Stress systems[*]

1. Introduction

Stress refers to the increased prominence associated with a certain syllable or syllables in a prosodic domain. The study of stress is complicated by the existence of considerable cross-linguistic variation in the acoustic correlates of stress, the domain over which stress is assigned, the presence of secondary stress, and the relationship between stress and other types of prominence, such as phrasal pitch accents (see Beckman 1986, Hayes 1995, Ladd 1996 for overviews of these issues). Nevertheless, the formal investigation of stress has been a fruitful area of research in the phonology literature since the seminal work on generative metrical stress theory in the 1970s and early 1980s (e.g. Howard 1972, Liberman and Prince 1977, Hayes 1980, 1995, Prince 1983, 1990, Halle and Vergnaud 1987, Halle and Idsardi 1995). The last 30 years have witnessed important advances in both the typological knowledge of stress and its formal analysis, though many of the basic observations about the data serving as the basis for early generative work still underlie current research in metrical stress theory.

The advent of the constraint-based framework of Optimality Theory has provided a new framework for analyzing stress systems (e.g. Crowhurst and Hewitt 1994, Bakovic 1996, 1998, Walker 1996, Alber 1997, 2005, Eisner 1997, Kenstowicz 1997, Elenbaas 1999, Elenbaas and Kager 1999, Kager 1999, 2001, 2007, Gordon 2002, Hyde 2002, McCarthy 2003). One feature of OT that has been a boon to metrical stress theory is the relative ease with which analyses may be computationally implemented. This has facilitated evaluation of the predictive power of metrical theories and has also enabled testing of learning algorithms that model the acquisition of a stress system by language learners (e.g. Tesar and Smolensky 2000, Tesar 2004, 2007, Hayes and Wilson 2008).

This chapter examines the current state of metrical stress theory both from a typological and theoretical perspective. The structure of the chapter is as follows. Section 2 provides a typological overview of the various types of quantity-insensitive stress systems found cross-linguistically. Section 3 sketches a representative foot-based

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approach to these data couched within Optimality Theory. Section 4 introduces syllable weight effects observed in stress systems, while section 5 discusses the relationship between word-level stress and phrase-level prominence. Section 6 examines the relative merits of foot-based and grid-based theories of stress in terms of their typological coverage. Finally, section 7 summarizes the chapter.

2. Typology of quantity-insensitive stress systems

Quantity-insensitive stress systems, i.e. those in which syllable weight is not relevant in conditioning stress placement, can be broadly divided into two groups based on whether stress rhythmically falls on syllables at regularly spaced intervals within a word or whether it is fixed on a syllable at or near one or both edges of a word. The Australian language Maranungku (Tryon 1970) provides a representative example of a rhythmic stress pattern. Primary stress in Maranungku falls on the first syllable of a word and secondary stress docks on odd-numbered syllables after the first one. Note that I use the IPA symbols for primary ˈ and secondary ˌ stress in the examples throughout the chapter.

(1) Stress in Maranugku (Tryon 1970)
ˈtiralk ‘saliva’
ˈmæræˌpæt ‘beard’
ˈjaŋarˌmata ‘the Pleiades’
ˈŋaltiˌritiˌri ‘tongue’

A variant of this pattern is found in another Australian language, Pintupi (Hansen and Hansen 1969, 1978), in which stress falls on odd-numbered syllables but does not fall on final syllables. The result is a sequence of unstressed syllables, a stress “lapse”, at the end of odd parity words.

(2) Pintupi stress (Hansen and Hansen 1969)
ˈtʲutaja ‘many’
ˈpuɭiŋˌkalatʲu ‘we (sat) on the hill’
ˈtʲamuˌlimpaˌtʲuŋku ‘our relation’
ˈʈiɭiˌriŋuˌlampatʲu ‘the fire for our benefit flared up’
ˈkuraˌnʲuluˌlimpaˌtʲuɻa ‘the first one (who is) our relation’

In some languages, stress falls on even-numbered syllables rather than odd-numbered ones. For example, primary stress falls on the second syllable in Osage (Altshuler to appear) and secondary stress docks on even-numbered syllables after the second one.

(3) Osage stress (Altshuler to appear)
ɑːˈleː ‘I left’
nɑ̃́ːˈxo ‘break by foot’
ʰpɑːʃˈt͡sekɑ ‘strawberry’
ðyːˈʰkɑːmɑ̃ ‘to ring the bell’
xoːˈt͡soðiːbˌrɑ̃ ‘smoke cedar’
ɑ̃ːˈwɑ̃lɑːˌxyɣe ‘I crunch up my own (e.g. prey) with teeth’

Macedonian (Lunt 1952, Franks 1987) is a language with a fixed stress pattern. A single stress in Macedonian falls on the antepenultimate syllable of a word and there are no reported secondary stresses.

