

Computing Long-Distance Dependencies in Vowel Harmony

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This article develops an explicit procedural model of vowel harmony, and takes steps toward finding a lower bound on the computational power of phonological rules. The focus on formalization and procedural computation allows for simplification in models of representation and the discovery of interesting interactions involving the conditions in rules. It is shown that locality principles are derivable, which motivates the elimination of iterative rule application advocated here. Along the way, a novel analysis of neutral vowels in harmony processes is also provided.

Keywords: assimilation; locality; long-distance dependency; procedural phonology; SEARCH and COPY; substance-free; vowel harmony

1. Introduction

This article introduces the following proposals concerning the formal properties of a strongly procedural model of phonological assimilation:

- (1) *Phonological Assimilation*
 - a. Assimilatory processes comprise (i) a SEARCH algorithm from which locality effects can be derived (i.e. there are no locality principles encoded in the grammar) and (ii) a COPY operation which transmits feature values across segments.
 - b. SEARCH-derived locality relations are non-symmetric: If x is in a locality relation $L(x,y)$ with y , it is not necessarily the case that y is in a locality relation $L(y,x)$ with x .
 - c. SEARCH is always initiated from the recipient, or target, of assimilatory rules, and this fact leads to the elimination of iterative rule application.
 - d. Both SEARCH and COPY may have arbitrarily specified conditions on their application, and these formal distinctions allow for the analysis of empirical differences.



We proceed shortly to the illustration of proposals (1a-d), and show how they can derive a wide variety of phenomena that are traditionally grouped under the rubric ‘vowel harmony’. First we shall say a quick word about phonological rules and representations.

2. On Proceduralism and Precedence

In this contribution we propose a strongly procedural model for vowel harmony, and we expect to extend this analysis to other types of processes. We have provided arguments elsewhere (e.g., Reiss, in press) against non-procedural, constraint-based models. Our approach may appear to be at odds with the phonological *Zeitgeist*, given the popularity of Optimality Theory (OT), but closer inspection reveals that, confronted with the intransigence of opaque derivations, much current work in OT has retreated from the anti-procedural, two-level models that were first proposed. Kiparsky’s (2000) stratal LPM-OT, which involves multiple levels in the generation of a surface form, and McCarthy’s (2000) Harmonic Serialism, which is explicitly serialist and moreover involves iterative constraint application, are two examples of the return to a model that mimics the derivations of pre-OT work. The basic idea of a procedural approach is that the grammar should specify, not what is well-formed or ill-formed, but how to map an input to an output, as an explicitly characterized function. Our approach, maintains a procedural view, but eschews constraints altogether. Interestingly, our interpretation of phonological rules appears to simplify derivations in requiring fewer rule applications and fewer intermediate levels of representation than traditional models that required iterative rule application, a mechanism we avoid.

We accept Raimy’s (2000) arguments and adopt his proposal that phonological strings are ordered sets of timing slots associated with feature bundles, and moreover that any ordering on features is induced from this order.¹ Formally, then, we take a phonological string to be a total order $\Sigma = \langle X, \preceq \rangle$, and the expression ‘ $a \preceq b$ ’ is read “the timing slot to which feature bundle a is associated precedes the timing slot to which feature bundle b is associated” — for short, “segment a precedes segment b .”²

Following standard mathematical practice, we define immediate precedence as a special sub-case of precedence: $a < b \Leftrightarrow a \preceq b \ \& \ \forall c \neq a, c \preceq b \Rightarrow c \preceq a$. In words, a immediately precedes b if and only if a precedes b and for all c other than a , if c precedes b , then c precedes a . Reducing immediate precedence to a sub-case of precedence allows us to take the perspective that rules involving segmental adjacency are really just special cases of long-distance interactions. It

¹ In fact, Goldsmith (1979: 28) explicitly states that tiers are ordered as well: “Each autosegmental level is a totally ordered sequence of elements, a_j^i : this is the j^{th} element on the i^{th} level. Call the set of segments on the i^{th} level L^i .” Empirical considerations about contour tones, for example, support this view. Since this will not matter for our discussion, we do not address it further.

² The totality of the order means that we do not allow precedence “loops” unlike in Raimy’s initial account of reduplication.

then follows that long-distance interactions cease to have any special status since the machinery needed to formulate them is needed for adjacency as well. This view of long-distance dependency does go against the grain of most phonological research, where phonological rules are assumed to apply under adjacency, and non-local effects are either explained away, or else require special theoretical machinery.

3. The SEARCH Algorithm

We propose that assimilatory rules (and perhaps others) make use of a search procedure that stipulates a direction of search δ ('LEFT' or 'RIGHT') within a phonological string Σ , as well as initiation and termination criteria, denoted ζ and γ , respectively. The algorithm, which is reminiscent of Chomsky & Halle's (1968: 344) approach to multiple rule application, is given in Figure 1.

SEARCH ($\Sigma, \zeta, \gamma, \delta$):

1. Find all x in Σ subsumed by ζ and index them: $\zeta_0, \zeta_1, \dots, \zeta_n$.
2. For each $i \in \{0, \dots, n\}$:
 - a. Proceed from ζ_i through Σ in the direction δ until an element subsumed by γ is found.
 - b. Label this element γ_i .
3. Return all coindexed pairs, (ζ_i, γ_i) .

