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Phonology without sound

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# Table of Contents

The overwhelming majority of research in phonology has been focused on the spoken modality. While this is an understandable tendency, it has led to a blind spot regarding what phonology actually is. This paper will argue that phonology is critically not about sounds, but about the manipulation of abstract categories. The main method of arguing this is by means of analogy with writing systems, showing that writing systems can demonstrate many of the properties that we consider phonological in nature. The *Bidirectional Model of Phonetics and Phonology* (Boersma 2009) will be used as the theoretical basis from which a more generalized framework can be developed, and previous accounts (Evertz and Primus 2013, Hamann and Colombo 2015) will be analyzed to determine the extent of their applicability to the endeavor of this current paper. Hangeul and Devanagari will provide most of the theoretical examples, with some attention paid to the Roman script as well. The paper will conclude with suggestions for further development of the model discussed in the paper and a brief look into possible linguistic modalities not already discussed such as sign language and braille.

Phonology has historically dealt overwhelmingly with audible output. This is also true for morphology, syntax, etc. and it is a reasonable starting point; most of the world's languages are spoken and it makes sense to begin with what we are most familiar with. However there has not been enough attention paid to what phonology looks like without sound. Little research has been devoted to the phonology of signed languages (among them (Sandler 2012), and (Sandler to appear)) and even less attention paid to what the phonology of writing systems may be. If we are to truly understand phonology then we must pay close attention to how it works regardless of medium of input.

As a starting point, let us define phonology as that which joins an abstract category to an underlying form. It is distinct from phonetics, which links sensory input with a normalized category, as well as morphology, which links underlying forms to syntax. Phonetics takes individualized sensory input and generalizes this input into categories. Morphology is able to take meaningful units and combine them in structured ways to form more complex relations. Phonology then is the process by which meaningless categories are combined to form meaningful units. Crucially, these categories need not be auditory in origin. In theory they can be derived from any sensory input that is rich enough and reliable enough for the mind to detect the patterns inherent in the signal.

This paper aims to show that phonology extends beyond the spoken modality, focusing primarily on writing systems to demonstrate this point. The organization of this paper is as follows. The first section will explore the Bidirectional Model of Phonetics and Phonology (Boersma 2009), particularly its constraints. Section 2 is an overview of previous accounts of applying phonological principles to writing systems, while Section 3 will focus on Hangeul as an implementation of this system, Section 4 will look at the Underlying Form as it appears in the Hangeul and Devanagari scripts, and Section 5 will discuss cross-modality mappings. Finally, Section 6 will conclude the paper and explore avenues of further research.

## 1 The BiPhon Model and its constraints

The BiPhon Model of Phonetics and Phonology incorporates three forms that will be discussed in this paper- the Phonetic Form (PF), the Surface Form (SF), and the Underlying Form (UF). These forms correspond roughly to the domains of phonetics, phonology, and morphology respectively. Further, this paper will define the units that make up the PF as allophones (in line with the notion of an allophone as a physically realized category, but differing from the definition as used in the BiPhon model (Boersma 2009, Hamann and Colombo 2015, etc.), those that make up the UF as phonemes, and define those that make up the SF as chrosophones (derived from the Greek for surface). Thus a given string of allophones is a single Phonetic Form, a single string of chrosophones is a single Surface Form, etc. The interactions between these forms are coordinated via two types of constraints: mapping constraints and well-formedness constraints. Mapping constraints relate aspects of one form to aspects of another form. To give an example, a low F1 and a high F2 is associated with the phoneme /i/. A mapping constraint may then take the form [low F1]/i/, stating that there should be a mapping of the physical property [low F1] onto an abstract category /i/; this constraint [low F1]/i/ is referred to in the BiPhon model as a cue constraint.

In addition to mapping constraints, well-formedness constraints restrict what is an acceptable form at a given level. A typical example of a well-formedness constraint could be the OT markedness constraint NoCoda, which forbids coda consonants in the Surface Form. Together the mapping constraints and the well-formedness constraints transform a physical event into an abstract construct which is then linked to further abstractions and from there ultimately to meaningful segments.

Aside from these three forms, there is a fourth form that is not often discussed but deserves its own consideration: the Physical Form (FF). While often lumped together with the Phonetic Form, there is a slight difference between the two. While the Physical Form has reality in the world and can be recorded by various instruments, the Phonetic Form is a mental construction. The primary reason for conflating these two terms is that we never really have access to the Physical Form; the process by which we are able to comprehend sound necessitates that it be transformed into a signal that our brain can work with. It is therefore usually safe to disregard the FF and move straight to the Phonetic Form. However, for the sake of completeness, this paper will begin with a description of the Physical Form.

### 1.1 Physical Form

The first step in the linguistic chain (from the perspective of the listener) is the physical event- the Physical Form (FF). The FF can be considered to be composed of actual acoustic events. It can be measured by mechanical devices that are sensitive to the medium of its propagation; in the case of spoken language, air molecules act as the medium through which the sound wave travels. The Physical Form then is objectively measurable, physical, but most importantly unique. Any given Physical Form will be measurably different from another Form of similar type (e.g. saying the word “apple” twice will result in two distinct acoustic events, two distinct Physical Forms). This is an inherent limitation of the physical world. The real world is stochastic and can only be approximated and generalized. It is precisely this process of approximation and generalization that allows language to be possible (note that the reverse is not true; language is still possible if there is no variation in the FF). Without these processes it is not possible to see commonality, and without commonality there is no basis for meaningful communication.

Traditionally little has been said about well-formedness constraints of the FF, but this does not mean that there are none to speak of. As the FF is an acoustic form, it is limited by its medium of propagation- air. As we are usually very accustomed to being surrounded by air, we often forget about this limitation. However in mountainous regions the thickness of the air may have an impact on what frequencies of sound are able to be produced, propagated, and perceived (Maddieson et al. 2011). In this way there are well-formedness constraints on the PF.

As for constraints mapping the Physical Form to the Phonetic Form, there has been much debate. In the perception direction, there have been various arguments about normalization, usually centered around whether or not the FF is first transformed into an articulatory mapping (Hayward 2000). Whether or not this is true, it is certainly the case that the signal must undergo some processing before it can be perceived and manipulated by the brain. At first, the vibrations in the air are directed through the ear drum where they are translated into motion of the ossicles (the hammer, the anvil, and the stirrup). The last of these presses on the oval window of the cochlea and creates a wave that travels through this organ. The deformation of the fluid caused by the wave stimulates hair cells which is then translated into action potentials of neurons. Finally, the firing of these action potentials is passed on to the brain via the auditory nerve (Zsiga 2013, section 9.3).

The above process outlines the mapping in the direction of perception. However in the case of the mapping between the Physical and Phonetic Forms we must speak of mapping constraints both in the direction of perception *and* production. In the direction of production, Boersma (2009) notes that there are sensorimotor constraints which translate the abstractions of higher Forms to physical movements of muscles. Again, while the exact manner in which this takes place is not yet agreed upon, it is a necessary step when producing an utterance.

It is worth noting that in all modalities, the constraints between the Physical Form and the Phonetic Form will always be dual in nature. Because the organs by which we perceive are necessarily different than the ones by which we produce, there will necessarily be two sets of constraints corresponding to both the mapping and well-formedness of Forms in the production and perception direction due to the conversion of the signal. This applies as much to the modalities discussed in later sections (and those not discussed) as it does to the acoustic modality. Returning to the issue at hand, in the next section the Phonetic Form will be discussed in more detail.

### 1.2 Phonetic Form

If the Physical Form has reality that can be measured outside the mind, the Phonetic Form could also be measured via electrodes that recorded the electric signals of the auditory nerve. Like the FF, the PF is also unique; although the process of perception removes some of the information that was contained in the FF thus reducing its complexity and uniqueness, the chance that any two Phonetic Forms are exactly the same is vanishingly small. The Phonetic Form still has a gradient range of possibilities, and if there were no gradient to the Phonetic Form, our perception would be quantized and there would be no room for ambiguity.

The previous section on the FF noted that information is lost in the translation from the Physical Form to the Phonetic Form. This loss acts as a constraint on the type of Phonetic Form that we can perceive. One limitation is the frequencies to which we are sensitive: between 20 and 22k Hz (Hayward 200, section 3.3.2). Our ears are simply not capable of perceiving frequencies outside this range. Additionally, the logarithmic way in which we perceive frequencies means that we lose absolute sensitivity at higher frequencies (Hayward 200, section 5.4). Humans are sensitive to a number of properties of the acoustic signal, including a detailed spectral analysis (Hayward 2000, section 2.4.2).

There are also constraints in the production direction. The configuration of our muscles, bones, teeth, etc. serves as a strict limitation on what sorts of sounds we can produce. We cannot produce an F2 of 5000 any more than we can produce a velar trill (Ladefoged and Johnson 2006, cover page). These are in fact well-formedness constraints of the PF and not the FF because if we were equipped with a different articulatory configuration there would be no barrier to them being realized physically. Indeed, each of us has our own unique set of constraints restricting our Phonetic Forms because we are each gifted with a unique articulatory configuration (though of course there is broad overlap between individuals). These well-formedness constraints on the PF are inherently linked to the mechanism by which the FF is mapped to the PF, both in the production and perception directions. They are physical limitations that define the boundaries of our perception and production.

Regarding mapping constraints, in the BiPhon model the PF is mapped to the SF via cue constraints of the form “[x]/y/”. Here, [x] refers to a sensory event, and /y/ to a surface representation. For example, if a Dutch speaker uttered the word “kaas”, the lack of a voicing bar before the plosive release would be taken as an indication of the voiceless nature of the chrosophone. The transition from the release to the vowel would indicate that the chrosophone has the characteristics of being produced with the tongue touching the velum. These cues, in addition to others, give the indication that the chrosophone being produced is /k/. In the BiPhon model the cue constraints ideally map an acoustic event to a chrosophone. For example, [voicing bar lack]/k/ and [F2 transition]/k/ are both cue constraints that map a particular acoustic event to the chrosophone /k/. For sake of brevity these cues can be formalized as [voiceless]/k/ and [velar]/k/. Note that multiple cues are necessary to correctly identify the chrosophone. The lack of a voice bar is a cue not only for the chrosophone /k/, but also /t, p, s/ etc. The more cues available, the more easily the sensory PF can be translated to the abstract SF.

1.3 Surface Form

The next level of representation above the Phonetic Form is the Surface Form. The SF is composed of individual chrosophones that are mapped to the physical events of the Phonetic Form and the phonemic representation of the Underlying Form. As children, we are sensitive to the statistical distribution of acoustic events (e.g. Maye, Werker, and Gerken 2002), and from this distribution we are able to create categories that we can refer to as chrosophones. This creation of categories by abstracting away extraneous information from the physical signal is an important step in efficient communication. It is necessary, but not sufficient, as there are further phonological changes that relate the Underlying Form to various Surface Forms.

