The division of labor between segment-internal structure and violable constraints[*]

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This paper touches on a range of conceptual and practical issues that are relevant to current discussions regarding the nature of the phonological component of the grammar, including: featural, representational and constraint economy; representation versus evaluation; computation versus competence; the line between phonetics and phonology; categorical perception; full-specification of features versus minimal/contrastive specification; richness-of-the-base; the infinite candidate set; universality of constraints; the lexicon; and phonological acquisition. The paper begins with a review of several conceptual issues, highlights some interesting general problems and possible solutions (necessarily abridged due to space considerations), and then moves on to a detailed discussion of how one might model the segment inventory (including phonetic dispersion and variation) of a specific language in Optimality Theory (Prince and Smolensky 1993).

1. Conceptual

1.1 Classic (and not-so-classic) Optimality Theory

The classic Optimality Theory architecture is depicted in (1). OT is basically a *Theory of Computation* by which an input string is modified by a GEN(erator) function to produce a candidate set of possible outputs. This candidate set is evaluated by a language-particular hierarchy of violable constraints (i.e. the EVAL(uator) function), and the candidate that is most harmonic with respect to the constraint hierarchy is optimal and surfaces as the output string.

(1) Classic OT Model (P&S 1993)

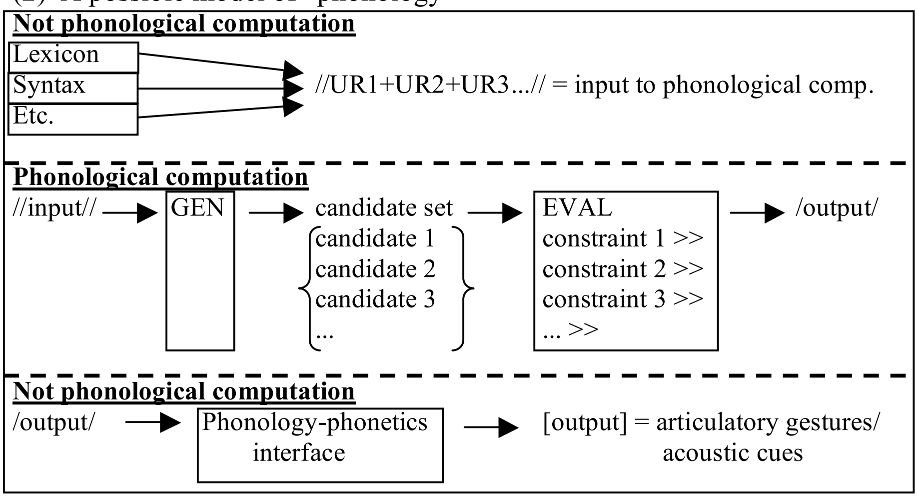
/input string/ -->	GEN	-->	candidate set -->	EVAL	--> [output string]
			{ candidate 1	constraint 1>>	
			candidate 2	constraint 2>>	
			candidate 3 }	constraint 3>>	

Although the classic OT model has been used extensively for over a decade in the field of phonology, and the model itself is fairly simple and elegant, the simplicity of the overall architecture belies many complications lying beneath the surface. Interestingly, although most people claim to be using classic OT, there is actually a range of differences in implementation and assumptions implicit in the published and unpublished literature that are left to the reader to discover for him/herself.

In this paper, I suggest that phonologists need to be more explicit in what they consider the object of phonological research and where the various components of sound (and sign) patterns fit into the overall structure the language faculty. Further, I suggest that it is partially the lack of a concrete set of theories relevant to representations, constraints and the lexicon (and their interactions) that is to blame for some of the confusion in the OT phonological literature and much of the criticism leveled at OT as a model of grammar. In an attempt to help clarify things, I will briefly review select issues with OT phonology and propose a concrete set of possible roads to follow in search of an explicit statement about the nature of the phonological grammar.

Let us begin with an articulated view of "phonology" in the broadest sense and make some claims about what is part of the phonological computational system and what is part of related areas of the conceptual system. This is important because it is often not clear where individual researchers draw the line between these related, but distinct systems.

(2) A possible model of "phonology"



As the diagram indicates, I suggest that several components commonly implied in the literature as integral parts of phonological computation are not. For example, underlying representations are lexical items that get mapped onto morpho-syntactic constituents and submitted to the phonological computational system for evaluation. They are language-particular representations that are independent of the phonological computation. As we will see below, this view has a significant impact on how one interprets the role of Richness-of-the-Base and Lexicon Optimization (Prince and Smolensky 1993) in evaluating OT as a model of phonological computation. In addition, the "output" of phonological computation is fed to the phonetics-phonology interface where it is mapped to phonetic (articulatory/perceptual) content. The phonological output itself does not include detailed phonetic information. This is contra more functional approaches to phonology (e.g. Flemming 1995, Boersma 1998, Kirchner 1998), but is along the same lines as recent work of Boersma (2006).

Under this view of "phonology", there is a clear distinction between phonological computation and phonological competence (for lack of a better term). Phonological computation is a means of building, manipulating and evaluating abstract representations that are for the most part devoid of lexical and phonetic content. This is similar in flavor to the "substance-free" phonology of Hale and Reiss (2000). In contrast, phonological competence is the result of interactions among the phonological computation, lexicon, morpho-syntax and phonetics.

To aid in disentangling phonological computation and competence, I will briefly review the various parts of classic OT phonology as a *Theory of Computation* and make some concrete statements about the nature of each part.

1.1.1. Lexicon

What is the lexicon? Although this is not a part of the phonology computation as conceived of in this paper, it plays a role in phonological competence and is often made reference to in the phonological literature (e.g. Hammond 1995, 2005; Russell 1995, 1999; Ito and Mester 1998; Meyer 1999; Harrison and Kaun 2000; Sanders 2003; Ota 2004). I take the common post-Lexicalist position that it is the residing place of stored items that are *not* composed productively. This includes unpredictable phonological information, morpho-syntactic information and encyclopedic knowledge.[1] Different kinds of information stored in the lexicon are available to different parts of the grammatical/conceptual system, but not all of that information is used by all parts of the system. What is most important for the current paper is that the lexicon does not normally involve online computation (contra the Lexicalist Model (Kiparsky 1982, 1985), its various descendents, and some recent work in OT (e.g. Hammond 1995, 2005; Russell 1995, 1999)).