(4) Macedonian stress (Franks 1987)
ˈzborot ‘word (def. sg.)’
ˈdonesi ‘bring (2nd sg. imper.)’
voˈdenitʃar ‘miller’
vodeˈnicari ‘miller (pl.)’
vodenitˈʃarite ‘miller (def. pl.)

The typology of rhythmic and fixed stress systems can be classified into three sub-types as follows. The first of these is the strict binary pattern involving stress on every other syllable, as in Maranunku. There are four logically possible types of strict binary systems if one varies the edge of the word at which the alternating pattern originates and whether the alternating stress pattern begins with a stressed syllable, i.e. “peak-first”, or unstressed syllable, i.e. “trough-first”: stress on odd-numbered syllables counting from the left, stress on even-numbered syllables counting from the right, stress on odd-numbered syllables starting at the right edge, and stress on even-numbered syllables commencing at the left edge. These four possibilities are shown schematically in (5).

(5) Typology of pure binary stress systems

Pattern	**Schematic forms**	**Example Lgs.**
1. Odd-numb'd from L to R	ˈσσˌσσˌσ, ˈσσˌσσˌσσ	Czech (Kucera 1961), Maranungku (Tryon 1970)
2. Even-numb'd from R to L	σˌσσˈσσ, ˌσσˌσσˈσσ	Cavineña (Key 1968), Warao (Osborn 1966)
3. Even-numb'd from L to R	σˈσσˌσσ, σˈσσˌσσˌσ	Araucanian (Echeverría and Contreras 1965), Sirenikski (Menovshchikov 1975)
4. Odd-numb'd from R to L	ˌσσˌσσˈσ, σˌσσˌσσˈσ	Chulupí (Stell 1972), Urubú Kaapor (Kakumasu 1986)

There are also a few languages that employ a ternary stress system, stressing every third rather than every other syllable. For example, Cayuvava (Key 1961, 1967) stresses every third syllable counting from the right edge of a word.

(6) Stress in Cayuvava (Key 1961, 1967)
ˈeɲe 'tail'
ˈʃakahe 'stomach'
kiˈhibere 'I ran'
ari.ˈu.utʃa 'he came already'
ˌdʒihiraˈri.ama 'I must do'
maˌrahaha.ˈe.iki 'their blankets'
ikiˌtapareˈrepeha 'the water is clean'
ˌtʃa.adiˌroboβuˈrurutʃe 'ninety-nine (first digit)'
meˌdarutʃeˌtʃe.iroˈhi.iɲe 'fifteen each (second digit)'

Turning to the fixed stress systems, there are five docking sites for stress in these languages: the first syllable (e.g. Chitimacha [Swadesh 1946]), the last syllable (e.g. Atayal [Egerod 1966]), the penultimate (second-to-last) syllable (e.g. Albanian [Hetzer 1978]), the antepenultimate (third-to-last) syllable (e.g. Macedonian [Lunt 1952, Franks 1987]), and the peninitial (second) syllable (e.g. Koryak [Zhukova 1972]). In most languages, only one of these syllables receives stress. However, there are also languages in which two of these syllables are stressed in a single word. In these systems, termed "hammock" (Elenbaas and Kager 1999) or "dual" (Gordon 2002) stress patterns, there is one stress at or near the right edge and the other at or near the left edge. For example, Lower Sorbian (Janas 1984) places primary stress on the first syllable and secondary stress on the penultimate syllable. The secondary stress is suspended in trisyllabic words in order to avoid a sequence of adjacent stresses, a stress “clash”.

(7) Lower Sorbian stress (Janas 1984)

ˈpisasʲ ‘write’
ˈdɔbrɨ ‘good’
ˈwɔsʲtsɔjska ‘fatherland’
ˈpsʲijasʲɛl ‘friend’
ˈspewaˌjutsɨ ‘singing’
ˈdɔpredˌkarski ‘progressive’

There are also hybrid systems in which stress falls rhythmically on alternating syllables but also occurs on a fixed syllable at the opposite edge of the word from which the rhythmic pattern originates. For example, stress in the South Conchucos variety of Quechua spoken in Peru (Hintz 2006) falls on the penultimate syllable and on even numbered syllables counting backwards from the penult. In addition, the initial syllable is stressed. There is some variation between discourse data and elicited data as to which of the stresses is the strongest. In elicited forms, the stress on the penultimate is judged by speakers to be the primary stress, whereas in discourse data the stress on the initial syllable is primary. Forms illustrating stress in South Conchucos Quechua appear in (8), with the location of the primary stress reflecting discourse pronunciations.