Figure 1: The SEARCH algorithm

Thus an application of SEARCH will find one terminating point — the closest one in the appropriate direction — for each ζ_i . The crucial point, however, is that SEARCH proceeding from two distinct starting points, ζ_i and ζ_j , may terminate on a common goal, returning pairs (ζ_i, γ_i) and (ζ_j, γ_j) , where $\zeta_i \neq \zeta_j$, but $\gamma_i = \gamma_j$. Such a goal will bear multiple indices: $\gamma_{i,j}$.³

This property of SEARCH, in which multiple initiation points may come to be associated with a single goal segment, effectively eliminates the need for iterative application of harmony rules that spread a feature value in “local” steps. In one fell swoop, each harmonizing segment finds the closest instance of the relevant feature. As a simple illustration of this, consider the following abstract string, where x_1 and x_2 are of type X , and y_1 and y_2 are of type Y :

$$(2) \quad \Sigma = [x_1 \prec x_2 \prec y_1 \prec y_2]$$

³ Note that ζ and γ are being used to refer to both types and tokens. Unindexed ζ and γ are always feature specifications that define the type (natural class) of the initiating and terminating segments of the SEARCH algorithm, while indexed ζ_i and γ_j are token segments subsumed by ζ and γ .

Assume now that we have invoked the procedure `SEARCH(Σ , x , Y , 'RIGHT')`, or in words, “identify segments of type x and search to the right for segments of type Y .” `SEARCH` will return the following set of pairs: $\{(x_{1i}, y_{1i,j}), (x_{2j}, y_{1i,j})\}$. That is, y_1 is the first element of type Y to the right of x_1 , and it is also the first element of type Y to the right of x_2 . The example makes it clear that the locality relations defined by `SEARCH` are non-reversible: Although y_1 is the closest element of type Y to the right of x_1 , it is not the case that x_1 is the closest element of type x to the left of y_1 . In fact, it is x_2 that is the closest element of type x to the left of y_1 .

Traditionally, locality has been taken to be a symmetric relation, and one could simply say that a pair of segments a and b were in the relation of locality. Given the stance that we have adopted, in which locality is not a grammatical primitive, but is instead derived from a typed and directionally-specified `SEARCH` procedure, we can see that the traditional, simplistic view is no longer sufficient. Although it seems that we have complicated the phonology, this is in fact not the case, since locality has now been taken out of the grammar. Moreover, we shall see that the derived relation allows for a unified analysis of seemingly disparate and complex phenomena. This capturing of empirical generalizations is the true litmus test of the suitability of our modifications to the theory of phonological computation.

This property of searching linearly, but for objects of a particular type, is crucial to the existence of long-distance interactions in phonology. In fact, rather than viewing this discussion as an analysis of locality, it may be more useful to view it as an exploration of the mechanisms that allow for long-distance interactions in phonology.

Long-distance dependencies have been considered one of the defining features of human language, at least since *Syntactic Structures* (Chomsky 1957), and so we find it curious that so much ink has been spilled attempting to explain away such relations in phonology. Given our view of adjacency as a special case of long-distance dependency, and given the obvious parallels with syntax, we find no motivation for the eliminative reduction of long-distance effects in phonology.

4. SEARCH and COPY: Standard as Target

In the subsequent discussion we focus on feature-filling vowel harmony processes. Such processes involve filling in a feature value, $[\alpha F]$ onto a recipient vowel by copying $[\alpha F]$ from a donor segment elsewhere in the phonological string. As mentioned in proposal (1c), we claim that the recipient segment in the `COPY` operation (see Figure 2 below) is always the initiation point of the `SEARCH` algorithm. This discovery is made possible by recognizing the inherently asymmetric nature of the relation established by `SEARCH`.⁴

⁴ A useful parallel is found in the Agree relation in syntax (e.g., Chomsky 2000b), in which a node with unvalued features probes for a matching feature. The mechanism motivating the filling-in of features in this view of syntax is Full Interpretation (cf. Chomsky 1995), but we do not intend this to be an explicit or implicit endorsement of a similar claim for phonology. See Nevins 2004 for an explicit attempt to link vowel harmony with syntactic Agree.

The proposal is stated in (3):

(3) *Big data claim*

Feature-filling vowel harmony involves *recipient* segments searching for and copying features from *donors*; donors do not search for and spread features to recipients.

Whether this claim is valid in other assimilatory processes is a question for further research — in this article we will limit our empirical domain and show that (3) appears to be valid. We will also suggest that (3) can be explained; in other words, it is not an arbitrary fact about phonological computation.

COPY ($\zeta_i, \gamma_i, \alpha F, C$):
Identify αF on γ_i and assign αF to ζ_i if the set of conditions C on γ_i are satisfied.

Figure 2: The COPY operation

5. Basic Illustration: Turkish

In this section, we show how the SEARCH and COPY approach generates the well-known basic⁵ vowel harmony patterns of Turkish. Turkish has suffixes whose vowels alternate between [e] and [a] in agreement with the value of [BACK] on the preceding vowel. An example is the plural marker *-ler/-lar*. We assume that the vowel in this suffix is underlyingly [–HIGH, –ROUND] and that the value for [BACK] is filled in by applying SEARCH and COPY as outlined above. We use V here to denote a vowel that is unspecified for the termination criterion, and follow this convention unless otherwise specified.⁶ The direction of SEARCH is leftward, and γ is [α BACK], that is, any token of a value for the [BACK] feature.

(4) *SEARCH in Turkish [BACK] harmony*

- a. $\zeta = V$
- b. $\delta = \text{'LEFT'}$
- c. $\gamma = [\alpha\text{BACK}]$ (a vowel with any [BACK] specification)

COPY then assigns the value [α BACK] that is found to the suffix vowel. This analysis generates the plural forms seen in the first column of Table 1.

⁵ Note that the facts of Turkish harmony are more complex than we show here. We will return to the issue when we discuss consonant-vowel interactions in vowel harmony, discussing data highlighted by Nevins (2004).

⁶ See Reiss 2003 for the mechanism by which it is possible to refer to a segment that necessarily lacks a value for a given feature.