1.1.2. Syntax

What is syntax? Again, this is not a part of the phonology proper, but it plays a role in phonological competence. Minimally, syntax is a computational system by which morpho-syntactic constituents are built/evaluated. For reasons of space, I have nothing more to say here, other than underlying phonological forms from the lexicon are mapped onto morpho-syntactic constituents and submitted to the phonological computation for evaluation.

1.1.3 Phonological input

What is the phonological input? If we assume the modular approach to phonological competence given in (2), there are at least three ways one might conceive of a "substance-free" input (i.e. not tied to phonetic or lexical implementation). First, it could be a collection of universally available morpho-phonological elements (assuming that the phonology manipulates morpho-phonological material). In which case, we might consider this the Richness-of-the-Base model. Second, it could be a collection of non-redundant/unpredictable morpho-phonological features/structures for which there is overt, positive evidence in the language. We might consider this the language-specific under-specification model. Third, it could be a collection of all surface morpho-phonological structures/features for which there is overt, positive evidence in the language. We might consider this the language-specific full-specification model.

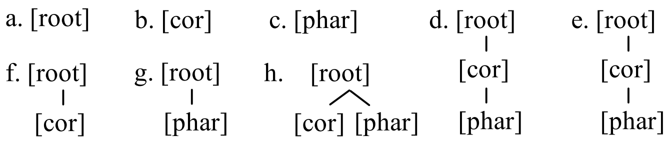
Because the first option places no restrictions on the input to the phonological computation other than it use the appropriate symbolic alphabet, it is the strong hypothesis and as such should be the starting assumption. If lexical storage and morpho-syntax are separate from the computational phonology, then the only restriction we can place on the input when addressing phonological computation is that it is morpho-phonological in nature. This is the Richness-of-the-Base hypothesis of Prince and Smolensky (1993). In stepping away from this strong hypothesis, we move into the realm of language-particular phonological competence and require an explicit statement about what we adopt as a *Theory of the Lexicon* and a *Theory of Representation*. Without such a statement, all restrictions placed on inputs to the phonological computation are stipulations.

Note that in modeling morpho-phonological computation (divorced from real language data and other grammatical/conceptual systems), Richness-of-the-Base is vital (as stated above) and Lexicon Optimization is irrelevant. Since Lexicon Optimization is a mechanism by which individual lexical items are stored given language-particular data and a language-particular constraint ranking, it is relevant to phonological competence and *not* phonological computation.

1.1.4. GEN

The GEN(erator) function produces a set of potential outputs known as the candidate set. When asking about the nature of GEN, we are really asking what a candidate is. There are at least three options.[2] First, a candidate could be any collection of universally available phonological elements (e.g. features, segments, moras, syllables) related to one another in all logically possible ways. For example, all of the structures in (3) are candidates in all languages (assuming feature geometry and ignoring supra-segmental structure for simplicity).

(3)



Second, it could be a language-particular collection of phonological elements related to one another in all logically possible ways. For example, (3c, d, e, g, h) are not candidates in a language that does not make phonological use of the pharynx. Third, it could be a language-particular collection of phonological elements related to one another in a language-particular way. For example, (Xd, e, h) are not candidates in a language where [cor] and [phary] never co-occur within a segment in the output.

The first option is the strong hypothesis and should be assumed as the starting point since it does not have any unstipulated restrictions placed on it. This is the classic OT option. Unless we adopt a specific *Theory of Representation*, we cannot step away from this strong hypothesis without stipulating restrictions on candidate sets. For this reason, work on features and representations is vital to constraining the infinite candidate set of the classic OT phonological computation. I will show that the partial *Theory of*

Representation that I use below restricts the output of GEN to only certain language-particular structures.

1.1.5. EVAL and CON

EVAL assesses sets of candidates with respect to one another and the input via a hierarchy of ranked, violable constraints. I have little to say about this and simply assume classic OT.

CON is the set of violable constraints. In classic OT, THE most important question is what the set of constraints is, followed closely by how they are ranked. However, rather than setting up a *Theory of Constraints* guiding their formulation and specifying the means by which they are violated, there has been a tendency to propose constraints to solve a particular language puzzle and not to worry about the conceptual, formal or typological validity of those constraints. While having an adventurous and laissez-faire attitude is a good place to start to explore the range of constraints we might need (particularly in the infancy of a constraint-based theory of grammar), there comes a point when a *Theory of Constraints* is vital to give OT phonology any credibility/explanatory power. Although there has been much insightful work toward a *Theory of Constraints* (e.g. Hayes 1999, McCarthy and Prince 2003, Smith 2004, the attempts to only propose constraints that make reference to established morpho-phonological constituents and the constellation of constraint "families"), there is an astonishing amount of disagreement, and many phonologists using OT simply do not concern themselves with the issue. This is quite surprising given the principal role constraints have in OT.

That said, there are two types of constraints in OT - markedness[3] and faithfulness. Markedness constraints require or penalize configurations of phonological elements (e.g. *[labial], ONSET, FootBinarity), while faithfulness constraints penalize differences between related forms (e.g. input-output). Both faithfulness and markedness constraints can be relativized to different structures, positions, (and perhaps) morphological classes, etc. (e.g. nucleus, prosodic heads, past-tense).

When conceiving of the phonological constraint set, there seem to be at least three directions one might go. First, one could assume that all constraints are universal and only make reference to phonological structures. Second, constraints could be built from universally available phonological primitives, on a language-particular basis, based on overt, positive evidence. Third, constraints might be built from universally available phonological primitives, on a language-particular basis, based on overt, positive evidence; and there is propagation across constraint families once a particular primitive is activated. The first option is the strong hypothesis and that taken by classic OT. Without adopting a specific *Theory of Constraints* or without evidence that the strong hypothesis is incorrect, we are obliged to assume this option. Otherwise, we are merely stipulating sets of language-particular constraints without a mechanism to either derive them or restrict them. That said, I will propose in the second half of this paper part of a *Theory of Constraints* relevant to phonological features and segment-internal structures that is consistent with the third option.

1.1.6. Output

Finally, the output of the phonological computation is not as straightforward as one might expect. There is a dramatic range of structures, morphological information and phonetics encoded in the outputs in many phonology papers. In taking a modular, substance-free approach, I suggest that the output of the phonological computation is a set of abstract structures with a minimum of morphological information and no phonetics encoded. The only morphological information available to the phonological computation is that relevant to productive phonological patterns, e.g. morphological class information is available to the phonological computation of a particular language if that language shows different phonological behaviors for different morphological classes. It is the role of the phonology-phonetics interface to map the abstract phonological structures to articulatory gestures/perceptual cues.