(8) South Conchucos stress (Hintz 2006)

ˈʃumaq ‘pretty’
ˈimaˌkuna ‘things’
ˈtʃupanˌkimanˌłachi̥ ‘you would likely have just gotten drunk,
ˈtʃakranˌtsikːuˌnataˌraːtʃir ‘yet our gardens supposedly’
ˈpiˌtapis ‘anybody’
ˈtuˌʃukuˌnaqḁ ‘dancers’
ˈwaˌraːkaˌmunqaˌnatʃi̥ ‘hopefully it will appear at dawn'

Indonesian (Cohn 1989) displays a minor deviation from this pattern in words with an odd-number of syllables, where the alternating pattern is suspended where it would result in a stress clash, i.e. a sequence of adjacent stressed syllables. Thus, unlike South Conchucos Quechua which has the following stress pattern in a word of seven syllables, ˌσˌσσˌσσˈσσ, an Indonesian word with the same number of syllables would lack the stress on the second syllable, i.e. ˌσσσˌσσˈσσ. Systems like the one found in South Conchucos Quechua in which rhythmic stress is observed even in clash contexts may be termed “binary plus clash” patterns, in contrast to “binary plus lapse” systems like that of Indonesian, in which a rhythmically placed stress fails to appear where it would clash with an adjacent fixed stress (Gordon 2002).

3. The formal analysis of stress

The fundamental contribution of generative metrical stress theory is its formal treatment of stress as a prominence relation holding between syllables. Certain syllables are metrically strong, characteristically reflected in their attraction of stress, while others are metrically weak and thus reject stress. Theories differ, however, in how they represent this relative prominence. The most common approach is to assume that words can be broken down into smaller constituents called “feet”, which consist of a single stressed syllable and typically one unstressed syllable. A representative foot-based theory of stress is presented in Hayes (1995). In Hayes’ theory, the Maranungku word ˈjaŋarˌmata would be represented as in (9).

(9)

Word level	(x . . .)
Foot level	(x .)(x .)
	ˈja ŋar ˌma ta

The first two syllables are grouped into a foot, while the last two syllables form a separate foot. Feet of the Maranungku type are “trochaic”, i.e. the stressed syllable precedes the unstressed syllable, in contrast to “iambic” feet, in which the stressed syllable follows the unstressed syllable, as illustrated by the Osage word xoːt͡sóðiːbrã ‘smoke cedar’ (10).

(10)

Word level	(. x . .)
Foot level	(. x)(. x)
	xoː ˈt͡so ðiː brã ‘smoke cedar’

The higher tier of constituency is the word level, where the first stressed syllable is the metrically strongest one in the word in both Maranungku and Osage, as reflected in the word-level grid mark that it receives.

3.1. A foot-based metrical stress theory

In this section, we examine the typological coverage provided by a metrical stress theory employing feet. The analysis considered here is Kager's (2007) Optimality-theoretic approach, although the metrical representations assumed in his account can be translated easily into a rule-based framework like that of Hayes (1995). We now briefly introduce the constraints assumed in Kager's analysis.

First, two constraints are relevant in determining whether feet are trochaic or iambic in a language: FTTYPE=TROCHEE and FTTYPE=IAMB. PARSE-SYL requires that syllables be parsed into feet. Another constraint, FT-BIN, requires that feet be binary either at the syllabic or moraic level. The determination of the relevant prosodic level of analysis at which FT-BIN applies depends on the role of quantity (syllable weight) in a language's stress system. In languages like those considered thus far with quantity-insensitive stress, FT-BIN applies at the level of the syllable, whereas in languages with quantity-sensitive stress, FT-BIN is relevant at the moraic level (for more on quantity-sensitive stress, see section 4). If FT-BIN is ranked above PARSE-SYL, the result is a binary stress system with a prohibition against monosyllabic, degenerate, feet. The Pintupi stress system in which stress falls on odd-numbered non-final syllables instantiates a binary system banning monosyllabic feet, e.g. (ˈtʲamu)(ˌlimpa)(ˌtʲuŋku) 'our relation', (ˈʈiɭi)(ˌriŋu)(ˌlampa)tʲu 'the fire for our benefit flared up'. If the opposite ranking obtains, strict binarity is produced even in cases where a monosyllabic foot results, as in Maranungku, e.g. (ˈjaŋar)(ˌmata) 'the Pleiades', (ˈŋalti)(ˌriti)(ˌri) 'tongue'

