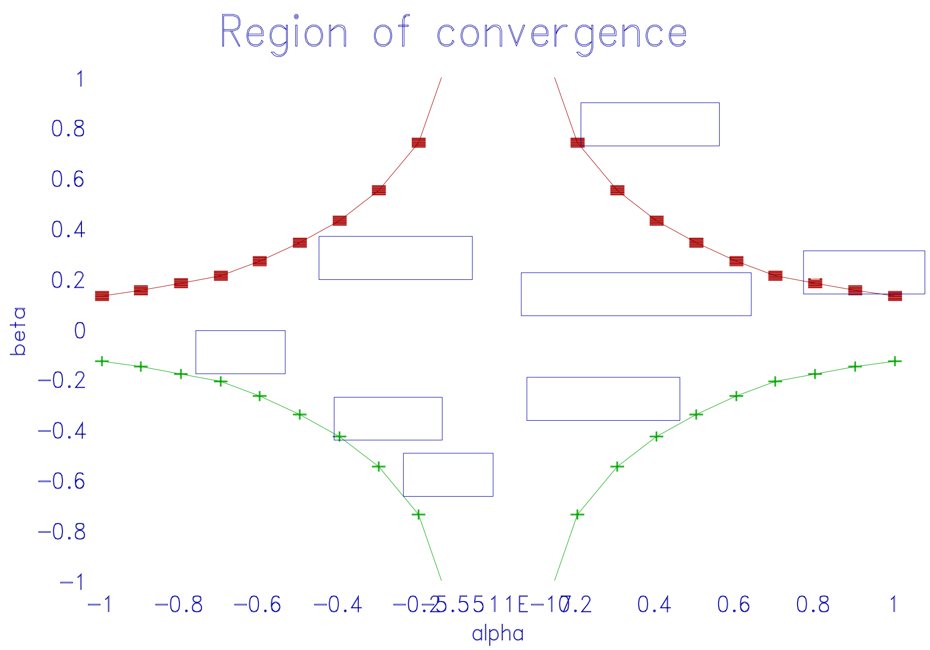
2. Quantity insensitive accent systems.

We will consider first a dynamic computational theory of accent for quantity insensitive systems. There are, for such systems, four essential parameters that can be independently varied: I, F, α, and β, as described above (assuming that the bias is zero, as we have noted). I and F represent the positional activation of the first and last syllable; α and β, the left and right coefficients described above. These parameters are fixed, once and for all, for each language; they define what the accentual pattern is for a given language.[7] The logic of this position is a familiar one in current linguistic thought, to be sure, though the particulars here are slightly different; just as one may specify a syntax as being the sum of the settings of the parameters specified by a Universal Grammar, and just as one may specify a metrical system as the sum of the parameter settings (End Rule (Initial, Row 1), for example, or QS [Quantity-sensitive]), so too dynamic computational models consist of a complete set of settings of parameters. The only differences in the present case is that, first of all, the settings need not be selected from a finite set (we have here a continuous set of values to draw from); and second, the parameters here are settings in the representations, not in a distinct set of rules.

The effects of increasing or decreasing the I or F variables is relatively straightforward: an increase in I or F will lead to a greater strength of the first or last syllable, respectively. "Increasing" or "decreasing" is, of course, a linguist's metaphor: the parameters are set once and for all for a given language, and learning a language amounts to discovering the appropriate setting of each parameter. The linguist, however, may wish to — in effect — play with the system, and see what results from varying each parameter's setting; each set of settings specifies a particular possible or existing accentual system.

However, if the effects of increasing I and F are straightforward, the effects of increasing or decreasing α and β are anything but transparent. It will be our goal in this section to explore the behavior of the accent systems that arise from various choices of α and β. A two-dimensional illustration of the space of all values of α and β is given in 0. The region bounded by the four hyperbolas represents the region within which the network will converge; outside of that region, the network will not converge — it will, to the contrary, explode, and not settle into an equilibrium state.[8]

(6) chart of α versus β



Regions of convergent behavior

The region in which the dynamic computational theory converges consists of the range of all the possible (and only the possible) quantity-insensitive accentual systems. There are, that is, only four principal parameters to consider: α, β, I, and F, and the quality of the system is largely determined by the choice of α and β, that is, by the location of the system within the coordinates of 0.

We will explore the behavior of the subparts of the graph in 0, beginning with the lower left-hand quadrant, that in which α and β are both negative. As we shall see, the negative values of α and β give rise to rhythmic patterns; after that, we shall explore the other regions, in which positive values may emerge.

Let us review the basics of some metrical systems which have been made familiar to us from the works of Hayes, Halle and Vergnaud, and others. These simple examples represent the basic cases that are familiar to metrical phonologists, and serve for us the end of illustrating how cases whose treatment within the familiar framework of metrical phonology finds a simple account within the present framework.

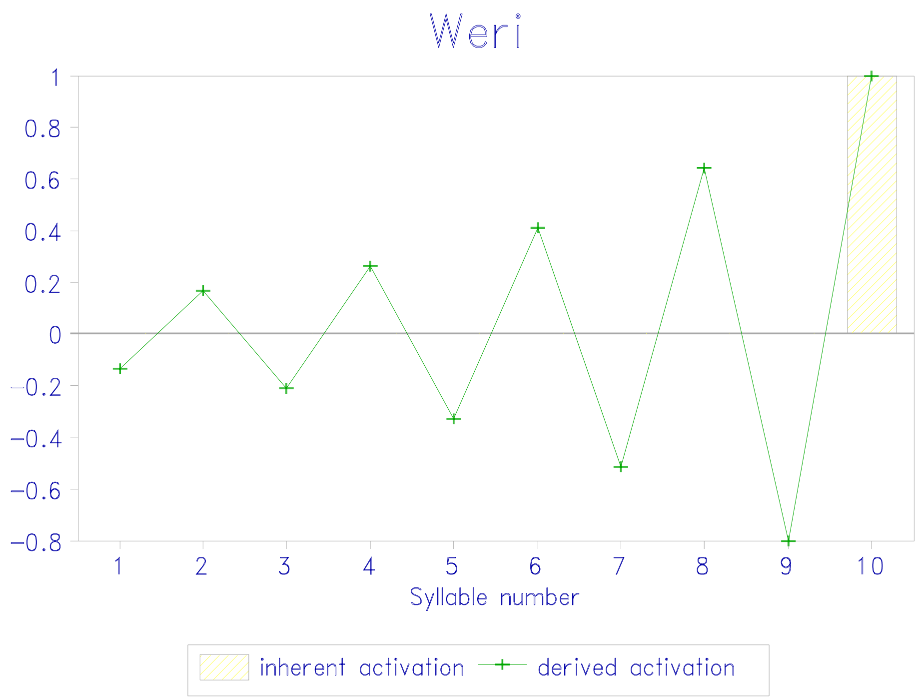
Weri (Boxwell and Boxwell 1966, discussed in Hayes 1980[9] and Halle and Vergnaud 1987, among other places) presents a system in which the final syllable is accented, as are all odd numbered syllables, counting from the end of the word. This is illustrated in 0. This pattern is achieved by setting α equal to a value between -1.0 and 0: -0.8, in the example in 0; F is equal to a positive number (we may normalize this value to 1.0), and I = 0.0. β is zero, since apparently no activation is passed to the right; we leave it, therefore, at 0.0. The graphic illustration in 0, as with the parallel examples to follow, consists of two descriptions of the system's state: the state described by the bar graph, in which only the 10th unit has a non-zero bar over it, illustrates the initial state of the system, while line graph shows the equilibrium state that it settles into.