	<i>-NOM.PL</i>	<i>-GEN.SG</i>	<i>-PL-GEN</i>	<i>gloss</i>
a.	ip-ler	ip-in	ip-ler-in	'rope'
b.	kız-lar	kız-in	kız-lar-in	'girl'
c.	sap-lar	sap-in	sap-lar-in	'stalk'
d.	yüz-ler	yüz-ün	yüz-ler-in	'face'
e.	son-lar	son-un	son-lar-in	'end'

Table 1: Turkish vowel harmony data

Note that the possessive suffix, like other Turkish suffixes with high vowels, shows a four-way alternation. However, we can assume that the same process that accounts for the values of back for the non-high suffixes accounts for it in the suffixes with high vowels. The representation of the vowel in the possessive suffix is [+HIGH], and since it has no value for [BACK] these high vowels also serve as initiation points for the SEARCH and COPY operations formulated above.

However, the high vowels also agree with the preceding vowel with respect to the feature [ROUND]. We can derive this distribution by again applying a SEARCH and COPY. In this case SEARCH is initiated by a vowel without a specification for [ROUND]:

(5) *SEARCH in Turkish [ROUND] harmony*

- a. $\zeta = V$
- b. $\delta = \text{'LEFT'}$
- c. $\gamma = [\alpha\text{ROUND}]$

COPY will then assign the value of [ROUND] found on γ_i to ζ_i . Note that this process makes no reference to the fact that the targets of [ROUND] harmony are all [+HIGH] — this follows from the fact that the [+HIGH] suffixes are lexically unspecified for [ROUND], whereas the [-HIGH] suffixes are lexically [-ROUND] and thus do not serve as initiation points for this invocation of SEARCH.

We now turn to the forms in the third column, the possessive plurals, which show both of the suffixes we have just considered. Applying the SEARCH and COPY rules for both [BACK] and [ROUND] produces exactly the desired result. In this case we have no evidence for which process applies first, and we will illustrate applying the process for [BACK] before the process for [ROUND]. The important details of the example are illustrated in Figure 3.

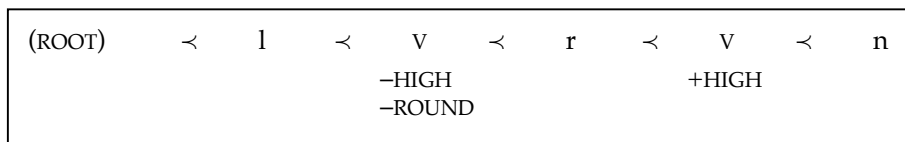


Figure 3: Schematic representation of unharmonized Turkish root-suffix combination

Following the root are the plural marker and possessive suffix, respectively. The

plural affix contains a vowel specified only for height and rounding, while the possessive has a vowel specified only for height.

The vowels of *both* suffixes are starting points for the [BACK] harmony process, since neither is specified for [BACK]. SEARCH starts at each of these standards and finds the left-closest segment that is specified for backness, whether it is [+BACK] or [-BACK]. Assuming the root vowels are all specified for [BACK], both suffixes will have SEARCH terminate on the final root vowel and will copy its specification for [BACK] — both recipients make use of the same donor. There is no need to apply the rule iteratively, to first give the plural suffix a value for [BACK] and then copy the value from the plural to the possessive suffix.⁷

We see that the terminating segment is “local” in the sense that it is the first eligible donor found by SEARCH. We propose that this is the only sense of locality that is relevant to phonological computation.

Now consider rounding harmony in the possessive plural. The vowel of the plural is already specified [-ROUND] so it cannot serve as an initiating point for SEARCH, thus it cannot be targeted by the rule. The vowel of the possessive, on the other hand, is not specified for roundness. SEARCH is initiated at that vowel and looks for the first specification of [ROUND] to the left. It always terminates on the [-ROUND] vowel of the plural marker, and so we only find [-ROUND] versions of the possessive suffix when it follows the plural suffix.

The two feature-filling rules of Turkish vowel harmony are thus as follows:

- (6) *Turkish vowel harmony*
- a. [BACK]
 - i. From [ζ : V] SEARCH left for [γ : α BACK].
 - ii. COPY [α BACK] to ζ .
 - b. [ROUND]
 - i. From [ζ : V] SEARCH left for [γ : α ROUND].
 - ii. COPY [α ROUND] to ζ .

There is no evidence for ordering between the rules. The rules do not apply iteratively to their own outputs, since each SEARCH can occur simultaneously to find the first source to copy from towards the left.

6. Accounting for Neutral Vowels

Scholars of vowel harmony have long struggled with the phenomena of *opaqueness* and *transparency*. In the case of opaqueness, a non-alternating “neutral” vowel blocks the spread of [α F] and spreads its own feature value. Transparent neutral vowels, on the other hand, appear to be invisible to the

⁷ A reviewer remarks that our simultaneous application of harmony to all suffixes implies that we are adopting a “phonology after morphology” approach to the grammar. These kinds of examples are convenient for the illustration of simultaneous application — polysyllabic suffixes would do as well — and aren’t meant as an explicit or implicit endorsement of any higher-level architectural design choices.

harmonic process, allowing features to spread “through” them. Generally, the explanations for neutral vowels invoke either (i) a special property inherent to the vowels themselves or (ii) additional rules or constraints that apply only to these vowels (Bakovic & Wilson 2000: 45). It is interesting also to note that there are so few unified accounts of both types of neutrality, in fact the properties of opaque vs. transparent vowels — or the rules that apply to them — are often claimed to differ in important ways. We shall show below how our theory achieves this unification elegantly, without appeal to “special” properties of neutral vowels or positing unmotivated theoretical machinery.