The directionality of footing is determined by two alignment constraints: ALL-FT-R and ALL-FT-L, which require that all feet fall at the right and left edge, respectively, of a prosodic word. The simplest case is a stress system with a single stress per word, a pattern that results from the ranking of one of the ALL-FT-X constraints above PARSE-SYL. Depending on the type of foot and which foot alignment constraint is highly ranked, different single stress systems are produced. Initial stress and penultimate stress reflect trochaic feet, where initial stress, i.e. (ˈσσ)σσσ, results from the ranking ALL-FT-L >> PARSE-SYL while penultimate stress, i.e. σσσ(ˈσσ), is attributed to the ranking ALL-FT-R >> PARSE-SYL. Peninitial stress and final stress are both the result of iambic feet with peninitial stress resulting from a left-aligned foot, i.e. (σˈσ)σσσ, and final stress reflecting a right-aligned foot, i.e. σσσ(σˈσ). The final type of single stress system to account for, antepenultimate stress (e.g. Macedonian) results from nearly the same rankings as those accounting for penultimate stress, except that a ban on parsing the final syllable into a foot, NONFINALITY, outranks ALL-FT-R; the result is a trochee spanning the antepenultimate and penultimate syllables, i.e. σσ(ˈσσ)σ.

The promotion of one of the stressed syllables to primary stress is a function of two alignment constraints requiring, in the case of ALIGN-HEAD-L, that the prosodic word begins with the primary stress foot or, in the case of ALIGN-HEAD-R, that the prosodic word end in the primary stress foot.

If the relative ranking of FT-BIN and PARSE-SYL is varied along with the parameters of directionality and foot type, eight possible patterns are generated. In addition to the four pure binary patterns, there are four systems in which deviations from binarity are observed in words with an odd number of syllables. Two of these systems have stress lapses at the word periphery in words with an odd number of syllables, whereas two have stress clashes. If FT-BIN outranks PARSE-SYL, the Pintupi-type pattern with stress on odd-numbered syllables from the left minus the final syllable and its mirror-image pattern of stress on odd-numbered syllables from the right minus the initial syllable are produced. The former is the result of leftward alignment of feet, while the latter reflects rightward alignment of feet. The latter pattern appears to be unattested in keeping with the general absence of evidence for initial stress avoidance in languages. The two binary systems with stress clashes in odd parity words that are generated turn out to be attested. If FT-BIN is ranked below PARSE-SYL and feet are trochaic, stress falls on even-numbered syllables from the right plus the initial syllable, the pattern found in South Conchucos Quechua. If FT-BIN is ranked below PARSE-SYL and feet are iambic, stress will fall on even-numbered syllables plus the final syllable, which corresponds to the stress system of Ojibwa (Kaye 1973, Piggott 1980).

The generation of “hammock” stress systems with two stresses per word requires a pair of alignment constraints that ensure that word edges align with foot edges. These alignment constraints thus differ from ALL-FT-L and ALL-FT-R, which require that foot edges align with word edges. ALIGN-PRWD-LEFT mandates that a word begins with a foot and ALIGN-PRWD-RIGHT requires a word to end with a foot. ALIGN-PRWD-LEFT and ALIGN-PRWD-RIGHT perform an important role in generating hammock stress systems. The initial plus penultimate stress pattern found in languages like Lower Sorbian reflects the existence of a trochaic foot at each edge of the word, i.e. (σ́σ)σσσ(σ́σ). Both ALIGN-PRWD-LEFT and ALIGN-PRWD-RIGHT are satisfied at the expense of ALL-FT-L and ALL-FT-R. In trisyllabic words, the ranking of FTBIN over ALIGN-PRWD-RIGHT ensures that only a single foot is formed at the beginning of the word: (σ́σ)σ not *(σ́σ)(σ́) or *(σ́)(σ́σ)

The ALIGN-PRWD-X constraints also play a crucial role in generating binary systems with a stress lapse word-internally in words of a certain shape. To illustrate this, consider the analysis of the stress system of Garawa (Furby 1974), in which stress falls on even-numbered syllables counting from right to left but skips over an even-numbered peninitial syllable in favor of stressing the initial syllable. The result is a stress lapse following the initial syllable (which carries main stress) in words with an odd number of syllables. Examples of Garawa stress appear in (11).