(7) Weri:

_ɪntíp	"bee"
kÙ_pÚ	"hair of arm"
ᴜ_Ùamít	"mist"
àkᴜnètepál	"times"

The proposal, then, is that the wave of activations illustrated in 0 *is* the prosodic structure of this system; there are no rules other than those that we have discussed. The system directly settles into an equilibrium pattern whose maxima (peaks) specify where the phonological accents are located.

(8)



α=-0.8
β=0
I=0
F=1

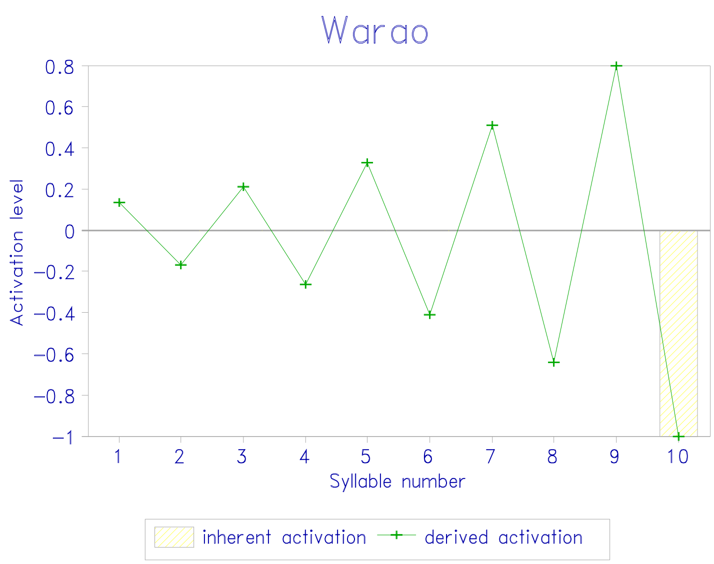
The next familiar example is that of Warao (Osborn 1966, cited in Halle and Vergnaud 1987), which differs from Weri essentially only in that the penultimate syllable in Warao is stressed, rather than the final, as in Weri; see the forms in 0. In traditional metrical phonology, this is accounted for by marking the final syllable as extrametrical, in effect hidden from later metrical rules such as the End Rule. In the present theory, there are no external rules, and no rule ordering, and such an account is entirely unavailable. Penultimate accent is, in the present theory, accounted for by the interaction of a negative value of F, the positional activation on the final syllable, together with a negative value of α. This is illustrated in 0, which differs minimally from the illustration in 0; it differs only in the negative value of F. In each case, a dampened wave propagates from right to left across the word. These examples illustrate clearly the way in which a negative value of α, along with a zero setting (or near zero setting) of β, produces the effect of stress iterating from right to left across the word. There are, within this theory, however, no explicit rules which iterate, and the passage of information from right to left is due to the inherent architectural properties of the system, rather than a language-particular characteristic.

(9) Warao:

yàpurùkitànehá se	"verily to climb"
nàhoròahàkutái	"the one who ate"
yiwàranáe	"he finished it"
enàhoròahàkutái	"the one who caused him to eat"

(10)

α=-0.8
β=0
I=0
F=-1



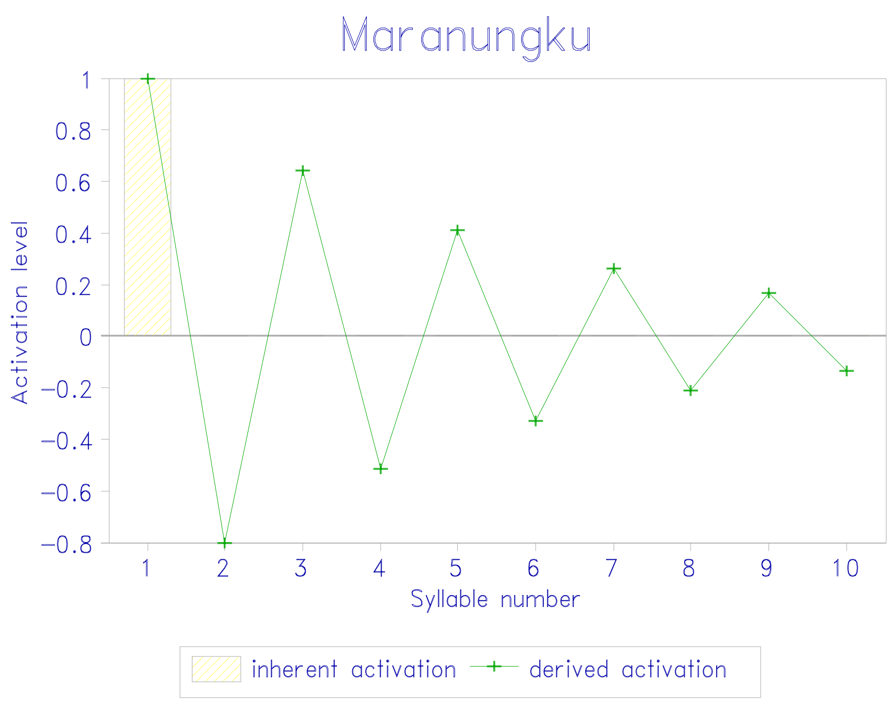
The third example to consider is the mirror image of the Weri case, such as in Maranungku (Tryon

1970), in which the initial syllable is accented, and an iterative wave propagates from left to right across the word. The parametric settings for such a system are I=1, F=0, $\alpha = 0$, β=-0.8. Examples of Maranungku forms are given in 0, and a typical dynamic representation is given in 0.