The well-formedness constraints of the SF are markedness constraints as normally defined in OT (Prince and Smolensky 1993, Kager 1999). They are of two types: co-occurrence restrictions and simplex restrictions. Co-occurrence restrictions militate against certain combinations of chrosophones in a certain order. Simplex restrictions militate against the appearance of a given allophone in a certain context. An example of a co-occurence restriction is the constraint militating against aspirated plosives following fricatives in English. Even if a heavily aspirated [pʰ] is produced, it will be perceived by naïve English speakers as not different from the voiceless chrosophone /p/. Likely they would judge it to be a less than ideal token, but nevertheless it would not be perceived as the theoretically equally viable chrosophone /pʰ/ due to the co-occurrence restriction. An example of a simplex restriction is the constraint that forbids a velar nasal in initial position in English and Dutch. Though the allophone /ŋ/ is a viable chrosophone in coda position for these languages, it is not allowed in initial position, and thus may be perceived as a strange /n/ or a sequence such as /ŋg/.

The mapping constraints from the SF to the UF are faithfulness constraints, as in other OT-based formalizations. A familiar example of this is Dutch devoicing. All voiced obstruents in Dutch are devoiced when word final, creating a neutralization of contrast; it is not possible to know from a single utterance to which Underlying Form a given Surface Form maps. However when knowledge of morphology becomes available it becomes possible to compare Surface Forms as composed of multiple morphemes. Before this point, a given Surface Form is a single string of chrosophones unrelated to other strings. When it becomes understood that a given string may actually be composed of multiple sub-strings (morphemes) it is possible to compare Surface Forms with similar but non-identical Surface Forms. That is to say that with this realization, it is possible to realize that there is a pattern in which a given set of features is changed in a given context. This allows for a mapping of chrosophones at the SF to phonemes at the UF that is not strictly one-to-one.

### 1.4 Underlying Form

The Underlying Form is the last level of meaningless abstract formal representation. At this level and above, all forms can be tied to the conception of the world that has been built in the mind. It is here important to again distinguish between the subjective conception of the world and the objective reality. While it is tempting to say that meaning refers to real objects or concepts in the world, this is impossible. This is perhaps best demonstrated with a word like “green”. The Underlying Form can be represented as something like |gɹin|, but to what is it mapped? It is mapped to a corresponding range of normalized wavelengths of light that have themselves been processed just as the acoustic events have been processed. The UF |gɹin| is not associated with actual physical wavelengths, but rather the abstract categorization of these wavelengths into arbitrary groups we call colors; it is an abstract to abstract relation. Different languages have different ways of grouping these wavelengths and thus different conceptions of color. Thus meaning is linking two or more abstract categories that do not have any *inherent* relation.

It is important to note that these abstract categories can come not only from the refining process of physical sensation, but also from a refining process of mental abstractions. The word “think” refers to the mind’s ability to produce its own sensations that need not be dependent on an external stimulus. The Underlying Form |θɪnk| is thus mapped onto a purely mental construct. As meaning is simply a relation between two abstract constructs, the Underlying Form is an abstract construct that maps to other abstract constructs.

1.5 Translating to non-acoustic modalities

As the intention of this paper is to clarify what phonology looks like in non-acoustic modalities, it would be useful to extend the terminology of the BiPhon model in such a way that is modality-independent. For the most part the terminology is sufficiently non-discriminatory, but in the case of the Phonetic Form this paper will substitute **Provided Form (PF)** for non-acoustic modalities. As for allophone and chrosophone, they can be substituted by alloform and chrosoform respectively.

To give an example, photons reflected from paper and ink compose a Physical Form in the visual modality. They are absorbed by the eye and sorted into colors according to their wavelengths. If there is a noted difference in colors in two adjacent parts of an image, this will be transformed into an edge (Lettvin et al. 1968). Together colors and edges are two types of physical events that characterize an alloform in the Provided Form. The orientation of edges is a further component of the PF. The difference between the white of the paper and the dark color of the ink will create a continuous edge that will then be interpreted as a line. This line is then an alloform of the Provided Form, just as a high F1 and a low F2 together may be said to represent the allomorph [a] (here it is important to note that the [a] is merely shorthand for the actual physical events). If multiple lines appear in a certain combination in respect to each other, they may be interpreted as a letter/character/graph. The distinction between a meaningless assembly of lines and a letter is analogous to the distinction between pure tones and a linguistic utterance. Both have a Provided Form, but only certain Provided Forms can be further connected to a linguistic Surface Form.

We can further distinguish those Underlying Forms that connect to further linguistic levels such as syntax and those that do not. To extend the visual analogy we can draw a contrast between a series of triangles and squares and a series of letters. While each individual shape has an Underlying Form that connects to a meaning, it may not be the case that the combination forms a coherent or recombinative meaning. That is to say, a series of triangles and squares have no meaning as a series, while a series of letters forms a word. The whole is more than the sum of its parts because the relations between the parts are also meaningful.

With the definitions thus being explained, the next section will focus on previous accounts of phonology of writing. While for the most part writing systems have been viewed as simply an auxiliary of spoken systems, some have attempted to argue in favor of their status as linguistic systems in their own right. However on closer scrutiny there appears to be a failure to truly justify these claims, and this paper will seek to go beyond their explanations.

This section has briefly discussed the constructs and formalizations of the BiPhon model that will be used throughout this paper. However in so doing the proper definition and domain of phonology remains to be seen. The next section will attempt to clarify the linguistic definitions in order to work with a clear set of concepts. Of particular interest will be defining phonology not only as it relates to phonetics and morphology, but as it may apply in non-auditory modalities.

## 2 Previous Accounts of Phonology of Writing

For most of the twentieth century and on into the twenty-first, writing systems have largely been left out of generative linguistic discussion. Tthis is slowly beginning to change, and this section will focus on two accounts of the Roman script that aim to analyze its structure and relation to the spoken system in systematic ways. Evertz and Primus (2013) develop a graphic hierarchy for the orthography of German and English that treats the orthography as having a system unto itself. Hamann and Colombo (2015) focuses on the orthography of Italian and the ways in which the BiPhon model can be successfully implemented to describe orthographic phenomena.

### 2.1 Syllabic structure: the graphematic foot (Evertz and Primus 2013)

Evertz and Primus (2013) put forward a model of graphemic structure that parallels phonological structure. In particular, they focus on elaborating a system for analyzing German and English written words in terms of graphemic syllabic structure. They put forth both structural and experimental evidence that points to the existence of structure in these writing systems.

Of particular note is that a change in the written form of the word has suprasegmental effects on the realization of the spoken word even when the phonology is kept constant. Evertz and Primus are keen to show that a linear approach to writing fails to capture the richness of phenomena we see occurring in English and German writing. However their explanation for the connection between writing and speaking somewhat weakens their claims for the necessity of written structure.

Evertz and Primus note that “in traditional graphematics words are represented as a linear sequence of letters” (2013, p. 1). The authors take issue with the linear nature of this representation, at least insofar as it is not supplemented by any other structure. They argue that written forms have hierarchical structures that resemble but are not identical to spoken hierarchical structures. This results in a significant mismatch that they then put to the test using a spoken production experiment.

One problem the authors have with a linear approach is how it deals with so-called “mute <e>”. In English, an <e> at the end of a word signifies that the preceding vowel is pronounced as “long” if there is only a single consonant between the <e> and the other vowel grapheme. A linear explanation of this is essentially what I have just said and makes no reference to hierarchical structure.

According to Evertz and Primus, this explanation is problematic for three reasons. First, it cannot explain why it is only a single consonant and not more. Secondly, it fails to account for sensitivity to stress. Finally, it is unable to account for the vowel quality of certain words such as “*table*, *noble*, *waste*, and *chaste*”. However these complaints are not valid for the following reasons.

The first issue with the linear approach is the strongest: there is no principled synchronic reason that there should be only one consonant between mute <e> and its vowel rather than multiple consonants. However although there is a lack of a synchronic principle does not mean that there is a lack of a diachronic principle that explains this pattern. Historically, this <e> was pronounced, and thus such words were phonologically disyllabic (Mossé 1968). Through diachronic shifting of the English language the second vowel was dropped altogether, though it remained in writing and came to be associated with a change in vowel quality. Synchronically, this is its only purpose.

Such historical constraints have been shown to come together to create new generalizations. Coetzee (2014) showed that in Afrikaans two unrelated constraints led to a diachronic shift such that there came to be a new generalization detectable by speakers. It is not unreasonable that a similar process has happened with the gradual changing of English orthography. In such a case the hierarchical structure is not necessary to explain the ability of English speakers to derive a pattern from the orthography, and the historic link to multiple syllables does not mean that speakers today are building similar structures for either in production or perception of orthography.

The lack of sensitivity to stress is not a major concern. As both the linear and hierarchical formalizations involve a close link with spoken phonology it is not out of the question that stress is factored in as well. Both Evertz and Primus as well as proponents of linear representations would agree that there is overlap between the processing of the written system and that of the spoken system; it is not purely serial. This being the case, it is completely acceptable that the mute <e> be affected by the stress. Furthermore, if the written form acts as a symbol pointing to a lexical entry we should not be surprised to find that we can speak only of generalities and that there may be exceptions to otherwise robust tendencies.

Finally, the third objection brought up by Evertz and Primus involves a list of words that supposedly violate the mute <e> principle. Some of these words are of the form <le>, and in these cases it is not unreasonable to suggest that the grapheme sequence <le> when following a consonant is interpreted as a syllabic /l/. As for the words *waste* and *chaste*, it is not unreasonable to call them exceptions to an otherwise strong rule. While such words form a general class of exceptions to the mute <e> rule, words such as *caste* or *aster* are problematic for the syllabic formalization given by Evertz and Primus (2013).

In order to support their claims for a hierarchical structure in orthography, Evertz and Primus set up a production experiment. In this experiment, subjects are presented with a nonce word of German. These nonce words ended in either a vowel, an <h>, a single consonant grapheme, or a geminate grapheme. The nonce word was then embedded in a German sentence and participants were asked to pronounce the entire sentence (complete with morphosyntactic affixes attached to the nonce word). The aim was to see whether these various spellings would have an effect on the pronunciation of the word.

The authors argue that between the words ending in a vowel and the words ending an <h> there should be no difference from an auditory phonological standpoint (and the same holds true for the difference between the single and geminate consonant graphemes). Thus they argue that any difference in production between these groups is a result of the difference in graphemic representation, and therefore points to a hierarchical structure of orthography.

The results of this study were significant: participants apparently restructured their pronunciation of these words based on difference in orthography. However this is hardly a surprising result. Even though these pairs were chosen to be phonologically similar in terms of vowel quality, there may still be a tendency for orthographically heavy syllables to signify stress. In fact just as Evertz and Primus argued that a linear approach cannot account for the sensitivity to stress, it is just this sensitivity to stress that denies confidence in the hierarchical model they put forward. Because their model relies on the interplay between the auditory phonological system and the orthography, it is not possible to say whether the sensitivity to stress is due to this relation or to a hierarchical system within the orthography. Unfortunately this experiment is not sufficient reason to conclude that the orthographic representation itself has any structure beyond a linear account.