We assume that in a language with both harmonizing and neutral vowels, those vowels that alternate have no value specified underlyingly for the harmonic feature [F] and surface as [+F] or [-F] depending on the specification of the vowels with which they harmonize, while non-alternating vowels fail to undergo harmony because they are *underlyingly already specified* for the harmonic feature, and the relevant rule is feature-filling. We see, then, that there is nothing special about neutral vowels. In fact, they could be considered the more “normal” vowels, being underlyingly more specified than their alternating counterparts.

Since we treat all non-alternating vowels as being underlyingly fully specified, it is clear that the terms OPAQUE and TRANSPARENT are stripped of any theoretical significance. Ultimately, we will show that these labels reflect differences in properties of *rules*, rather than intrinsic properties of the vowels themselves.

In the following sections, we show how our model accounts for neutral vowels without recourse to a difference between consonant and vowel place features or nodes (cf. Clements & Hume 1995), or other enriched representational apparatus. Both opacity and transparency can be shown to follow from the nature of the rules applied to the vowel representations we posit.

7. Opaqueness

We propose that the situation we observed in Turkish, in which the [-ROUND] value on the plural suffix “blocks” access to the value for [ROUND] on the preceding root vowel, sheds light on the phenomena that characterize opaque vowels in harmony systems.

A traditional interpretation of the Turkish phenomena might say that the vowel of the plural is opaque in the sense that it prevents the harmonic feature of the root vowel from spreading across it to the high suffix vowels. Such an account typically appeals to special representational properties of the vowel in question, or, in an autosegmental framework, to a ban on crossing association lines.⁸ Our own derivation of the opaque behaviour did not require either of these theoretical devices, and in fact only appealed to independently-motivated properties of phonological rules and representations: segmental underspecifi-

⁸ See Coleman & Local 1991 for an argument that the NO CROSSING CONSTRAINT is incoherent.

cation and linear string scanning.⁹ The vowel of the plural just happens to already have a value for [ROUND], and this value is visible to the SEARCH procedure which scans for any value [α ROUND]. We also did not appeal to the inventory of vowels in the language — there are round, non-high vowels in Turkish, but they happen not to participate in the harmonic alternations. In other words, opacity among vowels is not dependent on the structure of the surface vowel inventory, since the Turkish non-high vowels /a, e/ have round counterparts /o, ö/ — they are harmonically paired, to use a current phrase (cf. Bakovic 2003 and Mahanta 2005, *inter alia*) — and yet they are opaque. We think that this general approach can be applied unchanged to cases that are viewed as more typical examples of opacity in harmony systems, such as the [ATR]-opaque low vowel in Tangale.

Tangale is a Chadic language with tongue root harmony. The /a/ vowel fails to harmonize, and it furthermore blocks copying of a harmonic feature to its left.

	<i>underlying</i>	<i>surface</i>	<i>gloss</i>
a.	/seb-U/	[sebu]	‘look’ (IMP)
b.	/kɛn-U/	[kɛnʊ]	‘enter’ (IMP)
c.	/peer-na/	[peerna]	‘compelled’
d.	/pɛd-na/	[pɛdna]	‘untied’
e.	/ɖob-Um-gU/	[ɖobumgu]	‘called us’
f.	/ɖib-na-m-gU/	[ɖibnamgʊ]	‘called you’ (PL)

Table 2: Tangale [ATR] harmony

(van der Hulst & van de Weijer 1995)¹⁰

In Table 2, items (a) and (b) show that values of the feature [ATR] spread rightwards (or are copied from the left, on the present account), while (c) and (d) show that /a/ fails to alternate. Item (f) is the crucial piece of data, showing that /a/ not only fails to alternate, but in fact behaves as a copying source for its own [−ATR] value, blocking the copying of [+ATR] from preceding vowels. These data are all accounted for straightforwardly by assuming that the vowels denoted by /U/ are underspecified with respect to the feature [ATR], and that such vowels serve as the initiating points for SEARCH in the [ATR] harmony rule. SEARCH terminates on any vowels specified for [ATR] and this includes /a/, the only low vowel in the language, which happens to be [−ATR].

(7) *Tangale [ATR] harmony*

- a. From [ζ : V] SEARCH left for [γ : α ATR].
- b. COPY [α ATR] to ζ .

⁹ See Inkelas 2006 on underspecification. A linear scanning procedure is at least necessary for identifying potential environments of application for phonological rules, or constraint-violation locations in OT.

¹⁰ Item (e) is from Bakovic (2003).

Because /a/ is underlyingly specified [-ATR], it cannot initiate the SEARCH for this feature-filling rule. Also because it is underlyingly specified [-ATR], it terminates SEARCH initiated by vowels to its right. This provides a complete explanation for the opaqueness of this vowel: Opaqueness follows from the nature of the rule system and the straightforward representation of the vowels.

To reiterate our point about inventories, Turkish [e] and [a] are “paired” with round counterparts /ö/ and /o/, respectively. However, this surface fact is irrelevant to the behavior of these vowels with respect to the [BACK] and [ROUND] harmony systems. In alternating suffixes, these surface vowels reflect a feature bundle which is not specified for [BACK], and thus does not cause a SEARCH for [α BACK] to terminate; but it is specified for [-ROUND], so it does cause a SEARCH for [α ROUND] to terminate, giving rise to ‘opaqueness’. The Tangale /a/ is specified [-ATR] and thus causes a SEARCH for [α ATR] to terminate, giving rise to opaqueness.

The Tangale opaque vowel, like the other harmony triggers, is fully specified, and there are no [ATR] underspecified vowels of the same height as the opaque one. The parallel situation holds in Turkish — there are no [-HIGH] vowels in Turkish underspecified for [ROUND].