(11) Maranungku:

tíralk	"saliva"
mérepèt	"beard"
yángarmàta	"the Pleiades"
lángkaràtetì	"prawn"

(12)



α=0
β=-0.8
I=1
F=0

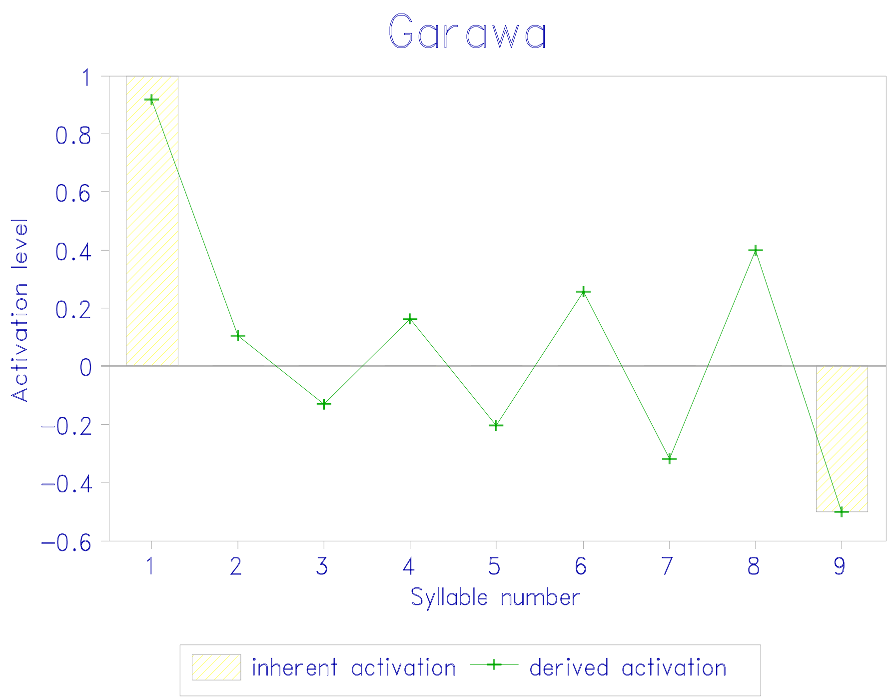
In the three cases which we have considered so far, the choice of parameters that we have explored has been especially simple, in that there was only one positional activation — either I or F was zero in all three cases.[10] But the normal case that we find in accentual systems is that the positional activations are *not* zero; it is typical to find that I is positive (i.e., the first syllable is accented), and that F is either positive or negative, but not zero (i.e., either the final or the penultimate syllable is accented, though there is more to say about this, as we will see below). Let us consider first the common system in which I is positive, and F is negative. Again focusing on the case where α and β are negative, the negative positional activation on the final syllable gives rise to a positive activation on the penult (through an α-effect).

Garawa (Furby 1974) illustrates this quite common class: accent falls on both the initial syllable and on the penult, corresponding to a positive setting of I, a negative setting of F, and a negative value of α (in order that the negative value of F should translate into a positive value for the penultimate syllable). In such systems, we typically find either accent iterating from left to right, on odd-numbered syllables counting from the first, or else accent iterating from right to left, on every other syllable to the left of the penult, depending on the relative magnitudes of α and β. Garawa falls into the latter category, as illustrated in 0, and this pattern illustrates the result of a system in which the α-effect is stronger than the β effect: in which, that is, $\alpha < \beta$ (though, more to the point, the absolute value of $|\alpha|$ is greater than that of $|\beta|$, since α is negative); see 0.

(13) Garawa:

púnjala	"white"
wátjimpà_u	"armpit"
ná_i_inmùkunjìnamì_a	"at your own many"

(14)



α=-0.8
β=0
I=1
F=-0.5

In Garawa, despite the large α-effect — the large magnitude of the leftward moving wave — we observe a clash avoidance effect, whereby when a word has an odd number of syllables, we would expect the second syllable to be accented, because it is on the positive side of the wave propagated leftward from the final syllable. However, the second syllable is *not* stressed in Garawa, a familiar effect known as stress clash avoidance (Prince 1983).

Stress clash avoidance appears to be universal among quantity-insensitive systems, though it is far from universal among quantity-sensitive systems. The impossibility of accent on two successive syllables emerges directly from the interpretation of the equilibrium state of the network that we suggested earlier, that is, that a syllable is phonologically accented if and only if it is a peak, or local maximum; by definition, two successive syllables cannot both be peaks — if they were, each would be higher than the other, a logical impossibility. Hence, as long as we maintain this particular interpretation of phonological accent, stress clash avoidance will not be additional specified, but will rather emerge directly out of the equilibrium state that is derived. We observe precisely this effect in Garawa; the second syllable may be positive, but it is less than that found on the first syllable, and hence it is not a peak — hence not phonologically accented.

We have so far explored systems that resemble traditional metrical systems in that they apparently iterative either leftward or rightward.[11] The quantitative typology of figure (2) leads us to consider the significance of the intermediate zone, where neither α nor β are near zero, and both are negative. This is, in effect, the region in which both a leftward and a rightward propagation of a wave should be apparent, and, of course, the observation of such a system would be strong support for this wave-oriented conception of rhythmicity, as contrasted, in particular, with the constituency view of Halle and Vergnaud and others.

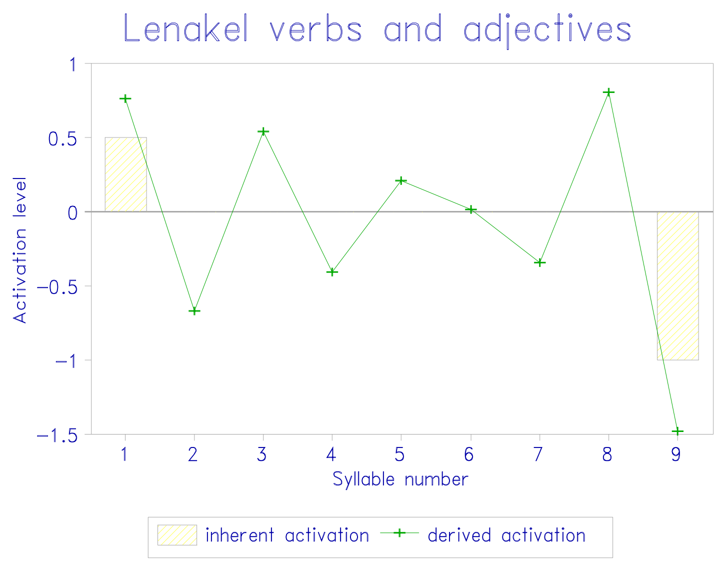
The well-known example of Lenakel is just such an example. As is well-known (cf. Lynch 1978, Hayes 1980 and others), accent in Lenakel is unusual in that stress is assigned according to principles that appear to be quite different in nouns when compared with the principles operative in verbs and adjectives. Verbs and adjectives (see 0) are stressed on the penultimate syllable, on the first syllable, and on every alternate (odd numbered) syllable as we count from left to right, starting with the beginning of the word, with the exception that the antepenult is never stressed. Nouns, on the other hand, bear penultimate stress, and show a pattern of accent assignment on alternate syllables counting from the *end* of the word, alternating leftward from the penultimate syllable. See 0.