2.2 The role of orthography in loan adaptation (Hamann and Colombo 2015)

In contrast to Evertz and Primus' hierarchical proposal of orthography, Hamann and Colombo (2015) do not rely on such an approach for mapping a written form to an auditory form. Instead, they argue that the orthographic form is mapped onto the auditory Surface Form via mapping constraints. In doing so they allow the native well-formedness constraints of the auditory Surface Form do the heavy lifting in determining the pronunciation of a given written form.

In modeling the Italian language, Hamann and Colombo need only a very few constraints to derive the generalities between the written form and the auditory form. These are fairly straightforward and state that a given grapheme (or sequence of graphemes) corresponds to a chrosophone, and that an empty unit from either form should not be mapped onto a substantive unit on the other form. Additionally and most importantly for their paper is the constraint (1) d. that maps sequential identical graphemic consonants onto a geminate in the SF:

(1) a. <α>/A/: A grapheme <α> should be mapped onto the phonological surface form /A/.
b. *<α>/ /: A grapheme <α> should not be mapped onto an empty segment in the surface form.
c. *< >/A/: The absence of a grapheme should not be mapped onto the phonological surface form /A/.
d. <βiβi>/Cː/: If there is a double consonantal grapheme it should be mapped onto a geminate and vice versa.

With these constraints (and several other well-formedness constraints of the auditory SF to handle phonological restrictions on the SF in Italian) Hamann and Colombo are successfully able to predict the correspondence of pronunciation and orthography.

Looking into the phonology of loanwords borrowed from English in the past century, Hamann and Colombo find a significant influence of orthography on the eventual pronunciation. While in English a pair of identical consonants is not pronounced as a geminate (except in compound words such as *bookkeeper* or *night-train*), the authors find that when borrowed into Italian this is not the case. English loanwords into Italian such as *buffer* or *horror* are pronounced as geminates in Italian: /.'baf.fer/ and

/.ˈɔr.ror/ respectively. As this effect is not due to the English pronunciation of such words, the authors conclude that the effect is due to the influence of orthography, and more specifically due to the constraints mapping sequential identical graphemic consonants onto geminates in the auditory SF. The authors also note that when the consonant cluster is non-native, such as <ck>, a geminate is not formed. This adds further weight to their claim as it suggests that the pronunciation is due not merely to a profusion of consonantal graphemes but also to positive interference from the native graphemic constraints.

While Italian orthography is admittedly much more straight-forward than either English or German orthography, the ease with which Hamann and Colombo are able to model the correspondence between the written and spoken forms of the language undermines the need for a hierarchical account for the Roman script such as that put forward by Evertz and Primus. By using a constraint-based approach it is for the most part not necessary to duplicate hierarchical structures in orthography when they exist already in the phonology of the language.

## 2.3 Orthography as hybrid phonology

The accounts described above have generally assumed that there is a more or less direct link between the spoken form and the orthography. The written form is not assumed to have an Underlying Form, and auditory phonological constraints play a crucial role in determining the proper pronunciation given a certain written Surface Form. However there are several reasons why it is useful to elaborate a parallel phonology for the written Forms as for the auditory Forms.

Hybrid systems assume that orthography is essentially a stand-in for the auditory SF. Such a system works relatively well for shallow orthographies such as Italian or Spanish. The use of Roman scripts with these languages results in a fairly direct mapping from the written Surface Form to the auditory Surface form. As such it could be argued that for these languages there is no need for a written Underlying Form as no information is lost between the mapping from the written SF to the auditory SF.

This is not always the case of course. English is well known for its idiosyncratic spelling. It is not unusual to find homophonic doublets or triplets distinguished only by their writing (*their, they're, there; see, sea*). These words are almost always identifiable in context, but this need not be the case. Even in shallow orthographies there may be some words that can be distinguished only in the written form, and not in the auditory form. Some words in non-Roman scripts need a written Underlying Form to be readily identified.

If this is the case for some words, is it the case for all words? Even for words that are unique both in their orthographic and auditory forms, it is surely much faster to store the entire written form as an Underlying Form rather than having to derive its meaning by mapping to an spoken Surface Form each time; readers become proficient and gain speed in recognizing words. That is to say that although a mapping is possible by taking each graph and mapping it to a spoken SF, it is not necessary to say this occurs all the time. It is not enough to argue that a word will receive an Underlying Form only when it is a homophone, and thus with no other criteria it is best to argue that each written Surface Form has a corresponding Underlying Form.

One major call for treating writing systems as worthy of phonological study in their own right is the existence of well-formedness constraints on the written SF. While some scripts such as Roman in principle allow any graph to follow any graph, this is not the case for all scripts. Any constraints employed in the writing system that go above and beyond those used in the spoken language must necessarily be explained in terms of the written system. Two examples of scripts with such restrictions are Hangeul and Devanagari.

Hangeul, the script used for the Korean language, has a number of constraints on which graphs may appear in which place in which combinations. A more detailed description of the well-formedness constraints at all levels of Hangeul will be given in sections 3 and 4.1 below, but for now it is sufficient to note that this script makes use of "natural classes" of graphs. In Hangeul the graphs used to represent consonants are both functionally and visually distinct from those used to represent vowels. Additionally, this script incorporates several orthographic syllable restrictions such as *ONSETLESS AND *HIATUS; in Hangeul each orthographic syllable must begin with a consonant graph (even if it is null in the spoken form) and it is impossible to place two distinct vowel graphs next to each other (though orthographic diphthongs are acceptable).

Devanagari is a script used for many languages in South Asia including Hindi, Nepali, and Marathi among others. Like Hangeul it also has several well-formedness constraints. In Devanagari the written vowels take two forms: one form when following a consonant and another when not. It would be as ungrammatical to use the incorrect form in the written language as it would be to use an incorrect vowel in the spoken language, though each form corresponds to the same chrosophone in the spoken language. This is a constraint that exists purely in the written system as a well-formedness constraint on the SF. In addition to these differing vowel forms, consonants also undergo a shift in form when they form a cluster (Monier-Williams 1899). Again, this change of form has no effect on the spoken form of the language, and so any attempt to fully capture the richness of the system must concede the independent structure of the written form.

While there are some scripts that are inherently structured, the Roman script is not one of them. The arguments put forward by Evertz and Primus (2015) for structure in the German and English written form can be explained more simply as an interaction between the spoken and written forms of the languages. So while it is possible for written systems to have structure, we should not impose more structure than is already there and instead only posit what cannot be explained by other means.

Other means in this case refers to the well-formedness constraints on the auditory SF and the mapping constraints between the written SF and auditory SF. As Evertz and Primus themselves admit, users of German are able to use the auditory sonority principle to parse such forms as *Dirndl*, which have an unfortunate dearth of vowel graphs. Yet if this is the case, why should we argue that users of English are unable to do the same for words such as *candle* (supposing they ignore the final <e>)? Evertz and Primus use words such as *candle* to argue for foot structure and against a flat interpretation for English, but this structure can be arrived at just as easily through combinations of known systems, such as a system of mapping that interacts with markedness constraints on the SF.

To give an example of this, we may look again at the experiment they claim shows evidence of orthographic structure. In their experiment, Evertz and Primus argued that the orthographic minimal pairs they presented to participants did not differ in phonology, and that therefore any difference must derive from orthographic structure. However, as the orthographic minimal pairs are indeed separate, it is not unreasonable to argue that they are mapped differently. The difference between <CV> and <CVh> is one that is easily seen, and the addition of <h> could very well serve as an indication of stress. A hidden orthographic structure is not necessary to explain the differences found in their experiment.

2.4 Roman script: without limitations

While it is certainly possible to have limitations and restrictions on scripts (as seen above with Hangeul and Devanagari), there do not appear to be any such restrictions in the Roman script. If there are no such restrictions in the script itself, it seems that there is also a corresponding lack of systematicity. It is possible to talk about generalizations of strings (a <z> may be more likely to follow a <u> than a <g>), but this is language dependent. For this reason it is important to distinguish between the restrictions on the script itself and the languages that employ that script.

Roman is relatively free. Unlike Hangeul there are no restrictions on which graph may appear after another. A vowel may follow a vowel, or a consonant, or five consonants and there is no restriction in the writing system to forbid this (of course there are such restrictions in the spoken system). Neither are there any natural classes among the graphemes; the form of a grapheme cannot be correlated to their auditory nature. There are no syllable restrictions and indeed no indication as to when one syllable begins and another ends.

Additionally, the graphs of Roman script are generally independent of each other (barring aesthetic ligatures and the like). While in Devanagari the form of a graph is dependent on the surrounding graphs, this is not the case for Roman. Again it may be important to distinguish between tendencies and restrictions. While in Roman there is a tendency that <z> will not precede <x>, there is no restriction against doing so; *zx* is an acceptable if odd form.

Of course the Roman script does have some restrictions. Like Devanagari it has multiple forms for certain graphs. Unlike Devanagari, Roman has two forms for all of its graphs (not to mention the multiple forms that may be present in different fonts). Generally capital letters are always used for the first letter of the first word of a sentence and for the first letter of a “proper noun” in all languages that employ the Roman script (and all nouns for German). This restriction may be becoming less strict than it used to be due to the proliferation of texting and the Internet, but for now it remains in place.

Because of the lack of restrictions at the SF, the link to the UF in Roman script is almost always completely straight-forward. While the UF is generally not categorically restricted but only observes certain tendencies, and as the Roman script as a writing system is generally unrestricted at the SF, it is no surprise that we should find a relatively straight-forward mapping between the two.

In both writing and spoken linguistic systems, it is generally the case that the only time a non-faithful mapping is required between the UF and the SF is when there is a phonological alternation that can be discerned only by comparing like forms. For example, given the Dutch voicing restriction on coda consonants, it is not possible to know whether a given obstruent is underlyingly voiced when it appears as a coda consonant at the SF. It is similarly impossible to tell whether a given flap in American English is underlyingly a |t| or a |d| when it appears intervocalically.

This being the case, we can see why there is only ever one instance in which there is not a direct relation between the SF and the UF in Roman: that of capital letters. Due to the restriction on capital letters at the beginning of a sentence, it is not strictly possible to know if a new word in such a position ought to be capitalized or not (its status as a proper noun is indeterminate). Only when the word appears in another position in the sentence would it be possible to know the Underlying Form, and the only unfaithful mapping from the UF to the SF in Roman is when a word with non-capital letters begins a sentence. Not only is this the only unfaithful mapping, but it is arguably the only *possible* unfaithful mapping due to the lack of restrictions.

While the Roman script is thus relatively uninteresting in terms of its phonology, this is not the case for all scripts. The next section will cover in detail how the BiPhon model in particular and constraint-based theories in general can be applied to writing systems as linguistic systems in their own rights.

## 3 Korean Script (Hangeul)

This section will provide a thorough description of Hangeul as it can be analyzed in a phonological manner. Hangeul is a thoroughly systematic script that employs structure at nearly all its levels. As such it is an excellent example for the richness of form and systematicity that is possible in writing systems at all levels of representation. The Physical Form will be ignored, as the process by which visual forms are rendered perceptible is generally beyond the scope of this paper. Instead, the Provided Form will be taken as the starting point, followed by a description of the Surface Form as it appears and operates in Hangeul.