Assuming a substance-free output is vital for two main reasons. First, sign languages clearly challenge any theory of universal features that relies on detailed articulatory gestures and/or acoustic cues. Not only does segmental phonology seem to be consistent across modalities despite quite different phonetics, but the range of articulatory combinations allowed in sign languages is greater than those allowed in spoken languages. This suggests that the phonological system is more abstract and combinatory than usually assumed and it is not possible to simply map sign language gestures onto spoken language features. See Morén 2003 for a more detailed discussion. Second, we have known for years (since the Structuralists, at least) that the same phonological representation can have different phonetic realizations 1) in different phonetic contexts within a language (e.g. articulatory overlap), 2) in the same phonetic context within a language (e.g. free variation) and 3) in different languages, and we have also known that the same (or very similar) phonetic realizations can map to different phonological representations depending on the contrastive segment inventory of the language.

To illustrate this point, I present a phonetic and phonological comparison of the Yiddish and Standard Italian vowel systems (ignoring length) in (4). The shaded cells indicate phonetic similarity as indicated by fairly standard transcriptions, while the indices show one possible analysis of phonological identity. What we see here is that while these inventories share only two phonetically similar short vowels, many phonological analyses would assume that they share five phonological short vowels as defined by contrastive phonological features. For example, the Yiddish high front vowel is laxer than the Italian high front vowel, but this laxness/ tenseness seems to be a phonetic property, not the result of a phonological feature difference. In contrast, the phonetically similar vowels could be analyzed as being phonologically different in that the Italian mid lax vowels seem to have a feature the non-lax vowels and the Yiddish vowels do not, as indicated by their phonological behavior.

(4) Vowel systems of Yiddish and Italian

Yiddish			Italian		
			i$_1$		u$_2$
ɪ$_1$		ʊ$_2$			
			e$_3$		o$_4$
ɛ$_3$		ɔ$_4$	ɛ		ɔ
	ɐ$_5$				
				a$_5$	

It is difficult to compare these vowel inventories and assume there is a 1:1 correspondence between phonetic realization and phonological specification - at least if we believe there is some systematicity to phonological feature specifications. Given the usual approach in the OT literature of fully specifying bundles of SPE-like binary features read directly from the phonetics, it is less than obvious what features various researchers would assign to each of these vowels since the decision of how much phonetic information is phonologically full-specified is usually idiosyncratic and rarely discussed.

1.1.7 Summary

Classic OT is a simple and elegant computational system assuming the strongest hypotheses with respect to the input (Richness-of-the-Base), the candidate set (unrestricted) and the constraint set (universal). Any deviation from these strong hypotheses requires a substantive theory of the lexicon, representations and/or constraints. I suggest that many of the criticisms of classic OT currently found in the literature are correct in that they either implicitly or explicitly call for a comprehensive *Theory of the Lexicon*, a *Theory of Representation* and/or a *Theory of Constraints*. However, these criticisms are fairly empty since they rarely provide viable alternatives/ theories of their own and simply advocate abandoning OT - essentially "throwing the baby out with the bathwater."

I suggest that if we only look at the phonological computation system, then the exact nature of underlying representations is irrelevant, Lexicon Optimization is irrelevant, and Richness-of-the-Base is vital. Finally, given an acknowledged lack of parity between phonological structure and phonetic realization, it seems prudent to assume a substance-free phonology and a phonetics-phonology interface component that maps between abstract phonological structures and articulatory gestures/ perceptual cues.

The remainder of this paper will take these points seriously and will suggest part of a *Theory of Representation* and part of a *Theory of Constraints* that impact on phonological competence and a *Theory of the Lexicon*.

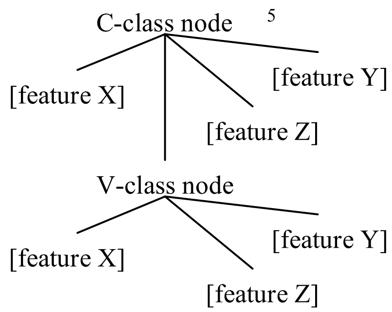
1.2. Toward a *Theory of Representation* - the Parallel Structures Model

There are currently many competing feature theories and models of segment-internal representations. Despite differences in detail, however, the general proposals are fairly uniform, each making minor modifications to the feature set of the Sound Patterns of English (Chomsky and Halle 1968) and the geometry of Clements (1985) – with four notable exceptions. First, Clements (1991a) proposed an innovative unification of consonant and vowel place features, which greatly economizes the set of those features and helps to explain C-V place harmony asymmetries and assimilations. Second, Clements (1991b) proposed a set of vowel height features that makes a more direct connection between those features and degrees of vocal tract constriction. Third, Steriade (1993, 1994) proposed that consonant manners are differentiated via different types of root nodes corresponding to different degrees of vocal tract constriction. Fourth, Particle Phonology (Schane 1984), Dependency Phonology (Anderson and Ewen 1987, van der Hulst 1989, 1999) and Element Theory (Harris and Lindsey 1995) differ radically from the SPE feature tradition in a number of ways – most notably, they assume that vowels and consonants make active use of the same set of features/elements.

The Parallel Structures Model of feature geometry (Morén 2003, 2004a,b, 2006) combines insights from each of these lines of research. It extends the mechanism of Clements' place model to other areas of the phonology, unifies Clements' constriction model and Steriade's aperture model, and incorporates some of the segment-internal organization proposed in Particle Phonology, Dependency Phonology and Element Theory. In addition, it makes use of structural and featural economy to the greatest extent possible. The result is a feature theory that eliminates a large number of features from the grammar (including the major class features); provides a unified analysis for consonants, vowels, place and manner; and captures consonant-vowel interactions, alternations and harmony asymmetries in a natural and straightforward way.

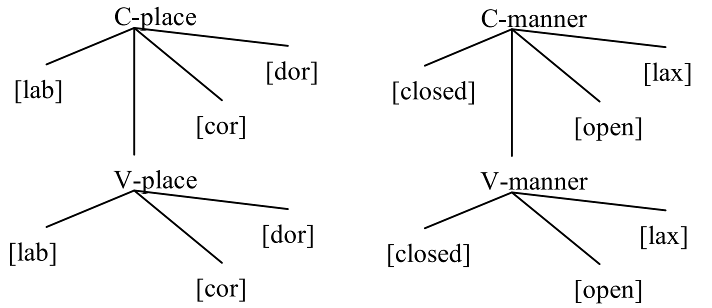
According to the Parallel Structures Model, phonological segments are composed of a limited set of identical structures and a limited set of privative features.[4] The form of the basic structure is essentially that proposed by Clements (1991a) and is given in (5). A significant difference between this model and Clements' is that I claim that the same token feature cannot associate with both a C-class node and a V-class node simultaneously.