(15) Lenakel verbs, adjectives

_imlgygɛy	"he liked it"
nima_lgygɛy	"you pl. liked it"
nimamà_lgygɛy	"you pl. were liking it"
tinagàma_lgygɛy	"you pl. were liking it"

(16) Lenakel verbs, adjectives

α=-0.4
β=-0.6
I=0.5
F=-1.0

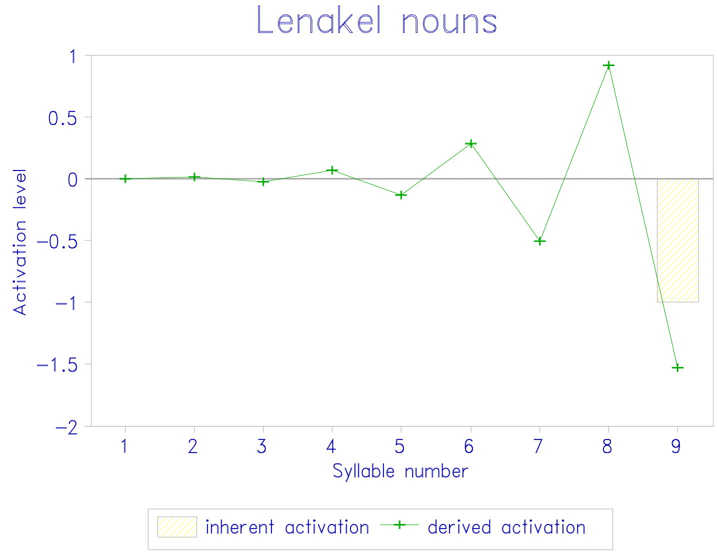


(17) Lenakel nouns

kàmadóa "k.o. taro"
nim^{w}àg@lág@l "beach"
tub^{w}àlugálʊkh "lungs"

(18) Lenakel nouns

α=-0.4
β=-0.6
I=0
F=-1



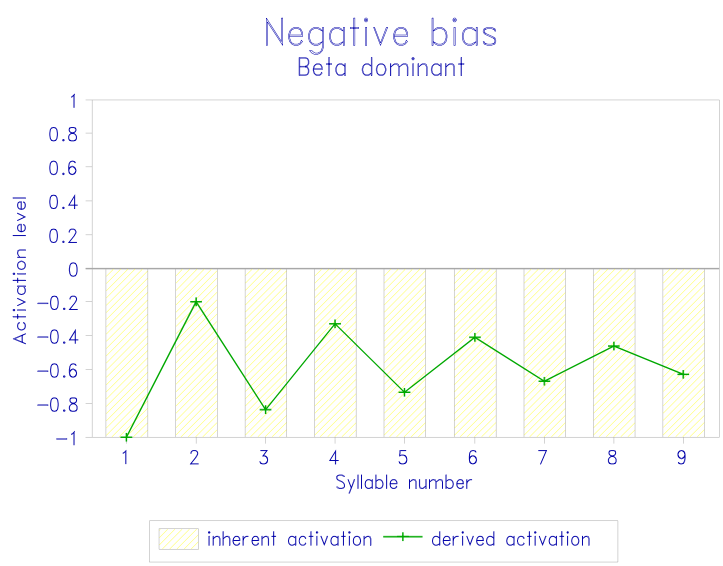
This pattern is a peculiar embarrassment to traditional accounts of Lenakel, accounts which distinguish essentially between rules and representations. In nouns, not only is the initial stress of the verbs missing, but the direction of iteration of the rule that creates alternating stress must change depending on lexical category. In the present model, however, nothing of the kind is necessary; not only is this case not an embarrassment, it is precisely the kind of case that is predicted by the theoretical model. We need simply say that in the case of nouns, there is no Initial activation; crucially, however, the values of α and β remain fixed across the entire language. Because there is no Initial activation in the case of nouns, there is no rightward-spreading wave for the β-coefficient to pass on. There is, from a mathematical point of view, both a wave propagated leftward and a wave propagated rightward; the one which is stronger will, by and large, drown out the other from a purely quantitative point of view, but when the rightward moving wave is removed, by the non-occurrence of initial stress in the nominal system, the wave moving *sotto voce* leftward from the penult becomes entirely audible.

3. Quantity-insensitive systems with bias, and some observations on quantity sensitivity

We have so far considered only cases where the internal activations to all segments was zero, equally and across the board. By definition, quantity-insensitive systems assign equal internal activation to each unit, but that activation need not be zero; it may be a quantity (which we shall refer to as *bias*) which all the units uniformly receive. A non-zero bias will give rise to a rhythmic system as well, as illustrated in 0, where a negative bias is applied, and in 0, where a positive bias is assigned. Rhythmicity of much the sort that we have already explored is inherent to the system, whether activation comes in from one unit or from all of them.[12] In these two examples, the rhythm emerges in a β-dominant system, i.e., one where β is significantly negative and α is zero or negligibly close to it. This is similar (though, as we shall clarify, not entirely equivalent to) the traditional conception of a rhythmic pattern assigned from left to right, just as an α-dominant system is similar to the notion of a rhythmic system assigned from right to left.