### 3.1 The PF in Hangeul

When dealing with the Provided Form in Hangeul (or any other script) the issue is essentially how the graphemes are constructed. Well-formedness constraints at this level deal with the question: “what is an acceptable form for a given grapheme?” A form must be legible (easy to perceive) while at the same time efficient (easy to produce). These two general principles of ease in perception and production exist in a trading relationship, and the extent that one is valued over the other will depend on the context. Mapping constraints between the PF and the FF (sensorimotor constraints) will be set aside for the moment, while the cue constraints between the PF and the SF relate the various forms a grapheme can take onto a single abstract representation.

Stroke order is one class of well-formedness constraint on the PF. In Korean, as in Chinese, there is a prescribed stroke order that guides ones in writing the characters (Kim 2012). While a character can still be formed using an order that differs from the prescribed, it may look a little odd to one used to the order, just as a heavily aspirated [p] at the beginning of an English word will be accepted by an English speaker though likely perceived to be slightly off. This stroke order can be summed up with the following constraints in this ranking:

(2) a. *Clockwise: assign a violation for every circular stroke written clockwise
b. *Rightward: assign a violation for every stroke written right to left
c. *Upward: assign a violation for every stroke written bottom to top
d. Max Stroke: assign a violation for every stroke in the input that is not in the output
e. Align Stroke High: assign a violation if the next stroke does not start as high as possible
f. Align Stroke Left: assign a violation if the next stroke does not start as left as possible
g. *Leftward: assign a violation for every stroke written left to right
h. *Downward: assign a violation for every stroke written top to bottom
i. Corner: assign a violation if two lines joined at a corner are not written as a single stroke

There are several points to note about this ranking of constraints. First, the top three constraints are never violated in formal writing. That is to say, no strokes are written right to left, from bottom to top, or are left out. We will see later that *Rightward and Max Stroke can be violated in a certain popular handwriting style.

Secondly, there are the constraints *Leftward and *Downward; their ranking is to ensure that when two strokes could be written at the same location, it is the horizontal stroke that will be realized first. If this were not the case, there would be no way of determining at such a point which stroke should be drawn and variation would be predicted. Thirdly there is the constraint Corner, which essentially dictates that there should be no unnecessary movement of the hand. Fourthly, diagonal strokes in Korean are treated as horizontal in that a diagonal stroke connecting the top right of a grapheme to the bottom left will be treated in the stroke order as if it were a simple top to bottom. Lastly, the *Clockwise constraint accounts for the two graphemes that employ circular elements. Together these constraints are sufficient to produce all Korean graphemes, stroke by stroke.

To show this is the case, we can take a simple example: ㅁ/m/. This grapheme contains four lines: two vertical lines and two horizontal lines. We must make sure that our first stroke is placed as high as possible due to Align Stroke High. There are three lines that could start in the highest place: the two horizontal lines and the top vertical line. However Align Stroke Left eliminates the rightmost horizontal line. Left with the top vertical line and the left horizontal line, we find that *Leftward eliminates the top vertical line as a candidate, and we make our first stroke as the leftmost horizontal line.

As it turns out, the next stroke will be the next most optimal candidate: the topmost vertical line. But at this point Corner tells us that as the next stroke will be joined to this line, so we should join the two in one motion. Our last stroke will be the bottommost vertical line. In this way there are three strokes: leftmost horizontal, topmost vertical and rightmost horizontal conjoined, and finally the bottommost vertical.

In the case of different fonts or handwriting styles, the order of these constraints can be varied to produce different effects. For example, re-ranking Corner above *Rightward can result in a different stroke order than formal writing. In such a case the grapheme ㅂ/p/, in which the bottommost horizontal line would normally be written last, would instead have the same line written second to last, resulting in a slightly different shape.

These differences in stroke order are not inherently meaningful, but they do change the way in which the grapheme is written, particularly when written quickly. However although they are not meaningful in Korean, stroke order and direction can be meaningful in other writing systems. In the Japanese Katakana script the graphemes representing /si/ and /tu/ are identical but for the direction of stroke (Simon 1984). And of course while this writing system is explicitly taught in Korean schools as part of the prescriptive knowledge of the language, it is probable that we would find similar constraints when looking at scripts in which the stroke order is not explicitly taught, such as the Roman script.

As for the cue constraints mapping the PF to the SF, it may actually be best to formalize this as a mapping of a stroke combination to a grapheme. In typewriting or very neat handwriting the intended grapheme is relatively easy to make out, and one might assume that the mapping is one of line combinations to graphemes. However this becomes problematic when freer handwriting is taken into account. In such a style, the grapheme ㅁ/m/ may be realized as something closer to a triangle than the square due to the writer's anticipation of the last stroke. In such a case, the rightmost vertical line is realized as a sharp diagonal line ending in the bottom right corner. This is even more apparent in a grapheme like ㄹ/L/, in which case both horizontal lines are realized as diagonals and the entire grapheme takes on the appearance of a saw tooth.

For these reasons, it is best to regard the stroke as the alloform of the Korean script. Cue constraints then relate the stroke configurations onto an underlying grapheme, which can be considered a chrosoform at the SF. A specific configuration of strokes signals a unique grapheme just as a specific combination of acoustic features (such as aperiodic noise with the presence of a voicing bar) signal a unique chrosophone. While these features can be shared with other units (such as ㅈ/tɕ/ and ㅅ/s/), it is the specific combination that points to a unique unit. The next section will explore the Surface Form in Hangeul in more detail.

3.2 The SF in Hangeul

While the well-formedness constraints in the PF are essentially defined in how the strokes should be written, the well-formedness constraints on the SF determine the arrangements of the graphemes. In Hangeul, the graphemes in each syllable are composed in such a way that the whole of the syllable approximates a square. Additionally, unlike the Roman script where there is no inherent difference between vowels and consonants, Hangeul employs a system in which these two types of graphemes act differently at the SF. Vowel graphemes can also be further divided into vertical and horizontal classes, with the horizontal class comprised primarily of round vowels (but also unrounded /ɯ/) and the vertical class comprising the remainder. The constraints and ranking for this level may be given as follows:

(3) a. *Onsetless: assign a violation for each syllable that does not contain a consonant grapheme
b. Max Graph: assign a violation for each grapheme in the input that is not in the output
c. Align Vowel Right: assign a violation if the vowel is not placed rightmost
d. Align Onset High: assign a violation if the onset is not placed topmost
e. Align Vowel High: assign a violation if the vowel is not placed topmost
f. Align Onset Left: assign a violation if onset is not placed leftmost
g. Align Coda Left: assign a violation if the coda is not placed leftmost
h. Justify: assign a violation if the edges of a grapheme do not align with other edges

By following these constraints one may produce a correctly formed syllable in Hangeul. We can demonstrate the results of these constraints with two Korean syllables: 짱 /tɕ̰aŋ/"awesome!" and 중/tɕuŋ/"middle". Note that while the bottommost graph has been rendered rather faithfully in this typesetting instead of being distorted to fit the square frame of the syllable, this is not typically the case.

For our first syllable, 짱/tɕ̰aŋ/, we note that the vowel must be placed rightmost and topmost, so it will be placed in the upper-right corner. Our onset consonant ㅉ/tɕ̰/ will be placed in the upper-left corner. Finally the coda consonant ㅇ/ŋ/ will end at the bottom of the syllable frame.

For our next syllable, 중/tɕuŋ/, placing the vowel to the right of the onset would not be feasible as it would extend past the borders of the syllable frame. However by placing it under the onset consonant it is still maximally rightmost, and only incurs a relatively minor violation of Align Vowel High in order to satisfy the higher-ranked constraint Align Onset High. Thus the onset consonant will be placed first, followed by the vowel, and lastly the coda consonant is placed in the bottom.

The list above is incomplete and only representative of the constraints most commonly in effect. Many For example, *Complex Onset would forbid multiple consonants at the start of a syllable. *Hyper-Complex Coda would forbid more than two consonants from appearing in the coda position, and OCP type constraints could forbid "vertical" and "horizontal" graphemes from combining with their respective groups. These constraints mirror the phonotactic constraints that exist in Korean as it is spoken today. However even though this parallel exists, it is not necessarily the case that Korean speakers will transfer these constraints to the writing system and not form any restrictions or predictions on top of them. Empirical tests will need to be done to see if a malformed written form is judged to be as ungrammatical as a similarly malformed spoken form.

The next section will deal with the UF of Hangeul and compare it to that of other scripts. Because the link is so straight-forward between the SF and the UF in Hangeul, it is more useful to show how the Underlying Form can vary in different languages. Similarly, because the link between the written SF and the written UF is usually so close, it will be useful to examine cases in which they are not identical.

## 4 The Underlying Form in Hangeul and Devanagari

The Underlying Form is in some sense a “morpheme”. Whether written or spoken there is a unity to the UF that comes from an awareness of the morpheme as a meaningful unit in its own right, something that is lacking at lower levels of the linguistic chain. In the written modality the Underlying Form consists of multiple graphemes that together form an orthographic morpheme, and as with the other levels the UF is bound by well-formedness constraints. The link between the Underlying Form and the Surface Form in writing is generally rather straightforward/completely faithful, however in the case of Devanagari we may show that there are interesting exceptions to this. The following sections will compare the UF in three scripts: Hangeul, Roman, and Devanagari.

4.1 Constraints on the UF in Hangeul

As with other phonetic scripts, the Underlying Form in Hangeul is composed of multiple graphemes. The well-formedness constraints of Hangeul militate against certain combinations of graphemes in the UF, while the faithfulness constraints linking the SF to the UF determine the nature of change (if any) that takes place in the conversion of one to the other.

As for the faithfulness constraints mapping the SF to the UF, there are only a few cases in which there might be reason to posit an unfaithful mapping. In the case of adjectives ending in ㅂ/p/ in the infinitival form said consonant is often omitted, creating an alternation with the vowel ㅜ/u/. Thus 맵다 /mepta/”to be spicy” becomes 매워/mewʌ/”spicy” when finite. Secondly, in the case of verbs ending in ㄷ/t/ this consonant is changed to ㄹ/l/. The verb 듣다 /tɯtta/”to hear” in the infinitive thus becomes 들어 /tɯɾʌ/ when finite. In such situations it may be the case that users of this writing system see a pattern and end up with constraint rankings where the faithfulness for these two symbols is lowered, allowing them to alternate. However this is a bit of a stretch and it would be difficult to define this relation in terms of constraints and features. For now then, this paper will take the position that the SF is faithfully mapped onto the UF in Hangeul.

However it is important to remember that it is not the case that in *spoken* Korean the mapping between the SF and the UF is completely faithful (indeed, this is far from the case). Rather it is only to say that as we have defined the SF of the written modality there is no reason to posit such a change in the *written* system. It is not the case that the grapheme ㅈ /tɕ/ alternates with another grapheme ㅊ /tɕʰ/ for example. This is not necessarily the case. Languages can and do display alternations of graphs across boundaries (as we shall see with Devanagari in Section 4.2), while Hangeul is a writing system that does not do so.