(5)



Minimally, there is a set of place and manner features that associate with identically configured place and manner class nodes, as shown in (6).

(6) a. Place of Articulation[6] b. Manner of Articulation



The place features are currently in widespread use and will not be discussed - see Clements (1991a) and Morén (2003). The manner features are based on degrees of constriction and relative articulator rigidity. See Morén (2003) for a general discussion of these features. The manner features [open] and [closed] are demonstrated below.

The Parallel Structures Model also assumes that the grammar is structurally economical and that more complex structures are built from less complex structures. This is in keeping with some of the principles of Particle Phonology, Dependency Phonology and Element Theory, and the Modified Contrastive Specification Model (Dresher and Rice 1993, Dresher *et al.* 2004), as well as other work of Avery and Rice (1989), Rice and Avery (1990) and Rice (1992). One consequence of this is the prediction that languages have simple segments that are featurally minimal - e.g. have only a manner feature or only a place feature.

To demonstrate how the Parallel Structures Model establishes minimal feature specification for a given contrastive inventory, let us assume the following very limited set of segments: [t, ɬ, s, l, ɹ, i, e, a]. This imaginary inventory does not have any place contrasts, but differentiates among stops, lateral fricatives, fricatives, lateral approximants, rhotic approximants, high vowels, mid vowels and low vowels. In other words, it contrasts among three major classes (obstruents, sonorant consonants and vowels), and within each of these major classes, there are manner and height distinctions. In addition, the mapping from a given feature specification to a phonetic realization is determined on a language-by-language basis based on a combination of contrasts and behavior. Therefore, a given phonetic transcription (i.e. IPA symbol) can correspond to different feature specifications in different languages. Using the features in (6b), and building complex feature combinations from simpler feature combinations, we might describe this inventory as in (7).

(7) PSM feature specification for the target segment inventory

		C-manner		V-manner			
		[closed]	[open]	[closed]	[open]		
Stop	[t]	✓					
Lateral fric.	[ɬ]	✓	✓				Obstruent
Fricative	[s]		✓			Consonant	
Lateral approx.	[l]	✓		✓			
Rhotic approx.	[ɹ]		✓	✓			
High vowel	[i]			✓			Sonorant
Mid vowel	[e]			✓	✓	Vowel	
Low vowel	[a]				✓		

Note: shaded cells indicate simple (i.e. single) feature specification.

There are a number of observations that are important here. As discussed in Morén (2003), the major classes are not defined via separate major class features (e.g. [+/-sonorant]) but can be defined structurally via combinations of C-manner and/or V-manner features, as shown in (7). Consonants have a C-manner feature, while vowels do not, and sonorants have a V-manner feature, while obstruents do not. Sonorant consonants have both a C-manner and a V-manner feature. Second, "lateral" consonants are not defined via a distinct lateral feature, but rather as a combination of a C-manner[closed] and a more open gesture. Third, manner of articulation and vowel height are captured using the same set of articulator-based features distributed across two related class nodes. Fourth, relative markedness relationships among manners and heights can be captured via relative structural complexity. That is, plain stops and plain fricatives are structurally less marked than lateral fricatives because they each have only a single manner feature, whereas the lateral fricative has two. Similarly, high and low vowels are structurally less marked than mid vowels because they each have only a single manner feature, whereas the mid vowels have two. Sonorant consonants are also more structurally marked than either simple obstruents or simple vowels for the same reason.[7]

To summarize, there has been much insightful work done on segmental features and geometry over the past three decades, and we continue to refine the feature sets and representations that we assume to be universal. However, there are still unresolved issues and many important questions to answer. Specifically, what is the full set of universal features, and what are the ways in which they can combine to form all the segments found cross-linguistically? The Parallel Structures Model takes the insights and formalisms of several current feature theories and combines them into a new model using parallel structures and feature sets when possible.

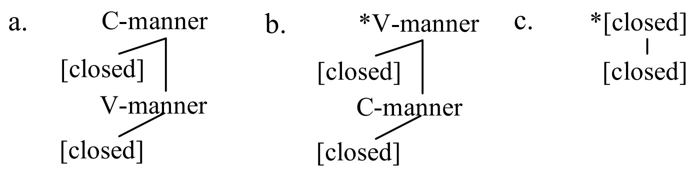
As we will see, the assumptions that more complex structures are built from less complex primitives can be mirrored in the building of more complex feature co-occurrence constraints from less complex primitives. This will then have an impact on the types of segments that are actually categorically perceived by individuals.

1.3 Toward a *Theory of Constraints* - building segment inventories

Most OT analyses in the literature do not explicitly state the mechanism by which the segment inventories of languages are captured using constraints. Nor do they motivate the feature specifications they assume for given segments. Rather, they assume particular (usually fully-specified) bundles of SPE features for given segments and use constraint interaction to account for specific phenomena without questioning the validity of those features and constraints for the rest of the language. While such analyses are certainly interesting and address particular theoretical and empirical questions, it is also important to put analyses within the larger context of the grammar of the language under investigation. Therefore, I suggest that all phonological analyses of languages are obligated to provide a justification for the features and structures assumed for individual segments. This is something that was quite important in the pre-OT literature but has since been largely ignored.

Before providing an OT analysis of the segment inventory of a language (i.e. Hawaiian), I will state some concrete assumptions. First, I assume that only the representations of the Parallel Structures Model are possible segment-internal structures. Therefore, universally illicit structures are impossible outputs of GEN and are thus absent from the candidate set. This is a statement about the nature of the grammar, in which GEN, not the constraint ranking, ensures that only particular representations are universally available. Thus, I am making a proposal about one aspect of a *Theory of Representation* and an explicit statement about the division of labor between segment-internal representations and constraints. The representations regulate the possible relationships among segment-internal elements while the constraint ranking determines which representations occur in a given context in a specific language. Some examples of possible and impossible sub-structures are given in (8).

(8) Examples of possible and impossible structures



Second, I assume the Correspondence Theory (McCarthy and Prince 1995) version of faithfulness constraints in which features are treated as autosegments, not attributes (Lombardi 1998, 1999). This is compatible with the monovalent features employed by the Parallel Structures Model. Thus, I use MAX and DEP constraints rather than IDENT constraints. Third, the feature markedness and faithfulness constraints make reference to both class node and feature specification, as shown in (9)[8] and (10).