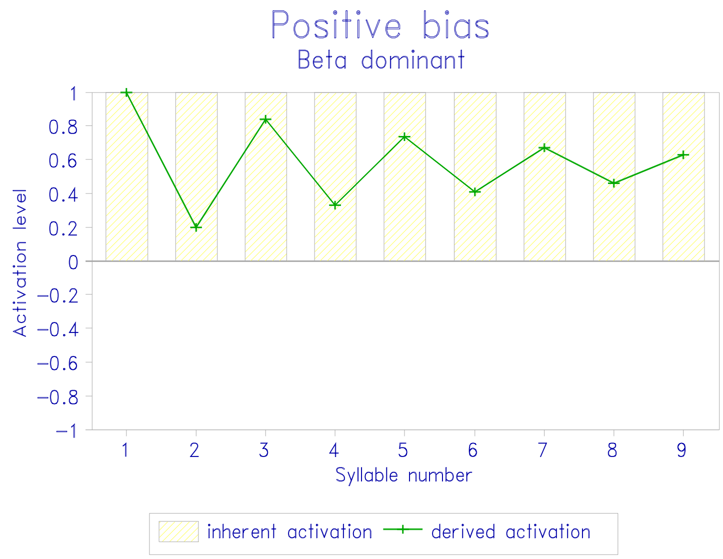
(19)

α=0
β=-0.8
I=0
F=0
bias=-1.0



(20)

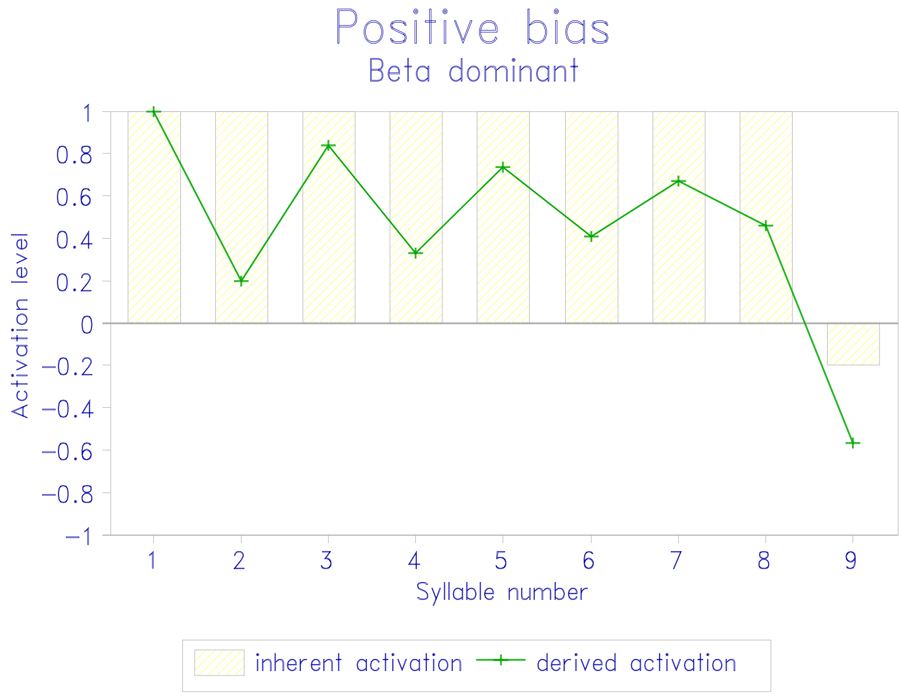
α=0
β=-0.8
I=0
F=0
bias=1.0



We may now notice an interesting result arising from the combination of the bias effect and the positional activations that we have explored to this point. In a β-dominant system such as that given in 0, if the Final parameter F is set to a negative value, such as -0.5, we will get a similar but distinct pattern, that given in 0. This pattern is precisely that which is described in metrical phonology as a left-to-right alternating stress pattern with final extrametricality, i.e., where the final syllable is unable to bear stress. This example should make clearer the sense in which this dynamic computational theory is not an implementation of metrical theory, though it does contain subparts that correspond, in certain ways, to familiar subparts of metrical theory. We have just seen that certain effects that are associated with extrametricality correspond to a negative F coefficient in the present framework. Such a setting is not specially created *for* extrametricality, however, as we have already seen. There is, then, arguably a tighter theoretical fit among the entities at work in this model.

(21)

$\alpha=0$
$\beta=-0.8$
I=0
F=-1.2
bias=1



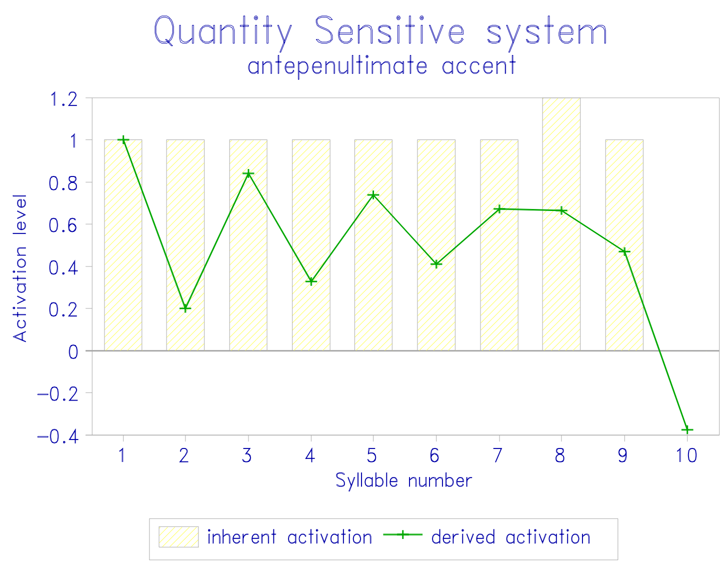
As we explore further, we see that the present theoretical model includes some of the equivalents of extrametricality of this sort, but in a qualititatively different fashion from that which we are accustomed to seeing in traditional metrical theory. In particular, the final syllable is not "invisible" in any sense of the term, though invisibility is the governing metaphor for extrametricality in metrical theory. This difference leads to an interesting prediction. In the present system, there is no way to use the equivalent of extrametricality in conjunction with a α-dominant, i.e., a "right to left" pattern of rhythmicity. That is, we cannot directly generate a pattern of accent in which the accent regularly falls on the antepenult syllable, a result which is extremely easy to generate within traditional metrical phonology. Within a traditional metrical approach, one need simply mark the final syllable as extrametrical, and then assign a trochaic foot to the right-hand end of the word.

The only way to generate this pattern within the present system is within a quantity-sensitive system; within such a system, it is easy to generate antepenultimate accent, illustrated in 0. A quantity-sensitive system is, by definition, one for which the activation of each of the (non-peripheral) syllables is not uniform: some syllables have more internal activation than others. As the following diagrams illustrate, it is a simple matter to establish a system with a local maximum on the antepenult (and *not* the ultima) when there are differences in the internal activation of the penult and the antepenult.