The well-formedness constraints on the UF are another matter. In any language these constraints dictate what is an acceptable morpheme structure. These constraints can go above and beyond what is an acceptable combination of chrosoforms or alloforms (constraints on the SF or PF). This is particularly evident in the case of writing systems where there is not a one-to-one correspondence of sound to grapheme. Although there is plenty of overlap, in such cases it is not sufficient to say that the writing system is merely acting as an extension of the spoken system.

Boersma and Hamann (2009) note that when American English words with closed syllables are borrowed into Korean we can see the effects of well-formedness constraints on the UF. For example, the word "internet" /ɪn.tʰɹ̩.nɛt.] was borrowed into Korean as "인터넷" /in.tʰʌ.net/. Note that the final grapheme is one that is *underlyingly* |s|. This phenomenon is also true for borrowings like "shot" ("샷" /sjat/), and "good morning" ("굿모닝" /kut.mo.niŋ/). As Korean has a process whereby all underlying coronals reduce to a surface /t/ in coda position, there are no less than eight graphemes that could be used to represent what is on the SF a /t/. In such a case, it is the ranking of the well-formedness constraints on the UF that determine what will be the generally accepted written form for this borrowing. In the case of Hangeul, the grapheme ㅅ |s| is more likely to be found in the coda position than other graphemes, and thus it is more likely to be posited as the Underlying Form.

In Korean, the range of well-formedness constraints on the written UF results in a preference for a given graph to be posited. However, such constraints about which grapheme or combination of graphemes is most likely to underlie a given spoken SF can also be the source of spelling errors. Those learning to write Hangeul will at first have no intuitions as to which grapheme is the correct Underlying Form of a given spoken form. However over time these intuitions will develop into a workable inventory and ranking of constraints that are used productively for new forms. For Hangeul the most relevant opportunity for these mistakes to arise is by choosing the wrong underlying grapheme that nonetheless would be pronounced the same as the correct grapheme. Of course for other languages (English) this need not be the case, and general constraints may lead one to a wrong conclusion that must instead be memorized rather than derived (as is the case with *bread*/bɹɛd/ or *cough*/kɔf/).

Aside from this type of well-formedness constraints that essentially inform the likelihood of finding a given grapheme in a different position, we can also classify other types of well-formedness constraints that play a more direct role in what is and is not an acceptable Underlying Form. Vowel Harmony in Korean is generally considered to no longer be synchronically active (Park 1990), though such an account has been attempted (Choi 1991). It is acknowledged that at least at the time of the invention of Hangeul in the 15th century the vowel system of Korean could be divided into two categories, which are referred to as "light" and "dark". In Hangeul this difference was instantiated such that light vowels were right or upward facing while dark vowels were left or downward facing. While today this distinction is more or less phonetically arbitrary (Park 1990) it is still a highly salient feature of the writing system that interacts with productive morphology.

In Hangeul when the final vowel of a verbal morpheme belongs to the light group, the present finite form of that verbal morpheme will be followed by the corresponding light vowel inflection. If instead the final vowel is not light, the verbal morpheme will be followed by a corresponding dark vowel inflection. For example, the verb "to know" 알다 |al+ta| and the verb "to freeze" 얼다|ʌl+ta| form a minimal pair. When deriving the finite form from the infinitive, they become 알아 |al+a| and 얼어 |ʌl+ʌ| respectively. We could formulate this as a written harmony constraint:

(4) Light Harmony (Written): assign a violation if a dark grapheme follows a light grapheme at a boundary

This is a very weak constraint, and only plays a productive role in this verbal paradigm. Although historically this sort of harmony was present in both particles and verbal inflection (Lee and Ramsey 2000), this is no longer the case in present day Korean. Weak as it is, it is still a very reliable constraint as it has almost no exceptions to its application. Still one might question whether it is truly a well-formedness constraint of the UF or more properly belongs as a constraint on the SF, or again is more properly a constraint on the UF of the spoken system, and not of the written system.

The primary reason that this constraint should not be seen as a constraint on the SF and not the UF is precisely because it is so often violated. This constraint applies only across a derivational boundary, while root internally this constraint is violated so often as to be nearly irrelevant. However the Surface Form is blind to morphemic/derivational structure, and therefore its well-formedness constraints are not concerned with such boundaries. While historically this may have been active at the level of the SF or even at the PF, this is no longer the case.

The constraint defined above *can* be expressed without the written system. It may in fact be the case that for most users of Hangeul they will avoid violation of this constraint due more to the avoidance of violating a parallel constraint in the spoken language; constraints of the spoken language may outrank those of the written language. As an example of this, we may have the mini constraint ranking seen below:

(5) a. Light Harmony (Spoken): assign a violation if a dark vowel follows a light vowel at a boundary
b. IO(facing direction): assign a violation if the direction of the UF is different from the SF
c. Light Harmony (Written): assign a violation if a dark grapheme follows a light grapheme at a boundary

| {know+finite} | Light Harmony (Spoken) | IO(facing direction) | Light Harmony (Written) |
|---|---|---|---|
| \|al+ʌ\|/알어/ | *! | | |
| \|al+a\|/알어/ | | *! | |
| ☞\|al+a\|/알아/ | | | |
| ☞\|알+아\|/알아/ | | | |

Tableau displaying equivalence of output for either a spoken UF constraint or written UF constraint

It is not always clear whether a given constraint applies to the spoken form, the written form, or both. As seen from the tableau above, whether the constraint is posited for the written form or for the spoken form does not typically matter, and given the fact that most speakers will derive such a constraint more from speaking than writing in most cases it is sufficient to assume only one constraint. However this question can actually be tested empirically: do deaf writers of Hangeul make similar grammaticality judgments about these forms as do hearing writers? If this turns out not to be the case it would be a strong criticism against the line of reasoning put forward in this work. However should this prove to be the case it would strengthen the claim that serious linguistic work can be done on writing systems in and of themselves, and not merely as cross-modal extensions of spoken systems.

## 4.2 Alternations involving the UF in Devanagari

Devanagari is a script that demonstrates both the need for a written Underlying Form as well as some of the regularities that can arise from a sufficiently complex writing system. While it is used for many languages, the examples in this paper are taken from Hindi. As noted with Roman script, the UF may be nearly or entirely superfluous when it comes to certain writing systems. Although this is the case for certain scripts, others such as Devanagari require an Underlying Form if they are to be reliably explained. In particular, the existence of a UF in Devanagari does a great deal to explain the relation between the two forms for each vowel, the various regular ligatures, and the several irregular ligatures.

The first and most obvious alternation in Devanagari is that between the vowel graphs in their full and *matra* forms (Monier-Williams 1899). When a vowel appears in an onsetless syllable the full form of the graph is used. Like in the Roman script, these vowel graphs are not noticeably different in character from the consonantal graphs, and there is no systematic difference between full vowel graphs and consonantal graphs as there is in Hangeul.

However when the vowel graph follows a consonant graph the *matra* form is used. The *matra* form is clearly distinct from the full vowel graphs and consonantal graphs and takes up considerably less space. There is no clear visual relation between the full form of a vowel graph and its *matra* form just as there is not always a clear relation between uppercase and lowercase letters in the Roman script.

The relation between these two forms of vowel graphs is made evident in compound words. Thus just as in the spoken modality, evidence for links between apparently dissimilar forms at the level of the Surface Form is provided by knowledge of the Underlying Form. If the second member of a compound word begins with a vowel graph, this graph will be seen in its full form because it appears in an onsetless syllable. However when combined with another word, resyllabification can cause this graph to morph to its *matra* form in the compound word.

To provide an example, the compound word <अनात्म> /ənatm/ “non-self” is the combination of the negative prefix <अन> /ən/ with the word <आत्म> /atm/ “ego/soul”. The vertical bar <ा> immediately following the graph <न> in the compound form is the *matra* form of the graph <आ> as seen in the simplex form. Alternations such as these indicate to the users of this writing system that these two forms are connected in the same way that Dutch speakers pick up on the alternation between /hɔnt/ and /hɔndə/. In both cases there are two similar Surface Forms that are related to a single Underlying Form.

There is a crucial difference between this type of written alternation and the alternation commonly found in spoken languages. In spoken languages it is usually possible to decompose the forms being related into features. In doing so it is found that some features remain the same while others vary in systematic ways. In the case of the Dutch example, place of articulation and release type remain the same while only the value for voicing changes. Thus it is simpler to see the relation between the two forms as there still remains at least one feature in common between them. This is not the case for the full and *matra* forms in Devanagari; there are no visual similarities between these two forms. Still, even without the aid of some natural relations between these forms, users of Devanagari are able to relate them consistently. This again serves as an example of the fact that just because spoken languages tend to have alternations based on natural classes does not mean that humans require alternations to be related naturally in order to form reliable relations.

Due to this lack of features it would be impossible to provide general faithfulness constraints mapping the SF to the UF in Devanagari. Instead, each full form in the SF receives a constraint relating it to its *matra* form in the UF (as well as relating a *matra* in the SF to the full form in the UF). To take our earlier example, the faithfulness constraints for /a/ would be /ा/|आ| and /आ/|ा|. Both constraints are necessary; the first applies in the case of resyllabification as seen above and the second applies in the case of consonantal deletion that then results in a hiatus of vowel graphs. These constraints are ranked lower than the fatuous faithfulness constraints of type /x/|x|, which are in turn ranked lower than well-formedness constraints on the SF that forbid a *matra* form appearing in an onsetless position and the full form appearing after an onset. The tableau below demonstrates this principle in action:

(6) a. *Full Onset: Assign a violation if the full form is used immediately following a consonant graph.

b. /आ/|आ|: Assign a violation if the given mapping is not carried out.

c. /ा/|आ|: Assign a violation if the given mapping is not carried out.

| {neg+ego} | *Full Onset | /आ/\|आ\| | /ा/\|आ\| |
|---|---|---|---|
| \|अन+आत्म \|/अनआत्म/ | *! | | * |
| ☞ \|अन+आत्म \|/अनात्म/ | | * | |

One point to note with the constraint *Full Onset is that the full form may appear to come after a consonant due to the fact that the *matra* form of <अ> is simply null <>. In the case of the surface candidate /अनआत्म/ this would be rendered phonemically as /ənəatm/ (note the extra schwa following the nasal). Thus the real reason the first candidate is unacceptable is due to the orthographic DEP constraint preventing epenthesis of null <>.

Of course the counterpart to *Full Onset is *Matra Onsetless, wherein a violation is assigned if a *matra* form is used when not following a consonant grapheme and the faithfulness constraint counterparts to (6) b. and c. exist for all of the various vowels and need not be elaborated here.