(9) a. ***C-manner[closed]** - "assign a violation mark for every C-manner[closed]."
b. ***V-manner[closed]** - "assign a violation mark for every V-manner[closed]."

(10) a. **MAXC-manner[closed]** - "assign a violation mark for every C-manner[closed] in the input that does not have a correspondent in the output (do not delete)."
b. **MAXV-manner[closed]** - "assign a violation mark for every V-manner[closed] in the input that does not have a correspondent in the output (do not delete)."
c. **DEPC-manner[closed]** - "assign a violation mark for every C-manner[closed] in the output that does not have a correspondent in the input (do not epenthesize)."
d. **DEPV-manner[closed]** - "assign a violation mark for every V-manner[closed] in the output that does not have a correspondent in the input (do not epenthesize)."

Finally, there are a number of possible ways to formalize constraints against feature co-occurrence. I suggest that the phonological grammar is economical and uses combinations of primitive constraints to form more complex constraints. This could be done using local conjunctions of simple feature markedness constraints in a way that meets the strictest requirements on local conjunction by defining the domain as the root node and only allowing related constraints from the same constraint family to be conjoined (Fukazawa and Miglio 1998). This is an explicit claim that feature co-occurrence constraints are not universally specified and thus a statement about the *Theory of Constraints*.

(11) Local Conjunction (Smolensky 1997) - The local conjunction of C_1 and C_2 in domain D, C_1 & C_2, is violated when there is some domain of type D in which both C_1 and C_2 are violated.

(12) ***C-manner[closed]&*V-manner[closed]** - the local conjunction of *C-manner[closed] and *V-manner[closed] is violated when both *C-manner[closed] and *V-manner[closed] are violated by the same segment.

With essential assumptions made, I will now implement this system by providing an analysis of Hawaiian segmental phonology.

2. Implementation and refinement - Hawaiian

2.1. Language description (based on Elbert and Pukui 1979)

2.1.1. Consonant inventory, phonetic dispersion and allophony

Hawaiian has a very small consonant inventory - only 11 surface consonants, phonetically described in (13). Interestingly, some of these consonants (shaded cells) are not contrastive and only appear as allophones - to be discussed. This leaves Hawaiian with an even smaller and rather unusual contrastive inventory - eight consonants and no "coronal" stop.

(13) Phonetic descriptions of surface consonants

	Bilabial	Dental-alveolar	Alveolar	Velar	Glottal
Stop	[p]		[t]	[k]	[ʔ]
Fricative	[v]				[h]
Nasal	[m]	[n]			
Lateral			[l]		
Rhotic			([ɾ])[9]		
Glide	[w]				

Note: Shaded cells indicate non-contrastive phonetic variants.

The underlying labial glide varies in the amount of rounding by both speaker and context. Some speakers consistently use [w] or [v] (at least at slower speech rates), while other speakers show phonetic variation based on the quality of the preceding vowel. The more rounded allophone appears after back round vowels [u] and [o], the less rounded allophone appears after front unrounded vowels [i] and [e], and either one may appear word initially or following a low vowel [a]. This variation suggests it is phonetic.

The most surprising fact about the Hawaiian consonant inventory is that there is variation in the realization of what looks to be underlying /k/. Some speakers randomly substitute [t], particularly in fast speech and when following [i]. However, it is clear from the descriptions that the phonetic velar stop is the more general surface segment corresponding to what we might call the phoneme (e.g. it appears in slow, careful speech), while the phonetic alveolar stop is a phonetic variant. This is a very interesting and striking fact (although not unheard of among Polynesian languages) because there is a conspicuous absence of typical coronal obstruents (i.e. dental/alveolar/ palatal) from the contrastive inventory - much to the puzzlement of those assuming a [coronal] unmarked place of articulation and a direct relationship between phonological feature specification and phonetic realization.[10]

From a phonetic dispersion perspective, the Hawaiian inventory is interesting because place of articulation is phonetically disperse in that five places are used for only eight consonants, and three places are used for only one consonant each. In addition, the less-sonorous segments tend to be articulated toward the rear of the vocal tract, while more-sonorous segments tend to be articulated toward the front of the vocal tract. The major questions to answer are what are the phonological features that make up this inventory and how do we explain both the contrasts and the variation?

2.1.2. Consonant phonological processes

Hawaiian has no documented phonological processes involving consonants, as one might expect from a language without adjacent consonants (i.e. no consonant clusters or codas).

2.1.3. Vowel inventory, phonetic dispersion and allophony

If we ignore vowel length, Hawaiian has a typical five-vowel system, phonetically described in the following chart:

(14) Phonetic descriptions of Hawaiian surface vowels

	Front	Central	Back/ Round
High	[i]		[u]
Mid	[e]~[ɛ]		[o]
Low		[a]	

As one might expect, these vowels are maximally dispersed from a phonetic perspective. The vowels showing a contrast along the front-back dimension use both tongue configuration and lip rounding to maximize their acoustic difference. In contrast, the one low vowel is central in the acoustic space since it is not in contrast along the front-back dimension and being central makes it more perceptually distinct from the non-low non-central vowels, as well as articulatorily more neutral.

That said, the actual phonetic realization of these vowels changes slightly depending on the prosodic and segmental context. The high and low vowels are slightly lower in unstressed syllables, while the low vowel is realized as slightly higher. The mid front vowel is more centralized when adjacent to a consonant made with an alveolar articulation (i.e. [l] or [n]). Both of these variations are consistent with known cross-linguistic phonetic tendencies and do not seem to be phonological in nature.

2.1.4. Vowel combinations (phonology)

Hawaiian has no documented segmental processes involving vowels. There are, however, restrictions on the allowable combinations of adjacent vowels within a single syllable (i.e. diphthongs). Importantly, the first vowel of a diphthong must be lower than the second. This results in six diphthongs, as shown in (15).

(15) Diphthongs

		Second V (unstressed)				
		i	u	e	o	a
First V (stressed)	i	--	--	--	--	--
	u	--	--	--	--	--
	e	ei	eu	--	--	--
	o	oi	ou	--	--	--
	a	ai	au	ae	ao	--

2.2. Phonological analysis (representational)

Given the phonetic and distributional facts, one might expect the Hawaiian phonological system to use a very limited and economical set of features and structures. The chart in (16) lists the segments and one interpretation of their phonological feature specifications using the Parallel Structures Model. There are only six phonological features used - two place features, two consonant manner features and two vowel manner features.