A deeper investigation of this system brings out an interesting and striking characteristic. Under most natural values of α and β (i.e., when they are not trivially near zero) and under natural assumptions regarding the range of variation in syllable weight between heavy and light syllables, we find that there must be a peak on either the antepenult, the penult, or the ultima — i.e., it is not possible to have three non-peak syllables in a row. This result is a familiar one, from the phonologist's point of view: the final three syllables of a word constitute a window inside of which a stress, i.e., a local peak of activation, must appear. From the perspective of the present theory, this is not a condition on sound-structure, nor a condition on permissible constituents, but simply a mathematical result that follows from the nature of the arithmetic relations between adjacent elements.

(22)

α=0
β=-0.8
I=0
F=-1
bias=1



A complete exploration of the various possibilities that can be produced with this system would take us beyond the scope of this short paper. But this brief discussion will help us nonetheless to see what the dynamic computational theory does when it determines that stress is assigned, for example, to the penultimate or the antepenultimate syllable. This determination is made on the basis of a simultaneous weighing of a number of distinct factors: in the cases considered so far, these factors are largely determined by the fixed bias applied to each unit, plus the lateral effects coming in from either side, and a unit which is more highly activated than its neighbor, then, is phonologically accented. Other factors, based on syllable-internal structure (or, in the odd case, on idiosyncratic information), can also be taken into account in just the same computation. The entire phonological system becomes, on this account, a large weigher of alternative configurations quantitatively expressed, and when alternatives come into conflict, the conflicts are resolved quantitatively. Categorical (that is, yes/no) effects are created, in the cases we have seen, on the basis of selecting which units are local maxima, i.e., more active than their neighbors.

We may briefly review the effect of adding the effects of quantity sensitivity. This consists, as we have indicated, of an internal activation to some syllables which not all syllables receive. Let us assume, for simplicity's sake, that some syllables — in familiar terms, the heavy ones — receive an additional amount of activation, H; the others, the light ones, do not. The factors that we have discussed up to now allow us to accurately model the kinds of metrical systems that have motivated in the traditional metrical literature a burgeoning of theoretical devices, such as obligatory branching foot structure of various types. Consider the contrast between two similar metrical systems (I follow here a discussion in van der Hulst (ms.) which provides a helpful discussion of the problems for current metrical theory; the point is a general one, of course): both Rotuman (Churchward 1940) and Yapese (Jensen 1977) are quantity-sensitive systems in which stress falls on the ultima or the penult, depending on syllable weight. If, in that final window of two syllables, there is only one heavy syllable, then that syllable is the stressed syllable. If there are two heavy syllables (i.e., if both the penult and the ultima are heavy), then the final syllable is stressed. The systems differ, however, with respect to where stress falls when both the ultima and the penult are light: in Rotuman, the stress falls on the penult, and in Yapese, the stress falls on the ultima.

(23) (after van der Hulst) Final Two Syllables' Weight: Light, Heavy

Language	H L]	L H]	L L]	H H]
Rotuman	*	*	*	*
Yapese	*	*	*	*

The complexities of such systems do not require derivational complexities, as the computations of the dynamic computational theories demonstrate. The results given in 0 are given by a dynamic grammar in which α=-0.8,[13] and heavy syllables receive an internal activation of 2.0 (i.e., 2.0 more than the other syllables, the light syllables). The difference between the two systems results from the character of the bias applied to the system, as the discussion just above suggests. When the bias is positive (+1.0), then the resulting system is that seen in Yapese, i.e., when all the syllables are light, the ultima has the highest activation level (1.0, in fact). When the bias is negative (-1.0), the penult has the highest activation (-0.20), as in Rotuman. These are the only cases that behave differently; when there are heavy syllables, the two systems work the same qualitatively, as 0 illustrates.

(24) Final Two Syllables' Weight: Light, Heavy

bias	Language	H L]	L H]	L L]	H H]
neg	Rotuman	1.8 -1.0	-1.8 1.0	-.2 -1.0	.2 1.0
pos	Yapese	2.2 1.0	-1.4 3.0	.2 1.0	0.6 3.0

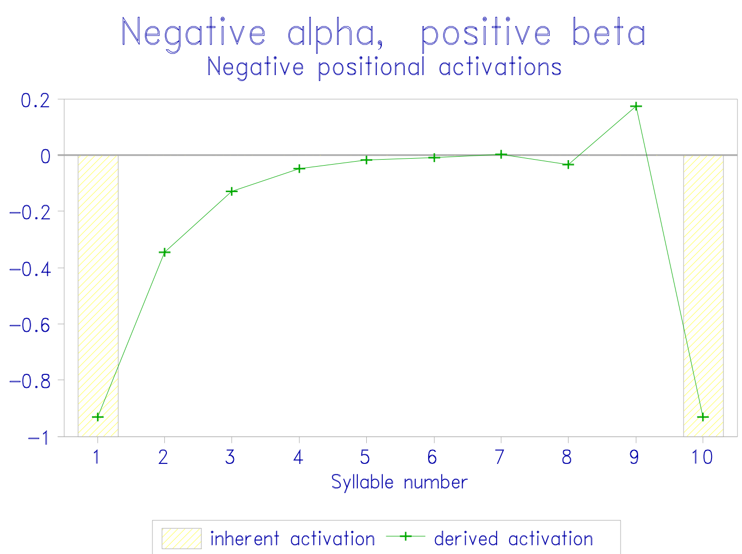
More generally, problems of quantity-sensitive accent assignment can be accounted for thoroughly within the present theory, without the use of ordered renderings of constituent structure, as this example illustrates.

4. Other quadrants

We have so far investigated the properties of only one of the four quadrants of the graph of α,β given in 0, that in the lower left-hand corner, where α and β are both negative. In this section, we will briefly consider two qualitatitvely distinct types of behavior found in the other quadrants.

Consider, first, the quadrant in which α is negative and β is positive (the upper left-hand quadrant), and the quadrant in which α is positive and β is negative (the lower right-hand quadrant). When the only inherent activation comes from I or F, the result is much like that given in 0. The phonological interpretation of this system is straightforward; these systems contain only one peak. When α is positive, the right-hand end of the word will be non-rhythmic in general, and when β is positive, the left-hand end of the word will be non-rhythmic. We find here, therefore, the case of words with non-rhythmic stress.