In addition to the alternation between the full and *matra* forms of vowel graphs, there is a fairly regular system of ligatures used for clusters of consonant graphs. As seen in the example above, <आत्म> /atm/ has just such a ligature. In normal circumstances the graph <त>/t/ is written with a vertical bar that descends from the horizontal line that is characteristic of nearly all Devanagari graphs. However in the case of consonant clusters this vertical bar is typically removed from the first member of this cluster and the remainder of the graph is then appended directly to the following consonant graph. The consonant cluster in question need not belong to a single spoken syllable; this conjoining will occur whenever there are multiple consonants with no intervening vowels.

Unlike the alternation of the vowels, the conjoining of syllables can be broken down into features. Nearly all of the graphs are written with a segment on their right side that connects the graph to the horizontal bar that runs across the entire word (c.f. <च>/c/, <ल>/l/, <स>/s/). Ligatures are created by removing this connecting segment and adjoining the remainder to the following consonant graph. In this way it is a generalizable process, and someone learning how to use this script for the first time has a reasonable idea of how to form a new conjunct even if they have never encountered a particular consonant cluster before.

With this in mind it is possible to develop a simple schema for deriving consonant clusters in Devanagari. If this connecting bar is seen as representing the inherent vowel /ə/ while the rest of the graph contains consonantal information then a fairly simple combination of constraints is sufficient to explain the process. It is not necessary and perhaps even unlikely that users of Devanagari actually associate this bar with this vowel; this formalization is arbitrary and only for the benefit of those trying to analyze this writing system in a tidy manner. With this in mind, the below tableau demonstrates derivation of ligatures from a cluster of consonant graphs:

(7)
a. DEP: Assign a violation for every segment in the SF that was not in the UF
b. *Orphan: Assign a violation for every graph not attached to the horizontal bar
c. *Complex: Assign a violation for every graph composed of more than one consonant

| \|आत’म\| | DEP | *Orphan | *Complex |
|---|---|---|---|
| /आतम/ | *! | | |
| /आत’म/ | | *! | |
| ☞/आत्म/ | | | * |

Due to technical limitations, the half form of <त> has been rendered with an apostrophe as it is impossible to represent the dependent half of a ligature without its other half.

In this tableau we see that the anti-epenthesis constraint DEP prevents the half form of the ligature from gaining a bar in order to connect it to the horizontal bar. In Devanagari this has noticeable effects- as mentioned earlier, the difference between the full form <आतम> and the connected form <आत्म> is indicative of the presence or absence of a schwa in the spoken form. It is for this same reason that I have chosen to represent the underlying form as the ligaturized form and not the full form. Because Devanagari chooses to represent schwa with an absence of graphs (or alternatively, that it does not choose to represent schwa), it is necessary to note that in the UF there is an absence of schwa. From an orthographic point of view this poses a problem: how does one represent the absence of an absence? One possibility would have been to give the Underlying Form exactly as it appears in the Surface Form:

|आत्म|. However in doing so it is not obvious that orphaned graphs are not acceptable. By choosing to represent these graphs in this way it is hopefully slightly clearer that there is a well-formedness constraint at the level of the SF that cannot be violated, and it is in order to satisfy this that the ligature comes into play.

There is one further alternation to note within Devanagari: that of irregular ligatures. Although there is notable regularity when forming consonant clusters within Devanagari, there is also a considerable number of exceptions. Among these exceptions there are those that are more or less clearly derived from their component consonant graphs, those related to the graph representing the rhotic <र>/ɹ/, and two ligatures which bear no discernible relation to their constituents.

The majority of the exceptional ligatures that do not follow the stroke deletion pattern as described above are formed by placing the two graphs one on top of the other instead of conjoined side by side. Other exceptions involve rotation or distortion of one or more of the graphs in order to arrive at a more aesthetically pleasing shape. And of course there are true exceptions; the ligature of <श> with <र> produces an unexpected shape that is nonetheless recognizable: <श्र> (Unicode 2011, p. 280).

The rhotic <र>/ɹ/ combines with other consonants in a unique manner. If this graph is the second element of the conjunction, it will appear as a small diagonal stroke appended to the first consonant graph, as in the case of <प>/p/ + <र>/ɹ/: < प्राण>/pɹaɳ/ ”vitality”. However when the rhotic is the first member of the conjunction it takes an entirely different form, that of a small curl. Thus <र>/ɹ/ + <म>/m/: <कर्मा>/kəɹma/ ”karma”. In fact this curl is attached not even to the graph <म>/m/ but rather the *matra* form of the vowel /a/ that follows it.

Interestingly enough, this suggests that the syllabic structure of the orthography is rather different from that of the spoken form. While the spoken form is naturally broken up into two syllables separating the rhotic from the nasal (/kəɹ.ma/), all of the rules governing both *matra* forms as well as ligatures suggest that the orthographic form lacks codas entirely and is instead divided into consonant clusters upon which the vowels graphs depend. In this schema it is the orthographic onset that is the most important member of the syllable, and not the nucleus as is often the case in spoken languages (Hayward 2000, Zsiga 2013).

Lastly, there are two ligatures that look nothing like their component graphs: <क्ष>/kʂ/ and <ज्ञ>/ɟɲ/. In the case of these two ligatures there is no resemblance to their component graphs. In fact they do not appear to be a combination of two graphs at all. In this case there are two possibilities regarding the UF that together pose an interesting problem. The UF may be composed of a combination of two graphs that combine into a unique, exceptional graph in the Surface Form. Alternatively it may be the case that the UF stores the unique graph and the mapping to the SF is faithful.

In order to attempt to solve this problem we can examine the case of a naïve learner. Having a fair understanding of the basic graphs and the regularities of vowel forms and ligatures, the learner then is faced with the question of how to represent the combination of <क>/k/ and <ष>/ʂ/. They might take the approach above and produce something like <क्‍ष>/kʂ/, and they would have no way of knowing this was incorrect until corrected, just as a Dutch speaker might incorrectly produce /hɔn.tə/ "dogs" if they were unaware of the Underlying Form. However when given more information the learner would become aware of two things: first, that there was a well-formedness constraint at the SF militating against the sequence <क्‍ष> and second, that the correct form was an exceptional ligature. In this case we may assume that the learner would retain separate consonant graphs at the level of the UF and develop an unfaithful mapping when producing the SF.

Alternatively we might suppose that the learner came across the exceptional form first. Having thus stored the exceptional form in the UF as singular, the learner would have *no way* of knowing this particular graph was a combination of two graphs. If then tasked to decompose the graph, the learner would be at a loss, just as if an English speaker were asked to decompose the letter <h> into its constituents. Such a learner would have to be explicitly taught that this graph were a combination of two other graphs before being able to understand the situation.

In either situation the learner must come to know two things: that <कष> is unacceptable at the SF, and that <क>/k/ and <ष>/ʂ/ combine to form an exceptional ligature. From this logic, the learner must choose an Underlying Form that is of <क> and <ष>. At least in some sense the Underlying Form for these exceptional ligatures must contain two elements, else it cannot be properly split when necessary. The same problem does not hold for the Surface Form because even though there is only one graph at the level of the SF, knowledge of the well-formedness and mapping constraints is sufficient to regain the lost information. That is to say that generally while the UF must contain enough information to derive the SF in any context, the SF need only contain enough information for the segment to be identifiable *given the context*; the UF is context-free and the SF is context-rich.

This section has explored the possibility and indeed the need for an Underlying Form in several writing systems. For at least some graphs there is a central abstract element from which derive multiple chrosoforms at the level of the SF just as multiple instances of graphs at the level of the PF derive from a single abstract chrosoform. Such an alternation necessitates (at least in this framework) a non-vacuous Underlying Form; it is not possible to map directly from the written Surface Form to morphology. The next section will briefly examine the ways in which elements in the written system map onto elements in a spoken language and vice versa, beginning with the proposal of Hamann and Colombo (2015) as mentioned earlier in this paper.

# 5 Cross-modal Mappings

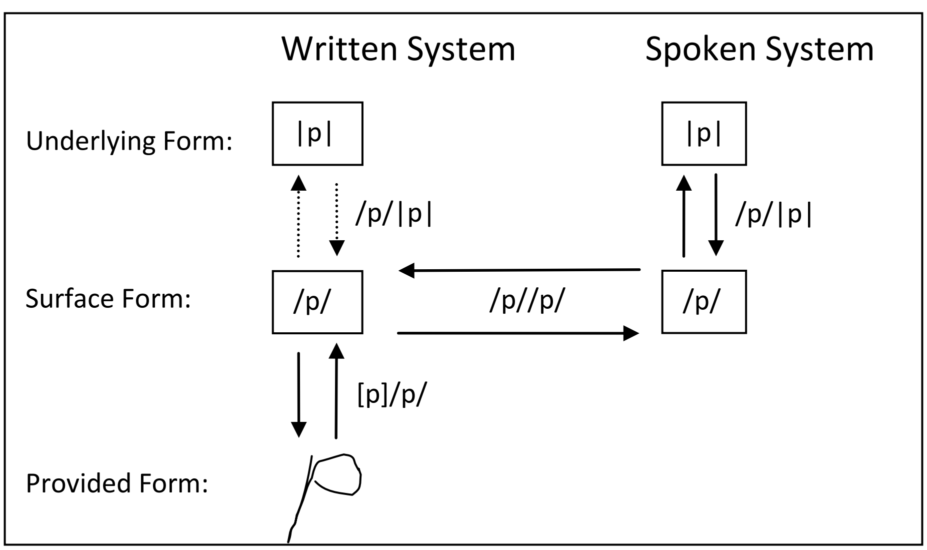
Writing systems are primarily used to represent language as it is spoken. Thus while it is possible to discuss the system as a linguistic system unto itself, it would be remiss not to at least mention the connection to the spoken language. This section will focus on the ways in which one system may map to another and at which level. For the sake of simplicity this will primarily involve the mapping from the written system to the spoken system and vice versa, but in theory the principles discussed in this section should apply to any cross-modal mappings.

## 5.1 Direct mapping to the spoken language: (Hamann and Colombo 2015) revisited

In their description of Italian orthography, Hamann and Colombo (2015) essentially assume a direct mapping from a grapheme (or series of graphemes) onto a chrosophone or series of chrosophones, that is to say a mapping from the grapheme to the spoken Surface Form. As the writing system is not analyzed as a system per se in their paper, it is not specified whether the mapping is from the written PF to the spoken SF or the written SF to the spoken SF.

It can be shown fairly convincingly that this sort of mapping must be seen as applying from the written SF to the spoken SF. If this were not the case and the mapping were instead from the written PF to the SF we would have to posit many cue constraints mapping various forms and fonts directly onto a given chrosophone. This is undesirable as it would suggest readers derive phonemic information from the form of a graph itself without having some abstract representation for any given graph. In other words, under this schema readers would have no unifying concept of <a> or <b> as categories unto themselves. It is therefore much more desirable to suggest that there is indeed a written SF, and it is from this form that mapping to the spoken SF takes place. An example of the sort of mapping proposed by Hamann and Colombo is provided below.