8. COPY is Independent of SEARCH

Thus far we have implicitly assumed that the description of the termination criterion for SEARCH and the description of what COPY copies are identical. For example, in Turkish [BACK] harmony, SEARCH looks for a specification for [BACK] and copies it onto the standard. In Tangale, SEARCH looks for an [ATR] value which COPY copies. However, there is no *a priori* reason to assume that the specification of γ and the description of what is to be copied must be identical.¹¹ In other words, we are justified in breaking down harmony into these two separate processes.

This mismatch between the specification of what is targeted by SEARCH and what is targeted by COPY gives rise in languages like Finnish and Wolof to what is called *transparency*, a kind of neutrality different than the opaqueness seen in Tangale, which we discuss in the following section.

9. Transparency

So called transparent vowels also fail to alternate, and thus by our previous assumptions — but contrary to most of the literature — must underlyingly have a value specified for the harmonic feature. In contrast to opaque vowels, however, they appear to allow harmonic features to be copied across them. In the following subsections we will show with data from several languages that the

¹¹ It does, however, seem to be the case that γ must be subsumed by the specification of the copied value. Otherwise the possibility exists of attempting to copy a feature value that is not present.

typical view of transparency as a unified phonological phenomenon is erroneous, and that transparent behaviour in vowel harmony has at least three distinct sources:

- (8) *Sources of transparent vowel behavior*
- a. Conditions on the target of SEARCH
 - b. Conditions on the target of COPY
 - c. Rule ordering

9.1. Transparency in Wolof via Conditions on SEARCH

In the Wolof system of [ATR] harmony the two high vowels /i, u/ are transparent to the harmony process, as the data in Table 3 show.¹²

	<i>underlying</i>	<i>surface</i>	<i>gloss</i>
a.	/toxi-IEEn/	[toxileen]	'go & smoke' (IMP)
b.	/seen-uw-OOn/	[seenuwoon]	'tried to spot'
c.	/tekki-IEEn/	[tekkileɛn]	'untie' (IMP)
d.	/tɛɛr-uw-OOn/	[tɛɛruwɔɔn]	'welcomed'

Table 3: Wolof [ATR] harmony

As usual, we assume that /i/ and /u/ are underlyingly specified for [ATR], as they do not alternate. However, the suffixes that follow these vowels appear to copy their [ATR] specification from the vowel before the /i/ or /u/. Why don't these vowels terminate a leftward SEARCH for [ATR] initiated by a vowel to their right? The answer we propose is simply that conditions on SEARCH (i.e. the initiating and terminating criteria) need not be singleton features, but are stated in terms of natural classes, that is, potentially complex conjunctions of phonological features. In the case of Wolof, SEARCH has as terminating criterion [α ATR, -HIGH], that is, SEARCH will only terminate at a non-high vowel that is specified for [ATR].

- (9) *Wolof [ATR] harmony*
- a. From [ζ : V] SEARCH left for [γ : -HIGH, α ATR].
 - b. COPY [α ATR] to ζ .

This kind of featural specification is widespread in phonological processes — one language may have a rule affecting all vowels in a particular environment, whereas another language affects only [+HIGH] vowels in the same environment. As another example, a language may have a rule affecting *voiced obstruents*, a

¹² The data are from Archangeli & Pulleyblank (1994), but we have standardized the transcription. Small capital letters denote vowels that do not alternate, and hence have no [ATR] specification. The symbols [i, u] denote high vowels that are [+ATR].

description that must be specified with a conjunction of features.

As in the case of opacity, we do not require any new representational machinery to capture transparency. In fact, there is nothing special about transparent vowels at all in Wolof; their transparency is not a property of the vowels themselves, but rather it follows from the conjunctive feature specification of γ in the [ATR] harmony rule.

9.2. Transparency in Hungarian via Rule Ordering

We addressed above the question of whether the presence of opaque vowels depends on the vowel inventory of a particular language. Transparency has also been said to depend on the lack of a harmonic pair. Basically vowels are said to be neutral in one of these two ways if they are not “matched” in the vowel inventory with respect to the relevant harmonic feature. Thus, much work on harmony makes crucial reference to the vowel inventory of a language in formulating a computational analysis of its harmony patterns. While inventories are commonly referred to by phonologists in describing linguistic forms, we believe that they play no explanatory role as part of the (mental) grammar of a language. After all, the inventory, if it refers to underlying vowels, is just a redundant catalog of the contents of the lexicon.

Most harmony work that refers to inventories directly or by referring to contrastive features does so because neutral vowels *tend* to be ones that do not have a harmonic mate in the surface inventory. We believe that neutrality cannot actually be explained by reference to the surface inventory, since this inventory is derived by the phonology — it can’t be the case that the derived inventory determines the phonology.

To support the idea that the phonology of a language demands an analysis, not just a superficial catalog of surface segments, we present some observations concerning the surface vowel [e] in Hungarian. All Hungarian data are from Siptár & Törkenczy (2000).

The non-low, front unrounded vowels in Hungarian can be transparent to vowel harmony. These are orthographic *i, í, e, é*. An example is found in the deverbal adjective forming suffix *-ékony/-ékeny*: *gyúlékony* ‘flammable’, *közlékeny* ‘talkative’. The first suffix vowel *é* is transparent, whereas the second vowel harmonizes for the feature [BACK] — it is [o] when the last root vowel is [+BACK] /ú/, and [e] when the last root vowel is [−BACK] /ö/.¹³

The features of the transparent vowels are shown in Table (4).

¹³ We have not found any explicit discussion of the failure of rounding harmony in *közlékeny*. It appears that the *o/e* alternation in this suffix, which does not include a front rounded [ö] version, requires an underlying representation different from any of the other alternating vowels — [e] alternates with either [ɔ] (orthographic *a*) or with [o] and [ö].