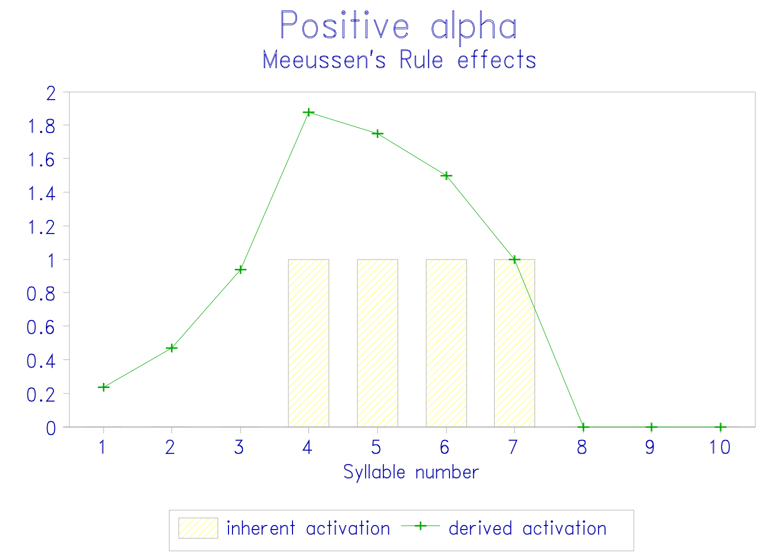
(25)
α=-0.2
β=0.6
I=-1.0
F=-1.0



The other case to consider is that where both α and β are positive. This region of the α-β phase space is of some interest when we consider the treatment of non-rhythmic, quantity-sensitive languages, systems in which certain syllables are specified as heavy (and which have an inherent activation for that reason). Consider the derived activation of a system in which α is positive (β is zero), and in which a sequence of three syllables is accented, i.e., has an inherent activation of 1.0. We assume in this example that I=F=0. This is illustrated in 0, where we see the effect that has been discussed in the literature under the rubric of "Meeussen's Rule" (Goldsmith 1984): in a sequence of accented elements, only the leftmost "wins", i.e., in the present terms, only the leftmost is a local peak of activation.

(26) Meeussen's Rule

α=0.5
β=0
I=0
F=0



Qualitatively distinct behaviors can thus emerge out of the interaction of the limited continuous parameters that define the dynamic computational theory. Larson and I explore these models in considerably greater depth in a work now in progress.

5. Concluding observations

It is helpful to draw a distinction in phonological theory between the theories of representations, of levels, and of rules. It may appear that the major proposal of the theory of dynamic computational systems is as a revision of our theory of phonological representations: the proposal entails, for example, a representation in which the positive and negative real numbers play a role, thus enriching our representation. This apparent focus on the theory of representations would be entirely in line with the trends in phonological theory since the mid-1970s.

Such a view would be inaccurate, however. The primary motivation and the primary goal of the work described here concerns the theory of phonological rules, and to a lesser degree the theory of phonological levels, and it is only marginally and in passing a modification of the theory of representations. In fact, the theory of the metrical grid as developed over the last ten years has been qualitatively integrated directly into this theoretical model. By contrast, the goal of this work is to explore the possibility of shifting the line between our traditional conception of rules and of representation: to shift the burden of dealing with dynamic modifications of representations from the rules back to the representations themselves.[14] I have explored the motivation and importance of this in other places (Goldsmith 1990, chapter 6.4-6.6; Goldsmith 1991, in press).

Our larger goal is a theory of formal grammar in which the central consideration is the quantitative resolution of conflict. This perspective is close in many respects to the autolexical view of Sadock 1991, and close as well to views of cognition that have been influenced by connectionist thinking, and to the broad class of computational treatments of soft constraint resolution. The treatment of accentual systems which we have explored in this paper is illustrative of a wide variety of traditional problems in linguistic analysis for which an arguably deeper account can be obtained without recourse to those aspects of more familiar linguistic theory which have served to place the greatest gulf between linguistic theory and the other cognitive sciences.

The present work has been heavily informed by current work on neural networks and connectionism, though its point of theoretical orientation is perhaps radically different from much of the work presented within that general perspective. A seeming gulf separates most of the theoretical work on language done within the traditions of generative grammar, and those informed by formal and mathematical traditions allied with the study of connectionist networks and dynamical systems.[15] This gulf serves only to isolate workers on either side from the benefits that can be achieved from a more open-minded perspective; I believe the present paper illustrates the ways in which additional theoretical tools can provide new and more compelling theoretical models for the phonologist.

References

Boxwell, H. and M. Boxwell. 1966. Weri Phonemes. In S. A. Wurm (ed.), *Papers in New Guinea Linguistics* No. 5. Canberra: Australian National University, pp. 77-93.

Churchward, C.M. 1940. *Rotuman Grammar and Dictionary*. Australian Medical Publishing Company.

Furby, C. 1974. Garawa phonology. *Pacific Linguistics*, Series A, No. 37. Canberra: Australian National University.

Goldsmith, John. 1984. Meeussen's Rule. In Mark Aronoff and Richard Oehrle, eds., *Language Sound Structure: Studies in phonology presented to Morris Halle by his teacher and students*. Cambridge, Mass: MIT Press.

Goldsmith, John. 1990. *Autosegmental and Metrical Phonology*. Oxford and Cambridge MA: Basil Blackwell.

Goldsmith, John. 1991. Phonology as an Intelligent System. In *Bridges Between Psychology and Linguistics: A Swarthmore Festschrift for Lila Gleitman*, edited by Donna Jo Napoli and Judy Kegl. Lawrence Erlbaum.

Goldsmith, John. In press. Local Modeling in Phonology. In Steven Davis, ed., *Connectionism: Theory and Practice*. Oxford University Press.

Goldsmith, John and Gary Larson. 1990. Local Modeling and Syllabification. In *Papers from the 26th Annual Regional Meeting of the Chicago Linguistic Society: Parasession on the Syllable in Phonetics and Phonology*. Edited by Karen Deaton, Manuela Noske, and Michael Ziolkowski.

Goldsmith, John and Gary Larson. In preparation. *Dynamic Computational Models in Phonology*.

Halle, Morris and Jean-Roger Vergnaud. 1987. *An Essay on Stress*. Cambridge: MIT press.

Hayes, Bruce. 1980. *A Metrical Theory of Stress Rules*. MIT PhD dissertation. Circulated by the Indiana University Linguistics Club, 1981.

Hulst, Harry van der. 1991. Notes on the Representation of Stress. Unpublished ms., University of Leiden.