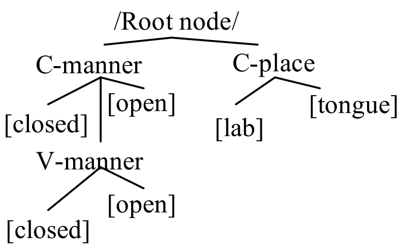
(16) Hawaiian segments defined by PSM features

			C-place		C-manner		V-manner	
			[lab]	[tongue]	[closed]	[open]	[closed]	[open]
Mannerless	/w/	[w]~[v]	✓					
	/l/	[l]~[ɾ]		✓				
Stop	/ʔ/	[ʔ]			✓			
	/p/	[p]	✓		✓			
	/k/	[k]~[t]		✓	✓			
Stop+ Continuant	/n/	[n]			✓	✓		
	/m/	[m]	✓		✓	✓		
Continuant	/h/	[h]				✓		
High	/i/	[i]					✓	
	/u/	[u]	✓				✓	
High+ Low	/e/	[e]~[ɛ]					✓	✓
	/o/	[o]	✓				✓	✓
Low	/a/	[a]						✓

Note: Shaded cells indicate segments composed of only a single feature.

The fully specified PSM representation used in Hawaiian is given in (17), and the representations of each segment are given in (18) through (22).

(17) Hawaiian PSM Geometry

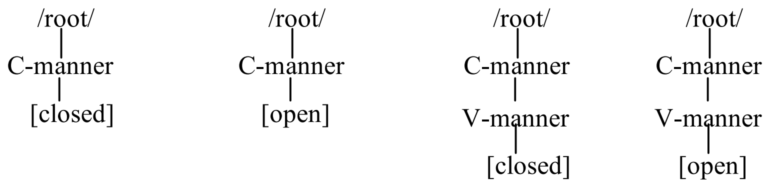


(18) Mannerless simple place segments

a. [w]~[v] b. [l]~[ɾ]

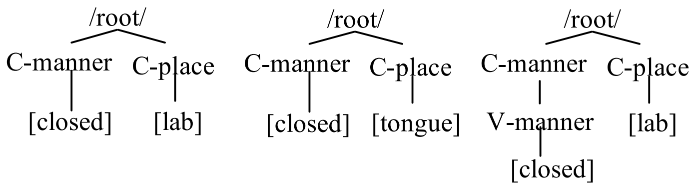
(19) Placeless simple manner segments

a. [ʔ] b. [h] c. [i] d. [a]



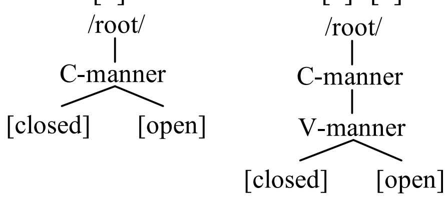
(20) Simple manner with simple place segments.

a. [p] b.[k]~[t] c. [u]



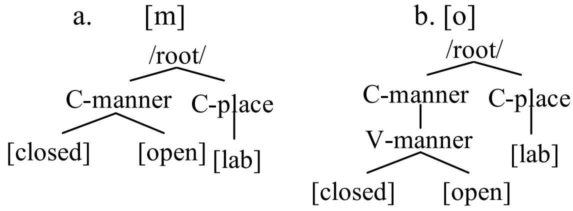
(21) Placeless complex manner segments

a. [n] b. [e]~[ɛ]



(22) Complex manner and simple place segments

a. [m] b. [o]



Given these phonological representations, the phonetic variation in the realization of [w]~[v] and [l]~[r] is explained by their lack of manner features. Because they are unspecified for phonological closure, they may vary in their closure realization either by phonetic context or freely. Similarly, the phonetic place variation of the mid front vowel is explained by its lack of a phonologically unspecified place feature - thus it is susceptible to co-articulation effects.[11]

This analysis provides a reason for both the conspicuous absence of contrastive dental/alveolar/palatal obstruents and the free variation (and lack of a contrast in any environment) that is seen between velar stops and alveolar stops in some dialects. Since there are no sub-place distinctions among obstruents using the tongue as an active articulator, then a simple raising of the tongue body to form an obstruent constriction does not have to be specified with respect to the part of the tongue making the constriction. Thus, the tongue dorsum makes as good an active articulator as the tongue blade, and the lack of a 1:1 correspondence between phonological feature specification and phonetic realization (free variation in this case) is due to a combination of an abstract substance-free phonology and a language-particular mapping between phonological features and sensory-motor coordinations.

Among vowels, restrictions on the types of diphthongs allowed (i.e. the first element must be more "open" than the second element) suggest that there are three phonological heights in Hawaiian. This was shown in (16), where relative vowel height/sonority is defined by V-manner features.

2.3. Summary

The privative features and restrictions on segment-internal complexity of the Parallel Structures Model lead to a simple account of the phonological segment inventory of Hawaiian. Although the relationship between phonological feature specification and phonetic realization in this analysis seems, at first glance, somewhat opaque since one cannot simply assume a traditional set of phonological features based on static phonetic descriptions (e.g. [k] and [t] are phonologically coronal in a sense), the actual behavior of the segments (both phonetic and phonological) makes that relationship quite straightforward. In fact, the puzzle of the lack of contrastive dental/alveolar/palatal obstruents and the unusual [k]~[t] free variation is very difficult to account for using theories in which phonological representations are universally mapped to particular phonetic realizations.

2.4. OT Analysis of the Hawaiian segment inventory

2.4.1. Simple segments, categories and restrictions on GEN

With essential representational assumptions made, we can move on to an OT analysis of Hawaiian. Recall that Hawaiian has six segments composed of only a single feature - two segments are mannerless and four segments are placeless. Using the standard OT strategy of ranking markedness constraints below faithfulness constraints to yield a surface contrast, the following constraint rankings yield these first order contrastive segments.

In each of these rankings, the faithfulness constraint against deleting an individual feature is ranked above a markedness constraint against that feature. The result is a set of six surface segments composed of only a single phonological feature.