A full analysis is not possible here, but it looks like it might work to posit underlying [−HIGH, −LOW, −ROUND] as the representation of this vowel. The feature-filling rule posited below would fill in values for [BACK]; another feature-filling rule would provide [ATR] in the context [BACK]; and then a feature-changing rule would change [−ROUND] to [+ROUND] on a non-low, [ATR] vowel which is [BACK].

<i>orthography</i>	<i>IPA</i>	<i>features</i>	<i>length</i>
<i>i</i>	[i]	[+HI, -LO, -BK, -RD, +ATR]	short
<i>í</i>	[i:]	[+HI, -LO, -BK, -RD, +ATR]	long
<i>e</i>	[e]	[-HI, -LO, -BK, -RD, -ATR]	short
<i>é</i>	[e:]	[-HI, -LO, -BK, -RD, +ATR]	long

Table 4: Transparent vowels of Hungarian

Note that, unlike the transparent vowels of Finnish, some of these surface vowels can also be the surface manifestation of alternating vowels. Short *e* surfaces in alternation with *a*, as in the inessive suffix: *dobban* ‘in a drum’, *szemben* ‘in an eye’. It also surfaces in alternation with the tense round mid vowels *o/ö*. This pattern is seen in the superessive suffix *-en/-on/-ön*: *szemen* ‘on an eye’, *tökön* ‘on a pumpkin’, *dobon* ‘on a drum’. The long *é* surfaces in alternation with *á*, as in the translative suffix *-vá/-vé* (the *v* assimilates to a preceding consonant): *dobbá* ‘(turn) into a drum’, *szemmé* ‘(turn) into an eye’, *tökké* ‘(turn) into a pumpkin’.

There is no problem with the fact that a surface vowel such as *é* can correspond to both a vowel of a harmonizing suffix and a non-alternating “transparent” vowel. The non-transparent cases of alternating *i, í, e, é* just represent surface realization of vowels that are partially underspecified underlyingly. These missing values are filled in by rule.

In the latter, “transparent” case, the vowel is fully specified (with the values in Table 4), and it does not alternate. Transparency effects in these non-alternating vowels can be derived using the simple mechanism of rule-ordering.

- (10) *Hungarian [BACK] harmony, version 1*
- a.
 - i. From [ζ : V] SEARCH left for [γ : +BACK]
 - ii. COPY [+BACK] to ζ
 - b.
 - i. From [ζ : V] SEARCH left for [γ : -BACK]
 - ii. COPY [-BACK] to ζ

Rule (10a) copies [+BACK] from the first [+BACK] found to the left. If one is found, then there will be no vowels left underspecified for [BACK] and thus feature-filling rule (10b) cannot apply. If no [+BACK] is found, then unspecified vowels will still initiate the SEARCH of rule (10b) and they will always find [-BACK], which can be copied. The innovation of this proposal is that the so-called ‘transparent’ vowel is only transparent due to the condition on (10a), but in fact, the apparent transparent vowel is the termination vowel of the SEARCH of (10b). Transparency again is epiphenomenal — a result of a particular system of rules and representations.

To reiterate, the surface vowel *é*, for example, corresponds to both a non-harmonizing, underlyingly fully specified transparent vowel, and to one surface manifestation of a harmonizing, underlyingly partially underspecified vowel. Obviously, the dual behavior of these “transparent” vowels can have nothing to do with the surface vowel inventory, since distinct underlying vowels are merged on the surface.

However, this account of Hungarian is still incomplete.¹⁴ Consider first the disharmonic stems in Table 5, in which the final vowel is front, but a member of the “transparent” class.

	<i>form</i>	<i>gloss</i>
a.	papír–nak	‘paper’–DAT
b.	kábít–om	‘daze’–1SG.DEF
c.	gumi–nak	‘rubber’–DAT
d.	Tomi–nak	‘Tom’–DIM–DAT
e.	kávét–nak	‘coffee’–DAT
f.	bódé–tól	‘hut’–ABLAT

Table 5: Disharmonic stems with transparent vowels

Since our rules are ordered to first seek [+BACK], the transparent vowels will be skipped and the preceding [+BACK] vowels will terminate the search, and [+BACK] will be copied to the initiator of SEARCH, i.e. the suffix vowel.

Conversely, the disharmonic stems in Table 6 contain, in (a) and (b), final front round vowels, which are not transparent.

	<i>form</i>	<i>gloss</i>
a.	sofőr–nek	‘driver’–DAT
b.	parfüm–nek	‘perfume’–DAT
c.	büro–nak	‘bureau’–DAT
d.	béka–nak	‘frog’–DAT

Table 6: Disharmonic stems with opaque vowels

Note that the suffixes agree with the immediately preceding vowel even in (a) and (b) where that vowel is [–BACK], and not the [+BACK] vowel that precedes. Thus, the ordered rules in (11) will generate the wrong output for these forms, although they will work for (c) and (d). However, exploiting the theoretical machinery that we already have in place for cases like that of Wolof, we can see that making SEARCH terminate on more narrowly specified segments will solve this problem. The following set of harmony rules correctly generate all of the forms that we have considered:

- (11) *Hungarian [BACK] harmony, final version*
- a.
 - i. From $[\zeta : V]$ SEARCH left for $[\gamma : +ROUND, \alpha BACK]$.
 - ii. COPY $[\alpha BACK]$ to ζ .
 - b.
 - i. From $[\zeta : V]$ SEARCH left for $[\gamma : \alpha BACK]$.
 - ii. COPY $[\alpha BACK]$ to ζ .

¹⁴ The data in the next two examples are well known, but we acknowledge Benus (2005) as the immediate source.