Jensen, J. 1977. *Yapese Reference Grammar*. Honolulu: University Press of Hawaii.

Larson, Gary. 1990. Local computational networks and the distribution of segments in the Spanish syllable. In *Papers from the 26th Annual Regional Meeting of the Chicago Linguistic Society:*

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Larson, Gary. in preparation. *Dynamic Computational Networks*. PhD dissertation, University of Chicago.

Legendre, Géraldine and Paul Smolensky. 1990. Can Connectionism Contribute to Syntax? Harmonic Grammar, with an application. In *Proceedings of the 26th Meeting of the Chicago Linguistic Society*. Karen Deaton, Manuela Noske, and Michael Ziolkowski, editors. Chicago Linguistic Society.

Liberman, Mark. 1975. *The Intonational system of English*. PhD dissertation, MIT. Distributed by IULC. Published by Garland Press, New York, 1979.

Liberman, Mark and Alan Prince. 1977. On stress and linguistic rhythm. *Linguistic Inquiry* 8: 249-336.

Lynch, John. 1978. *A Grammar of Lenakel*, Pacific Linguistics Series B No. 55, Australian National University. Canberra.

Osborn, H. 1966. Warao I: Phonology and Morphophonemics. *International Journal of American Linguistics* 32: 108-123.

Prince, Alan S. 1983. Relating to the Grid. *Linguistic Inquiry* 14:19-100.

Prince, Alan. 1991. Quantitative Consequences of Rhythmic Organization. Ms., Brandeis University.

Sadock, Jerrold. 1991. *Autolexical Grammar*. University of Chicago Press.

Smolensky, Paul. 1988. On the proper treatment of connectionism. *Behavioral and Brain Science* 11: 1-74.

Tryon, D.T. 1970. *An Introduction to Maranungku*. Pacific Linguistics Series B, Number 14. Canberra: Australian National University.

Notes

(1) This paper was presented at the Conference on the Organization of Phonology at the University of Illinois, Urbana, May 3, 1991, organized by Jennifer Cole and Charles Kisseberth, and will appear in the proceedings of the conference. I am grateful to Gary Larson, Caroline Wiltshire and Jessie Pinkham for their assistance in the preparation of this paper. This material is based upon work supported by the National Science Foundation under Grant No. BNS 9009678.

(2) The graphs and the calculations in this paper were produced by Quattro Pro 3.0, a spreadsheet program. Spreadsheet programs are excellent "blackboards" for working out the effects of various assumptions within a dynamic computational theory, as Gary Larson pointed out to me; in most cases, they have the additional advantage of producing useful graphical output at the same time as they perform the needed calculation. We are currently producing a set of programs for distribution to linguists interested in exploring this theory, so that they will not need to write their own programs.

(3) In other work, in collaboration with Gary Larson, we have explored a wide range of analyses of sonority and syllabification using precisely the same model.

(4) This third difference is less significant than it may sound, since virtually all lengthy treatments of metrical theory appeal at one point or other to principles which raise or lower the absolute height of a column, or set of columns, for the convenience of the analyst.

(5) In the discussion that follows, we assume that the internal activation for all units is zero. This is not necessarily the case; the internal activation may be the same for all units, but different than zero. This assumption has a significant impact on the results, which we shall return to below in section 3.

(6) Another way to think of this system is as the n^{th} power of a matrix which is applied to the vector which specifies the initial state of the units. We may think of the initial state of the k units as the k-vector **V**, and we may construct a k by k matrix which represents a single recomputation of the system, that is, a single passage of activation from each unit to its two neighbors. Such a matrix will be all zeros except for the supradiagonal ($x_{i,i+1}$), which is everywhere α, and the subdiagonal ($x_{i,i-1}$), which is everywhere β. The system takes on the value $V + M^t (V)$ at time t, where M^t is the t^{th} power of M. This matrix must reach — exactly, or asymptotically — a limit for the system to display the equilibrium state that is necessary for these dynamic computational models.

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established by Hayes in this work.

(10) When only one positional activation is present, it is difficult to detect the presence of two lateral effects; that is, when there is positional activation on the first syllable ($I>0$ or $I<0$), the appearance of a rightward β-effect (i.e., a rightward propagating wave as the result of a sufficiently large, negative β) will make it evident that β is, in fact, negative, and not zero or positive; on the other hand, in such a system, if there is no positional activation on the final syllable (if $F=0$, that is), it will be difficult to detect whether α is zero or not. When there is no reason to think that α is not zero, I have assumed that it is zero (similarly for β).

(11) The notion of constituency, the reader will observe, has only a limited status within this theory. There is a natural way to define metrical constituents within the present framework; there are, in fact, two natural ways, since the wave that results from the approach discussed in the text invites two natural ways in which to make the cuts: one can make cuts at the local maxima (peaks) or at the local minima (troughs). Metrical theory has traditionally chosen the former, while syllabification theory, when faced with exactly the same problem, has chosen the latter. This difference reflects the traditional phonologist's intuition that stressed syllables are foot-peripheral, while the nuclear element of a syllable is typically syllable-internal, at least in the presence of a coda. The present theory invites a greater reconsideration of these questions, which we address in a longer work presently in progress. Suffice it to say, for our present purposes, that constituency plays a minor and derivative role in present framework.

(12) Since everything is linear, the final state D of initial state X+Y ($D= f(X+Y)$) is equal to the sum of the final state derived from initial X plus the final state derived from initial Y (i.e., $f(X+Y)=f(X)+f(Y)$). Let us take X to be the state in which all segments have internal activation "1"; then we see that the shape of the curve derived from such an initial activation is independent of the strength of that activation — that is, varying the internal activation common to all the units will change only the scale (i.e., the height) of the wave that is produced, but nothing else. In particular, the location of the peaks and troughs will be unaffected. We may therefore consider only three cases with no loss of generality — the case where the bias is 0, the case where the bias is 1, and the case where it is -1.

(13) Though the specific value, of course, of this and most of the other values does not matter; the properties of the dynamical system that we are interested in here are qualitative, and we care about the entire subspace of the phase space within which the same qualitative effects are found.

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(15) Notable exceptions to this include the recent work of Legendre and Smolensky 1990 and Prince 1991. My own understanding of the potential of connectionist modeling is heavily influenced by Smolensky 1988.

Note to editor:

These graphs are not entirely consistent in their graphical style. I have assumed that they would be redrawn. If you need consistent camera-ready graphs, please let me know.

Please note the modifications of certain phonetic symbols as well.

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