(8) Mapping between orthography and auditory phonology



The illustration above demonstrates the mapping between the written and spoken systems Following Hamann and Colmobo (2015) the mapping of most graphs is fairly straightforward. It is fairly uncontroversial to posit that in Italian written /p/ will map to spoken /p/ and written /d/ will map to spoken /d/ and so forth. We then arrive at a series of mapping constraints of the form /x//y/ whose ranking determines the precise mapping. Note that the illustration above represents the mapping between the written SF and UF with dashed arrows in order to indicate that such a mapping is proposed in this paper, but not in Hamann and Colombo (2015).

At first the need for ranking of these constraints is not obvious: in a shallow orthography a one to one mapping is implied. However conflict comes about when multiple graphs are used to represent a single phoneme, as is the case with <ch>/k/ and <gl>/ʎ/. When this happens it is necessary for the constraints that contain multiple graphs to outrank those constraints that contain only single graphs in order for them to be represented correctly (Hamann and Colombo 2015, p. 8). It may be the case that this is a general rule of mapping constraints- constraints with multiple elements must be ranked higher than those with a single element. Were this not the case it would not be possible for the group of graphs to function as a group; this should hold true of any mapping and not merely between the written and spoken forms of a language.

Noting that complex mapping constraints must come before simple ones, there is still one type of constraint in mapping to the spoken SF that needs to be dealt with: the well-formedness constraints on the spoken SF. In most cases these well-formedness constraints will be vacuously satisfied. Because written languages are used primarily as ways to convey spoken languages, and because of the near one to one mapping available in languages such as Italian, it is rare that the well-formedness constraints will influence the outcome of mapping when reading. However as noted by Hamann and Colombo (2015), it is precisely these well-formedness constraints that play a large role when determining the pronunciation of loanwords.

For the most part, English written words can be borrowed into Italian with relatively few difficulties. A <g> that corresponds to a spoken /g/ in an English word corresponds to the equivalent chrosophone in Italian, as is true with <t>, <f>, etc. Of course there are exceptions when the word does not reflect a shallow orthography in English (such as the word *cough*), but this is for the most part manageable by speakers (presumably by taking English pronunciation as a guide rather than orthography). However there is a certain middle ground when the orthography is close enough to Italian that speakers attempt to pronounce is as such while still being aware that it is a foreign word. In such cases the well-formedness constraints on the spoken SF of Italian come into play and have an effect on the ultimate pronunciation of the borrowed word in spoken Italian.

To give an example, the word *hockey* is borrowed not with a geminate as might be expected from the sequence <ck>, but as a singleton. In this case the mapping constraints point very clearly in one direction(/c//tʃ/ + /k//k/ = /tʃk/), but the constraint against the chrosophonic sequence /tʃk/ in the spoken form bans such a mapping. It then becomes a matter of finding a pronunciation that is not completely faithful, but at least suitably well-formed to satisfy the constraints on the spoken language.

In this way it is important not to leave out the well-formedness constraints of the spoken SF when a mapping from the written form is considered- a faithful mapping is not always the most desirable one. Loanwords are perhaps the most plausible situation in which this applies, but this is not always the case. Evertz and Primus (2013) note the dialectal use of words such as *Dirndl* and argue that sonority sequencing constraints (which are well-formedness constraints of the spoken SF) are implemented to arrive at a correct pronunciation despite the apparently difficult cluster <rndl>. It seems then that both mapping constraints and well-formedness constraints are necessary to arrive at the correct reading of a word.

Direct mapping from the written SF to the spoken SF is clearly possible. Is it also possible that such direct mapping obviates the need for a written UF? In the case of Roman script in shallow languages such as Spanish or Italian there initially appears to be a case for this. If there is a direct mapping from the written SF to the spoken SF, and there is then a mapping from the spoken SF to the spoken UF, it is possible to arrive at an already existing (spoken) Underlying Form from the writing system without creating a separate (written) Underlying Form.

When first a writing system is learned it is fairly reasonable to map to the spoken language, as in most cases the spoken system will already be somewhat developed. Mapping from the written SF to the spoken SF is a reasonable step in learning to ultimately understand the meaning of a written word. However this is clearly not always the case. Even in the Roman script there are languages such as English wherein a mapping from the written SF to a spoken SF eliminates crucial information as to the morphemic content of those words; there are non-homonymic homographs. In such cases a written Underlying Form serves to distinguish words that are not otherwise distinguishable. Furthermore, it is undesirable to posit a mapping from the written SF to the spoken SF in all cases. While this mapping is certainly desirable when first encountering new words it is not necessary for proficient readers (Hamann and Colombo, p. 18).

There is also the case of those who can read a foreign language but are unable to speak it (Ortega 2009, p. 147). Though they are clearly able to manipulate and understand the words, it is entirely probable that they lack auditory chrosophones for this language, and in their case such a mapping is not even possible. Although not the norm, such cases show that it is possible to derive an Underlying Form and thereby link to morphology directly from the writing system without having the need to first map onto a spoken system.

5.2 “Reverse” mapping: from the spoken SF to the written SF

In reading, the written form may be mapped onto a spoken form in order to aid in comprehension. However this is only one half of the story. In writing it is possible that a written UF will map to a written SF, but it is just as possible that an auditory SF is mapped onto a written SF especially for newly learned words. In many cases this is not quite as simple as mapping an auditory UF through the SF to the written SF. The relevant well-formedness constraints (to what extent the apply) now belong to the written SF rather than the spoken SF, and in the case of English at least the possibility of error is greatly increased.

The orthography of Italian can provide a demonstration for some of this complexity. In the first step of the mapping, the spoken SF /gɛtto/ must be translated to the written SF. A naïve first attempt would produce <getto>, but there is a problem with this. Typically in Italian the sequence <ge> maps to a palatalized sequence /dʒɛ/. If one were to apply this mapping in reverse, one would then find that the written SF <getto> corresponds not to the target /gɛtto/ but rather to /dʒɛtto/.

In order to correctly represent the target SF an <h> must be added, thus /gɛtto/ is mapped to <ghetto>. Fortunately, this mapping from spoken SF to written SF is automatically achieved by learning the mapping from the written SF to the spoken SF. Given the complexity heuristic outlined above wherein complex constraints outrank simple constraints, in the direction of written to spoken the mapping <ge>/dʒɛ/ outranks the simple constraints <g>/g/ and <e>/ɛ/. As long as the mapping is done in parallel (each segment is not mapped as soon as it is identified but rather the form as a whole is taken into account) such regular exceptions are easily handled.

In this case it is important to point out that the error is not due to a well-formedness constraint on the written SF militating against the sequence <ge>, but is instead a mapping error. Many languages that use the Roman script demonstrate palatalization or fronting of the velar before front vowels in the orthography: Italian <ge>/dʒɛ/ “gemma”, Spanish <ce>/se/ “cena”, English <ge>/ dʒɛ/ “gem”, etc. However these languages also demonstrate in their orthography that this is not a synchronic process due to a constraint on the spoken SF militating against sequences of velars and front vowels: Italian <ghe>/gɛ/ “ghetto”, Spanish <que>/ke/ “que”, English <ge>/gɛ/ “geld”, etc. As both sequences are allowed both in the written SF and the spoken SF, the only possible conclusion is that this constraint exists as a “virtual” constraint via mapping. That is to say that what initially appears to be a synchronic process whereby a velar becomes more frontal is actually a remnant of such a process that is still reflected in the orthography, but no longer active in the spoken language. Such virtual constraints may be active not only in orthography, but anywhere there are tendencies shaped by historical processes.

Another type of error arises when multiple mappings are possible, as is the case in English. In languages with rampant homophony there may be multiple ways of representing the same auditory chrosophone in the writing system. The orthography of English has at least six ways of representing the rather simple chrosophone /i/: <ee>, <ea>, <e_e>, <ey>, <y>, <i>. When mapping a word for the first time, how is an English speaker to know which of these is the correct mapping? In truth, they cannot know; they must rely on inference to guide them to their best guess at the correct spelling, and even then this may not turn out to be the generally accepted version. However without a cultural authority to refer to it is possible to say that linguistically all such identical renderings are equally viable so long as they obey other sub-regularities.

What is more interesting are the cases of homophonous substitution. Common pairs of words such as <your> and <you’re> as well as triplets such as <their>, <there>, and <they’re> are the subject of much consternation for English teachers and students alike. Substituting one for the other is a common mistake for many, and for some it is a matter of routine. That this happens at all is further evidence that writing is not always a simple matter of mapping from the written UF to the written SF. If this were the case homophony would not be an issue as the auditory system would not be involved at all in the process. The most likely cause for these types of mistakes is interference: while normally the mapping from the written UF to the SF will result in the correct spelling, occasionally this is overridden by interference from the auditory system.

As an example, the conjunction <you're> is sometimes substituted by the form for the possessive pronoun <your>. In normal mapping we would expect that a written Underlying Form |you're| (or possibly |you+are|) would map to the written SF /you're/, which would then continue on to the articulators. However when /your/ is produced instead, we can make two assumptions as to the process. The first assumption is that at some point the auditory system is activated: whether it is activated by the morphological level or the written UF it is difficult to say. In either case the spoken SF is active and something like /jur/ attempts to map onto the written SF, which may then be rendered as written SF /you're/ or /your/. Ordinarily the combination of mapping constraints between written and spoken Surface Forms as well as the faithfulness constraints between written SF and UF will be sufficient to produce written /you're/.

Here is where the second assumption comes into play: the mapping /jur//your/ is more highly ranked than /jur//you're/. Strictly speaking this assumption is not necessary assuming stochastic ranking of constraints. Anecdotally however, <your> is much more likely to be substituted for <you're> than the other way around. Given this assumption if the faithfulness constraints between the written UF and SF are particularly weak (as may be the case due to distraction) or the auditory channel is particularly strong (as may be the case due to subvocalization), the result will be that /jur/ will be mapped onto /your/ as the most optimal candidate. Crucially under this assumption substitution of a lower-ranked mapping /jur//you're/ when the target is /your/ is not expected (or is expected to occur less often) even under the same conditions. Whether or not this holds true is a matter of further empirical research.

The mapping between written and spoken modalities is a necessary but complex process that defies neat and necessary classification. While much of generative linguistics has focused on grammars that are restrictive and produce only what is strictly necessary the different pathways by which a mapping can take place suggest that this approach is itself too restrictive to explain what we know speakers are capable of. At least for phonology then it seems appropriate to posit a principle not of restrictiveness but of connectiveness: language users will derive connections where they occur, between whichever forms are co-occurring.

The sheer scope of possible connections casts more doubt on the notion that all constraints are inherently given (Kager 1999). When taking writing into account the absurdity of this claim defies reasonable credence; it is ridiculous to assume that there might be constraints mapping given abstract auditory categories onto the myriad possible forms that human writing has taken, especially given the relative novelty of writing systems as a whole. Those constraints that relate to the physical world (well-formedness constraints of the FF and PF) may be considered innate, but as for the rest we must give some credit to the human mind's ability to derive connections without the aid of built in programming for every detail.