The fact that two different rules can potentially fill in the value of [BACK], may appear to be inelegant, but the mechanisms used are independently necessary: Rule ordering is a basic feature of the derivational model we assume, and an account that assumes underspecification for transparent vowels needs additional rules to fill in their surface values by the end of the derivation. Moreover, our account provides a principled explanation for the fact that “transparent” vowels trigger [-BACK] harmony when there are no other vowel types in the word.¹⁵

9.3. *Taking Stock*

We have seen thus far two of the possible sources of “transparent” behaviour in vowel harmony: In Wolof the featural specification of γ introduces the possibility of long-distance termination of SEARCH, while in Hungarian the ordering of two feature-filling rules with different termination criteria but identical targets of COPY leads to a “transparent” value being searched for and copied after a “non-transparent” value. We turn now to the final source of transparency, which takes the form of conditions on the application of the COPY operation.

9.4. *Kirghiz: Conditions on COPY*

Kirghiz, another Turkic language, displays a quirky exception to its otherwise general pattern of palatal and labial harmony: Non-high vowels do not assimilate in rounding to high back round vowels, but do assimilate to high *front* round vowels. This is shown in Table 7:

	<i>accusative</i>	<i>dative</i>	<i>gloss</i>
a.	taʃ-ti	taʃ-ka	‘stone’
b.	if-ti	if-ke	‘job’
c.	utʃ-tu	utʃ-ka	‘tip’
d.	konok-tu	konok-ko	‘guest’
e.	köz-tü	köz-gö	‘eye’
f.	üy-tü	üy-gö	‘house’

Table 7: Kirghiz vowel harmony data

The crucial data in Table 7 are the dative forms in (c) and (d), in which the *-kV* suffix does not copy [+ROUND] from a preceding /u/, but does copy it from a preceding /o/.

Since all alternating vowels assimilate in backness to the preceding vowel, a simple rule is sufficient, as in (12a). In order to deal with the failure of /u/ to trigger round harmony in a non-high vowel, we need two separate rules like (12b-c), which will assign [+ROUND] to a [-HIGH] vowel when the preceding vowel is [-HIGH] or when it is [-BACK], respectively.

¹⁵ Ignoring, of course, the exceptional stems in Hungarian that take [+BACK] harmony despite having only transparent vowels, e.g., *hid-nak* ‘bridge’-DAT.

- (12) *Kirghiz rules*
- a.
 - i. From $[\zeta : \vee]$ SEARCH left for $[\gamma : \alpha\text{BACK}]$.
 - ii. COPY $[\alpha\text{BACK}]$ to ζ .
 - b.
 - i. From $[\zeta : \vee]$ SEARCH left for $[\gamma : \alpha\text{ROUND}]$.
 - ii. COPY $[\alpha\text{ROUND}]$ to ζ if γ is $[-\text{HIGH}]$.
 - c.
 - i. From $[\zeta : \vee]$ SEARCH left for $[\gamma : \alpha\text{ROUND}]$.
 - ii. COPY $[\alpha\text{ROUND}]$ to ζ if γ is $[-\text{BACK}]$.

These rules generate the observed patterns of alternation. Since SEARCH looks for the immediately preceding vowel, there is no chance of observing transparency or opaqueness effects. However, this pattern is similar to transparency in that a given vowel, /u/, which we assume is specified for a particular value, cannot transmit that value to an underspecified vowel that probes it. In contrast to Wolof, where the mechanism used to generate the inertness of [+ATR] on high vowels was to put conditions on SEARCH, in Kirghiz we put conditions on the application of the COPY operation: COPY only applies if the segment that terminates SEARCH meets the conditions in (12b) or (12c). Note, moreover that if (12b) applies, then (12c) cannot, as ζ will no longer be underspecified with respect to rounding. The ordering of (12b) and (12c) cannot be determined.

10. Understanding Conditions on SEARCH and COPY

The difference between imposing conditions on the target of SEARCH versus the target of COPY is perhaps non-obvious, and so we take a moment here to discuss it further. Consider the following abstracted versions of the relevant harmony processes:

- (13) *Schemata for conditional harmony*
- a. SEARCH left for $[x,y]$; COPY x . (e.g., Wolof)
 - b. SEARCH left for $[x]$; COPY x if $[x,y]$. (e.g., Kirghiz)

The difference between templates (13a) and (13b) is illustrated by the following scenarios. Suppose you are told to go out into the world, find a man with a hat, and take his hat. On the assumption that there are such things as men with hats and that they are findable, you will always return with a hat. But the outcome is potentially different if you are told to go out, find a *person* with a hat, and take the hat *only if that person is a man*. You may in this case return hatless, if the first behatted person you met was a woman. The first task involved a condition on the search termination — take the hat of the first person you meet who is both a man *and* a hat-wearer; the second involved a condition on the hat-taking (COPY) operation — take the hat of the first hatwearer, only if that person is a man.

As it turns out, our account of harmony has thus far glossed over a potentially important point by unintentionally conflating the (21a) template with SEARCH terminated by a feature singleton. A rule like “From $[\zeta : \vee]$ SEARCH left for

[γ : -HIGH, α ATR]” in Wolof (cf. 13a) fails to specify that it is a *vowel* that is being searched for. That is, the specification for γ should in fact read [+VOCALIC, -HIGH, α ATR].¹⁶ On the assumption that vowels and consonants can share at least some features, this tacit omission of vowel specification can lead to incorrect predictions about output forms. We will see such a case in the following section.

11. Consonant–Vowel Interactions: Turkish Laterals

In this section we briefly examine a less-studied aspect of harmony, the interaction of consonants and vowels, exemplified with laterals in Turkish. We will show that the theoretical machinery we already have in place allows us to account straightforwardly for well-known cases, provided we are sufficiently explicit in specifying our rules and representations.