(23) a. MAXC-place[lab] >> *C-place[lab] (i.e. /w/)
b. MAXC-place[tongue] >> *C-place[tongue] (i.e. /l/)
c. MAXC-manner[closed] >> * C-manner[closed] (i.e. /ʔ/)
d. MAXC-manner[open] >> *C-manner[open] (i.e. /h/)
e. MAXV-manner[closed] >> *V-manner[closed] (i.e. /i/)
f. MAXV-manner[open] >> *V-manner[open] (i.e. /a/)

The tableaux in (24) and (25) demonstrate how this provides the correct results for the fricative and the high front vowel. In both tableaux, feature deletion in candidate (b) is ruled out by the higher-ranked faithfulness constraint.

(24)

//C-manner[open]// //h//	MAX C-manner[open]	*C-manner[open]
--> a. C-manner[open] /h/		*
b. --- / /	*!	

(25)

//V-manner[closed]// //i//	MAX V-manner[closed]	*V-manner[closed]
--> a. V-manner[closed] /i/		*
b. --- / /	*!	

In contrast, segments composed of features not used in this language (e.g. C-place[pharyngeal]) are prohibited. However, I propose that this is not because the relevant markedness constraint against these features outranks the related faithfulness constraint, as is usually assumed in the OT literature. Rather, I suggest that children learning the language have had no overt, positive evidence with which to propose an abstract phonological feature that is mapped to a set of phonetic characteristics signifying a pharyngeal place of articulation. Thus, such a feature (and segments making use of that feature) does not exist in that language in the constraint set, candidate set, or even the lexicon. In essence, categorical perception is an emergent quality resulting from a language-particular mapping of abstract phonological features with their phonetic realization. This emergent quality has a direct impact on the candidate and constraint sets.

This is the logical consequence of assuming a substance-free phonology. If we assume that the phonology does not make reference to the phonetics directly and that there are no universal mappings between abstract phonological features and sets of phonetic characteristics, then featural constraints must be learned via overt, positive evidence from the environment. This is a major departure from classic OT, which assumes that all constraints are universal. Thus, I am proposing part of a *Theory of Constraints* in which feature markedness constraints are developed as part of the acquisition process. Acoustic/visual signals are mapped onto abstract phonological features thus triggering a set of markedness and faithfulness constraints, which can be ranked in EVAL in the usual way. At some point during the acquisition process, the abstract features based on acoustic/visual signals are mapped onto articulatory coordinations (see also Boersma 1998, 2006). In addition, I suggest that there is simultaneous propagation of the acquired phonological feature across constraints making reference to features.

Developing a *Theory of Constraints* in this way has serious and restricting consequences for GEN and the lexicon as they pertain to phonological competence. Simply put, GEN can only produce a candidate making use of features for which there is positive, overt evidence in the language. This means that candidates not making use of the features of the language should simply not be considered in an OT tableau. This is distinctly different from a classical OT evaluation. However, as stated in section 1, classic OT is a theory of phonological computation, not competence, and what I am advocating here is a competence application of the OT architecture. Thus, this *Theory of Constraints* has a direct relationship to the *Theory of Representation* as instantiated by GEN and the *Theory of the Lexicon* as instantiated by specific underlying forms of morphemes.

2.4.2. Complex segments

As simple features are acquired and made available to the grammar via markedness constraints, they may be combined to form more complex structures. In Hawaiian, there are only six simple features used in the Parallel Structures Model analysis discussed in section 2.2. These can combine two at a time to yield 6C2 = 6!/(2!(6-2)!) = 720/48 = 15 second order segments/constraints. This means that there are 15 logically possible segments composed of two features. Of these, only five are actually used in this language.[12] The allowable combinations of two features are the result of the constraint rankings in (26). Tableau (27) demonstrates how the labial stop results from the ranking in (26a).

(26) a. MAXC-place[lab], MAXC-manner[closed] >> *C-place[lab]&*C-manner[closed] (i.e. /p/)
b. MAXC-place[tongue], MAXC-manner[closed] >> *C-place[tongue]&*C-manner[closed] (i.e. /k/)
c. MAXC-manner[closed], MAXC-manner[open] >> *C-manner[closed]&*C-manner[open] (i.e. /n/)
d. MAXC-place[lab], MAXV-manner[closed] >> *C-place[lab]&*V-manner[closed] (i.e. /u/)
e. MAXV-manner[closed], MAXV-manner[open] >> *V-manner[closed]&*V-manner[open] (i.e. /e/)

(27)

//C-place[lab] C-manner[closed]//	MAX C-place [lab]	MAX C-manner [closed]	*C-place[lab]& *C-manner [closed]	*C-place [lab]	*C-manner [closed]
--> a. /p/			*	*	*
b. /w/		*!		*	
c. /ʔ/	*!				*
d. / /	*!	*!			

Combining three markedness constraints at a time using local conjunction, we get 6C3=6!/3!(6-3)!=720/36=20 third order constraints. Of these, only two are used in this language. Tableau (29) demonstrates the evaluation of the segment /o/.

(28) a. MAXC-manner[closed], MAXC-manner[open], MAXC-place[lab] >> *C-manner[closed]&*C-manner[open]&*C-place[lab] (i.e. /m/)
b. MAXV-manner[closed], MAXV-manner[open], MAXC-place[lab] >> *V-manner[closed]&*V-manner[open]&*C-place[lab] (i.e. /o/)

(29)

//V-manner[closed] V-manner[open] C-place[lab]//	MAX V-manner [closed]	MAX V- manner [open]	MAX C-place [lab]	*V-manner[closed]& *V-manner[open]& *C-place[lab]
--> a. V-manner [closed]& V-manner [open]& C-place[lab] /o/				*
b. V-manner [closed]& V-manner [open] /e/			*!	
c. V-manner [closed]& C-place[lab] /u/		*!		
d. V-manner [open]& C-place[lab]	*!			
e. / /	*!	*!	*!	

Note that Hawaiian does not have a contrastive segment composed of just V-manner[open] and C-place[lab] (candidate (d)), so the question of how to represent such a feature combination in the phonological computation remains. There are a number of possibilities, none of which I have space to explore fully here, but several of which I will mention. One possibility is that GEN could not produce such a combination since it is not a linguistic category of the language (similar to the lack of [phar] in a language not making phonological use of the pharynx). In which case, we do not need to consider candidate (d) in Hawaiian. Another possibility is that GEN could produce such a combination and the constraint ranking rules it out. Given the evaluation in (29) which predicts that such a segment could be optimal, a more sophisticated set of feature co-occurrence constraints would be needed than those presented here. For example, the markedness constraints would have to be evaluated over entire segments, not partial segments. A third possibility is that GEN could produce this candidate and it could be the optimal candidate for some input, but it never appears because there is no surface data in the language that would lead to the required lexical item (see Blevins 2004). This is then a phonological competence explanation, rather than a phonological computation explanation. A fourth possibility is that GEN could produce it and it could be the optimal candidate for some input, but is could not be mapped onto a distinct set of articulatory gestures at the phonology-phonetics interface. This could cause phonological ineffability (i.e. a crash/gap) or it could be phonetically realized as indistinct from another licit category. Again, this would be a competence, rather than computational, explanation. I leave this an unresolved issue and the topic of future research.