The next and final section will conclude this paper and offer suggestions for future research and theory. As this paper has focused heavily on theoretical issues there remains a large amount of work to be done to determine whether these issues have merit. Yet even with the heavy focus on the theoretical there is more work yet to do; this paper has focused only on the written modality while setting aside the fascinating issue of sign languages. As such the space given to future research is larger than would be typically expected.

# 6 Suggestions for Future Research and Conclusion

This paper has sought to provide a definition of phonology that does not rely on the incidental fact that the majority of human language has been conveyed via the auditory modality. By drawing examples from various writing systems it was shown that this was not only a plausible endeavor but one that requires relatively little innovation in terms of theoretical framework. Even though the BiPhon model was developed for spoken linguistic systems it is fairly easy to adapt it to writing systems, and should prove to be readily adaptable to other systems such as sign languages, braille, etc.

The scope of this paper has limited discussion mostly to the written modality due to space constraints. Yet as interesting as they are, writing systems are perhaps one of the least interesting modalities that could have been explored. In light of this I would like to take some time to suggest further avenues of exploration, both experimental and theoretical, that could expand our linguistic understanding by making clear what is and is not shared across modalities. The most obvious candidates for continued research are sign languages, but theoretically there is no reason to limit language to only those modalities that have been historically implemented.

## 6.1 Phonology in various modalities

When the phonology of sign languages is considered, many parallels are found with spoken and written language. Sign languages are a quite new development relatively speaking, and although there is diversity in the ways in which it is implemented throughout the world, there is also a marked regularity to their phonology (Sandler 2012). Sign languages exhibit features, well-formedness constraints, and minimal pairs. There is also evidence for suprasegmental structure; the order in which individual motions of a sign are articulated is relevant to the meaning of the sign as a whole.

One of the features that conveys information is the shape of the hand. According to Sandler (2012), there are four configurations in which the active fingers can appear: open, closed, curved, and bent. Notably, active fingers cannot appear in multiple configurations. That is to say if the pinky and index finger are active, one cannot be bent and the other open. Note also that the distinction between active and non-active features requires that there be a visible contrast between active and non-active fingers.

The contrast between active and non-active also means that which fingers are active in a given sign can also serve as the basis for meaning. Finally there is also movement within the hand, as the active fingers change from one configuration (held in common with the inactive fingers) to another. Within the hand, the articulation can be summed with the following features: configuration of active fingers at beginning, configuration at end. Because which fingers are active is defined on the basis of their movement, it is a feature that can only be defined across time, thus it belongs to the sign as a whole. In contrast, finger configuration can be either static (unchanging) or dynamic, thus the sign can be subdivided into a beginning and an end regarding this feature.

Another feature relevant to sign phonology is location. Signs can form minimal pairs depending on the locations of the primary hand in regard to the body. Generally location is restricted to areas easily accessible to the dominant hand, such as the head and torso. As with Hand Form, this feature can be further subdivided as different positions on the head may signify changes in meaning. In some cases it is convenient to make broad generalizations about the general location, just as many languages may broadly distinguish dorsals from coronals or labials for some processes even though they exhibit more fine-grained distinctions in others.

In this way, location falls into natural classes, which can be further subdivided into more refined classes. However it becomes more and more difficult to draw parallels between sign languages and spoken or written scripts such as Roman. In their great degree of variability, hand signs more closely resemble the Chinese script, in that a great degree of semantically relevant variation can be packed into a very small amount of space. This is opposed to spoken languages, which are instead restricted to a fairly small auditory space, but may change this space very rapidly and so make more efficient use of time.

Further exploration on the phonology of sign languages may benefit more from trying to understand the constraints on the SF and the UF in these languages. That is to say that trying to examine these languages for the sorts of forms we do not see and which are avoided may prove more fruitful than trying to classify the many myriad forms into broad classes. It also seems likely that greater attention will have to be paid to the connections between morphology and phonology than might ordinarily be given in phonological research: what forms are able to interact with each other to form compounds and in which ways? The study of phonology in sign languages is just getting started and should prove enormously useful in understanding phonology in general.

As for truly linguistic systems other than those already mentioned, only one comes readily to mind: braille. In many respects braille is an extremely close cousin to the Roman script, with each sequence of dots being essentially equivalent to a graph, and all graphs being arranged in a strictly linear sequence. This being said, braille has an interesting mix of systematicity and arbitrarity that bears further consideration.

Braille differs from its flat cousin in the arrangement of its constituent symbols; each symbol has six locations each of which may be either raised or flat resulting in 64 possible symbols. It is possible then to group braille symbols into classes depending on subgroups. For example, the first twenty-six symbols of braille are arranged in such a way that the first ten form a subgroup with both bottom locations left flat, the next ten form a subgroup with the bottom left location raised, the next ten with both raised, etc.

Unfortunately, this system has been tied to the Roman script rather than any phonetic details of the language it is meant to correspond to. While the composition of braille is uniquely suited to encoding featural information this ability has largely gone to waste. With the six locations used in braille symbols today, even without adding further locations as would surely be possible it should prove quite reasonable to group symbols based on the features employed by the spoken language rather than the arbitrary order in which they find themselves based on the Roman script. To give a brief example, one might reserve the lower right location to mean vowel if left flat. One is then left with five locations, each of which alone could serve to represent a vowel and even in such a way as to be iconic: top left for /i/, top right for /u/, middle left for /e/, etc. At this point there may be little merit in changing such a system, still it might prove useful to think about such things next time it comes up for revision.

Of course this binary distinction and six locations is also an unnecessary limitation. There seems to be no reason why with today's technology one might employ a three-way distinction between raised, flat, and excised. This could be further expanded to nine locations if one were so inclined. While this would grant far more symbols than necessary for any language ($3^9$ = 19683) such latitude may actually make the language easier to learn if properly employed (provided our fingers are actually outfitted with such sensitivity). While the 64 symbols of braille are distinct, they are not as distinct as they could be. While all children that develop normally are able to achieve literacy, Sampson (1985) notes that the time at which they do so is in part dependent on the writing system: children learning Hebrew (whose graphs can differ in very slight detail) have a more difficult time than those learning the Roman script, who are in turn bested by the speed at which children learn Hangeul (a language with distinct graphs and noted featural construction).

It is not then ridiculous to assume that improving the braille system could have a measurable and lasting effect on children learning to use it. Fortunately this is decidedly a matter of empirical research: such a system could be developed and tested to see if it did indeed have an effect on timing and quality of literacy among its users. While altering Roman script to such a purpose may prove too large an undertaking given the weight of history, now would be the ideal time to test the possibility of such a utility for braille as unfortunately the number of resources available in this modality remains low, and therein lies one less problem for restructuring.

However what is perhaps most interesting is the vast amount of modalities that have yet to be employed by humans for linguistic capabilities. Even the ways in which we use the visual medium are incredibly limited when compared to what is possible. At the time, writing typically occupies only one dimension syntactically, two dimensions graphically, static figures, and one contrast of color (black and white being most common). Many of these are due to historical limitations of technology; colored ink does not come cheap, and we have yet to master holograms. To say that this is sufficient for most purpose is true, but to say that it could not be improved is another matter. With today's technology it could prove useful to explore these different aspects in a systematic way. If done properly color could be a better way of representing vowels as both are in one sense combinatory and in another gradient. Such things may prove to be of only novel use, but it may be that we find something about our use of language in doing so.

Finally, linguistic communication could theoretically take place in non-human modalities. Polarity of light, electrical signals, echolocation, infrared changes in body temperature: all of these are detectable by other animals but have no correspondence in human experience could be used as means of communication. What has hopefully been shown from this paper is that the modality of communication is not important. Rather what is important (for phonology at least) is that the signal used for communication can be divided into discrete units that have no meaning of themselves but can be *systematically* combined to form meaningful units. Whether these units are based on changes in air pressure or wavelength of photons should make no difference whatsoever.

6.2 Theoretical Improvements

Even if one does not take further modalities into account, there is still much to be done to develop this model with writing systems. In particular, prosody and suprasegmental aspects of phonology in writing have regretfully been left out. While it was argued that the prosodic structure of German and English as set up by Evertz and Primus (2013) was not necessary to explain the processes that served as their justification, it would be foolish to say that writing systems never had any such suprasegmental structure.

The cases of Hangeul and Devanagari both show how writing systems can group their component graphs in a visually explicit manner that suggests coordination greater than the level of the graph and lower than that of the word. In Hangeul, graphs are centered around an orthographic syllable that must contain an onset and a nucleus (with optional coda). In Devanagari, consonants or clusters of consonants form the frame upon which vowel graphs depend. Just how many other examples may be found in other scripts remains to be seen, though the Semitic scripts seem a good place to start.

This paper has also made a fair number of assertions that would benefit from experimental observations. The majority of these involve the user's knowledge of and ability to implement the mappings in question. While this paper has assumed that all users of English and other shallower orthographies are able to perform a mapping of individual graphs or letters to spoken chrosophones, this is not guaranteed. It may be that some users may not have this ability unless they are explicitly taught, and may instead map the entire written word to an entire spoken word (a UF to UF mapping rather than an SF to SF mapping). This may differ on an individual basis- some users if uninstructed may pick up on the systematicity suggesting such an SF to SF mapping while others may not.

Chinese script remains an even more complicated issue, particularly as it is implemented in Japanese. In the Japanese use of Chinese script a single character not only provides little clue as to the phonetic value of that character, but may have multiple phonetic values depending on the context in which it is used (Sampson 1985). In this case then there is a connection to meaning associated with each character, a connection to morphology for each word (which may comprise multiple characters), and multiple phonetic values for each character as well. Clearly there is much work that needs to be done in order to understand this system and see how it can fit into the model described above.

The scope of mappings is also a viable line of inquiry. Are there any restrictions on which forms may be mapped to which other forms? If so, what types or classes of restrictions do we see? That there are links between higher levels of linguistics such as syntax and lower levels can be easily seen in the fact that prosody is often affected by sentence structure; a rising intonation being found in a question sentence is just such an example. There are two plausible means of explaining this. First, is may be that information from the sentence structure is passed down through all the levels until it finally reaches the articulatory system. This information could be seen as floating, suprasegmental, or various other means of formalization. This would require a significantly different view of the linguistic process, suggesting that the seeds of prosody are already present in syntax remain latent through morphology and phonology, only to bloom upon reaching phonetics. The second approach is to suggest that there is a mapping between syntax and phonetics, and indeed all linguistic subsystems. The trouble with this approach then becomes how to manage all the various mappings; it may be that this is unworkably messy and alternative formulations could improve upon it.

### 6.3 Conclusion

While by no means a complete description of non-spoken modalities, hopefully this paper has given some small insight into the linguistic capacities of the written language. In looking at Hangeul and Devanagari it should be clear that there are writing systems have systematic structure and complexity that can be described and thought of in much the same ways as can spoken language, and even Roman script can benefit from further analysis. Most importantly, I hope this paper has demonstrated the need for open-mindedness as to the general properties we should expect of a language, namely as a means of communication via abstraction, rather than getting hung up on the forms by which the abstractions are translated. Modality should not be a barrier to phonological study.

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