Turkish has both palatalized and non-palatalized laterals, and these have been shown to interact with the general pattern of backness harmony.

	<i>bare</i>	<i>inflected</i>	<i>gloss</i>
a.	usul ^y	usul ^y -ü	‘system’-ACC.SG
b.	petrol ^y	petrol ^y -ü	‘petrol’-ACC.SG
c.	sual ^y	sual ^y -i	‘question’-ACC.SG
d.	okul	okul-u	‘school’-ACC.SG
e.	karakol	karakol-u	‘police.station’-ACC.SG
f.	tʃatal	tʃatal-i	‘fork’-ACC.SG
g.	petrol ^y	petrol ^y -de	‘petrol’-LOC.SG
h.	mefgul ^y	mefgul ^y -düm	‘busy’-PAST.1.SG

Table 8: Turkish palatalized and non-palatalized laterals

(Nevins 2004: 40)

Simply stated, alternating suffixes surface with front harmony if the final consonant is a palatalized lateral, even if the preceding vowel is [BACK]. If we look back at the rule templates in the previous section, and keep in mind that feature-matching in phonology is done by subsumption, the appropriate rules for the Turkish case are clear:

(14) *Turkish harmony, final version*

- a. [BACK]
- i. SEARCH left for [α BACK].
 - ii. COPY [α BACK].

¹⁶ We assume that the vowel/consonant distinction is featurally specified. The exact mechanism does not matter for our purposes.

- b. [ROUND]
 - i. SEARCH left for [+VOCALIC, α ROUND].
 - ii. COPY [α ROUND].

The first rule looks for *any* instance of [BACK] on any segment (i.e. vowel or consonant), whereas the second rule looks for [ROUND] exclusively on vowels. Thus, our initial formulation of Turkish back harmony in (6a) was correct in its form, but essentially by accident. The absence of a [VOCALIC] specification in part (14ai) above is crucial to a proper understanding of the role that consonants play in Turkish harmony.

Note that the account given above generalizes straightforwardly to all cases of consonant-vowel interaction in assimilatory processes. This eliminates the need for use of consonant and vowel features that are sometimes the same and sometimes not (cf. Spencer 1996).

12. Discussion: Phonology as Grammar

The present article is in many ways non-standard. It is not written from the perspective of Optimality Theory, the dominant theoretical approach to generative phonology for about a decade, and yet the framework on which it is constructed eschews many of the assumptions of so-called Classical Generative Phonology (viz. *SPE* and its descendants, up to and including Feature Geometric approaches). For these reasons we take a moment here to address some typical objections to our approach and summarize the motivations for the positions we have taken.

The most controversial aspect of this work for phonologists is likely to be our avoidance of any argument or analysis based on traditional typological and functionalist notions of markedness. Instead we adopt a “substance-free” approach, in which the computational system has no access to (and hence makes no use of) the phonetic substance of speech. The point is highlighted by Chomsky (2000a), who points out that it is a contingent fact that generative grammars give rise to language in humans, and that another creature may have a generative grammar that interfaces with completely different performance systems, for example, locomotion (cf. Lieberman 2000 on the “grooming grammars” of mice).

A puzzling type of comment evoked by work like this runs something like “You posit quantification, algebraic representations with variables, etc., and anything else you want, so you are just willing to posit any computational power at all in the phonology. If you do that, then phonology is not special in any way.” In fact, the idea *is* to ascribe to the phonology any computational power it seems to need — but no more. Our claim is that a procedural approach to vowel harmony, and perhaps all assimilatory processes, *minimally requires* ordered representations and operations akin to (i.e. with at least as much computational power as) SEARCH and COPY. Not providing the phonology with the power it requires seems like a dead end if we are trying to understand what phonology is.

Another potential criticism of this contribution is that our examples merely demonstrate that we are clever enough to create a notational system that gets the

results we are looking for. The alternative, not being able to be explicit about our claims and their consequences, seems unattractive at best. Moreover, we take a realist view of our notation — we develop notation that expresses what we assume to be the computational mechanisms used by the language faculty. As a recent example of how a simple decision to take notation seriously leads to theoretical insight, consider Raimy's (2000) explicit encoding of precedence relations in phonological representations. Either we can say that Raimy is “merely inventing a clever notation” or that he is making explicit the relations that the grammar has access to.

In general, the examples we have used to illustrate our approach are well-known and relatively simple, so our contribution offers little satisfaction for the reader looking for exotic data. This choice was a conscious one, since we adopt the view that the goal of particular sciences is to construct intelligible theories that yield insight into some narrowly circumscribed domain of the world of experience and observation. The data are typically too complex to be directly intelligible, and so it makes sense to start building our models with simple examples. Once the intelligibility and coherence of these models have been determined, we are in a position to move on to more complex phenomena. The notion that our data are too simple reduces to the suggestion that phonology has advanced enough that we no longer need to bother with such examples. We disagree.

We have aimed to provide a novel, yet simple account of phenomena that are fairly well-known by developing a rule-based framework with a minimum of ontological structure. The main contributions we hope to have made are:

- (A) a novel, unified treatment of neutral vowels;
- (B) clarification of the notion of locality in phonology;
- (C) some insight into target/trigger relations in phonological processes;
- (D) some ideas about the logical structure of rules.

In relation to (B), we remark here on the importance of distinguishing between descriptive and explanatory generalizations. Although putative “locality” effects are ubiquitous in phonology, we have showed that they are not properties of Universal Grammar *per se*, but rather are what Chomsky (2005) calls “third factor” effects, that is, they follow from extralinguistic facts about the nature of computation and search. This refinement of the boundary between ontological and epistemological facts is a clear sign of progress in the study of the properties of Universal Grammar.

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