To summarize, the constraint ranking necessary to account for the segment inventory of Hawaiian is given in (30). The feature co-occurrence markedness constraints define the categorical segments of the language, and their ranking relative to other constraints (e.g. faithfulness) determines the surface distribution of those segments.

(30) Hawaiian segment inventory constraints and ranking

MAXC-place[lab], MAXC-place[tongue], MAXC-manner[closed], MAXC-manner[open], MAXV-manner[closed], MAXV-manner[open]

>>

*C-manner[closed]&*C-manner[open]&*C-place[lab],
*V-manner[closed]&*V-manner[open]&*C-place[lab],
*C-place[lab]&*C-manner[closed],
*C-place[tongue]&*C-manner[closed],
*C-place[lab]&*V-manner[closed],
*C-manner[closed]&*C-manner[open],
*V-manner[closed]&*V-manner[open],
*C-place[lab], *C-place[tongue], *C-manner[closed], *C-manner[open],
*V-manner[closed], *V-manner[open]

2.5. Summary

This section explored the phonetic and phonological sound patterns of Hawaiian, proposed an economical set of feature specifications for the individual segments, and provided a constraint-based account of the inventory facts.

All in all, we see that the simplicity of the phonological grammar of Hawaiian makes it perfect for demonstrating the current proposal for marrying a particular model of phonological features with constraint interaction free of complex phonological alternations. In assuming that the phonology is substance-free in not encoding phonetic details, we are forced to conclude that individual abstract phonological features, their combinations and their mappings to phonetics are acquired via overt, positive evidence and are not initially/universally available. This has the effect of forcing us to conclude that constraints making reference to those features are also not initially present. It also has the effect of severely restricting the output of GEN to only those features acquired. What is universally available (minimally) is 1) an abstract phonological alphabet, 2) ways in which they can relate to one another, 3) a computational system that can manipulate them and choose among them, and 4) a means to map them to the physical world.

3. Conclusions

There were two main goals of this paper. The first was conceptual - to review the basic OT architecture, discuss some of the difficulties/ uncertainties that arise in trying to use it to model phonology, and suggest answers to some criticisms. I suggested that without a *Theory of the Lexicon*, a *Theory of Representation* and a *Theory of Constraints*, we are forced to assume the classic OT computational model at face value - including Richness-of-the-Base, an unrestricted candidate set and a universal set of constraints. However, I also suggested that the phonology is fairly substance-free and that phonetic details are not universally encoded in phonological features (supported by both work on sign languages, cross-linguistic variation, and phonetic variation). This has serious consequences for a *Theory of Representation* and *Theory of Constraints*, as well as a *Theory of Acquisition*. I proposed that we are endowed with a universal set of abstract phonological feature primitives that can be mapped during the acquisition process to phonetic content. Once features are acquired, they can be combined to form more complex structures and constraints given overt, positive evidence. The presence of acquired features and combinations of features, encoded in markedness constraints and conjunctions of markedness constraints, has the effect of enforcing phonological categories (categorical perspective) and limiting the output of the GEN(erator) function to only those categorical structures.

The second goal of this paper was practical - to show that integrating an economical and highly restrictive model of segment-internal structure into OT is possible. I did this by introducing the Parallel Structures Model, applying it to the segment inventory of Hawaiian, and incorporating it into an OT analysis of the Hawaiian inventory.

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1 Phonetic details may also be stored in the lexicon, as Bybee (2001) and other suggest. I remain agnostic about this.

2 There are, of course, a number of other possibilities, but they do not discussed here for reasons of space.

3 I consider alignment constraints to be markedness constraints, contra suggestions that they are a separate class.

4 The issue of substance-free phonology is important here since the PSM assumes "articulator-based features". In comparing spoken and signed languages, it is clear that both modalities use a set of articulators and degrees of constriction/rigidity (Morén 2003, 2006). Thus, I assume that the abstract phonological grammar makes reference to Place and Manner. It may be possible to reduce these to even more abstract class nodes and encode place and manner aspects in the phonetics-phonology interface, but I do not do so here. The actual features themselves are likely to be abstract and mapped by the phonetics-phonology interface onto sets of articulatory gestures/perceptual cues.

5 The use of "C" and "V" to indicate node type is a mnemonic device more than a statement about the phonological nature of the nodes. That is, vowels can have "C-node" features and consonants can have "V-node" features. In the lack of a contrast, all segments will have "C-node" features. However, if there is overt evidence in the language that consonants and vowels behave differently with respect to a particular feature, then the consonant has the "C-node" feature and the vowel has the "V-node" feature.

6 This is simplified in not including [pharyngeal] and not stating place in a more modality neutral way that could include sign language articulators.

7 It is important to note that this discussion is highly simplified and that phonetically similar segments in different languages have different feature specifications and, in fact, different phonological markedness relations.

8 This is not the only logical possibility, but is assumed here for concreteness and to simplify the remaining discussion. For example, these complex constraints could be formulated as local conjunctions of markedness constraints against individual class nodes and individual features, e.g. *C-manner&*[closed]. More research is needed here.

9 The rhotic is a very limited dialectal variant (Ni'ihau) of the lateral and will not be discussed as it seems solely conditioned by speech rate.

10 There is recent work arguing that the universal phonological unmarkedness of coronal place is a myth and that phonetically labial and dorsal segments are phonologically unmarked for place in some languages (e.g. Avery and Rice 2004, Morén 2006).

[11] While phonetic variation CAN indicate of a lack of feature specification along a particular phonological dimension, the lack of feature specification NEED NOT imply phonetic variation along that dimension. The relationship between phonetic variability and phonological feature un(der)specification is asymmetrical and language particular.

[12] The fact that Hawaiian only uses 5 of 15 possible second order feature combinations is a historical fact, not something that needs to be synchronically justified (see Blevins 2004). It is, however, synchronically explained by the ranking of the relevant markedness constraints above the relevant faithfulness constraints. Without sufficient exposure to the right type of stimulus, children learning Hawaiian would not be motivated to modify this default ranking.