(11) Garawa stress (Furby 1974)

ˈjami	‘eye’
ˈpun^{j}ala	‘white’
ˈwat^{j}imˌpaŋu	‘armpit’
ˈnariŋinˌmukuˌn^{j}inaˌmira	‘at your own many’

Let us consider the analysis of this pattern is some detail since it requires a rather complex set of rankings to produce: ALIGN-PRWD-LEFT >> PARSE-SYL >> ALL-FT-R >> ALL-FT-L. In addition to not violating ALIGN-PRWD-LEFT, the winning candidates also satisfy FT-BIN and FTFORM=TROCHEE. A sample tableau illustrating the analysis of stress in Garawa appears in (12). Violations of the foot-alignment constraints committed by each foot are given as numerals separated by a comma, where the total number of violations of a constraint is the sum of the violations committed by each foot.

(12)

punʲala	FT-BIN	FTFRM= TROCHEE	ALIGN-PRWD-LEFT	PARSE-SYL	ALL-FT-R	ALL-FT-L
☞ (ˈpunʲa)la				*	1	
pu(ˈnʲala)			*!	*		*
(puˈnʲa)la		*!		*	1	
(ˈpunʲa)(ˌla)	*!				0,1	**
(ˈpu)(ˌnʲala)	*!				0,2	*
nariŋinmukunʲinamira	FT-BIN	FTFRM= TROCHEE	ALIGN-PRWD-LEFT	PARSE-SYL	ALL-FT-R	ALL-FT-L
☞ (ˈnari)ŋin(ˌmuku)(ˌnʲina)(ˌmira)				*	0,2,4,7	0,3,5,7
(ˈnari)ŋin(ˌmuku)nʲi(ˌnami)ra				**!*	1,4,7	0,3,6
na(ˈriŋin)(ˌmuku)(ˌnʲina)(ˌmira)			*!	*	0,2,4,6	1,3,5,7
(ˈnari)(ˌŋinmu)(ˌkunʲi)na(ˌmira)				*	0,3,5,7!	2,4,7

To account for ternary stress, Kager and Elenbaas (1999) employ the constraint *LONG-LAPSE, which requires an unstressed syllable to be adjacent to either a stressed syllable or the word edge. This constraint has the effect of banning a sequence of three consecutive unstressed syllables word-internally or two at a word edge. Ternary stress systems result from the ranking *LONG-LAPSE >> ALL-FT-X >> PARSE-SYL. As we have seen in the analysis of single stress systems, ALL-FT-X has the effect of minimizing the number of feet in a word. However, *LONG-LAPSE ensures that there is no more than one unparsed syllable intervening between feet. For example, feet in Cayuvava (stress on every third syllable from the right) are trochaic and separated by a single syllable: (ˌtʃa.a).di.(ˌro.bo).βu.(ˈru.ru).tʃe ‘ninety-nine (first digit)’.

3.2. Constraining the foot-based theory: Position specific rhythmic constraints

Kager (2001) is an attempt to constrain the overgeneration of unattested patterns committed by the traditional foot-based metrical stress theory. In order to preclude the unattested mirror image of Pintupi, stress on odd-numbered syllables counting from the right minus the initial syllable, Kager posits that local rhythmic constraints working in conjunction with the constraints requiring alignment of word-edges with feet (ALIGN-PRWD-LEFT and ALIGN-PRWD-RIGHT) govern the directionality of footing rather than the

ALL-FT-X alignment constraints. For example, a constraint LAPSE-AT-END requires that stress lapses be confined to the right edge of a word, penalizing forms with stress lapses in non-final position. This position specific anti-lapse constraint ensures that lapses are preferred word-finally to other positions, including word-initially. Thus, the candidate with a right-to-left iambic parse and an initial stress lapse cannot under any ranking emerge victorious over a competing candidate with a foot at the left edge (13) (from Kager 2007:219).

(13)

σσσσσσσ	*LAPSE	LAPSE-AT-END	ALIGN-PRWD-L	ALIGN-PRWD-R
☞ (σˈσ)σ(σˈσ)(σˈσ)	*	*		
σ(σˈσ)(σˈσ)(σˈσ)	*	*	*!	

Kager (2001) also notices another skewing in the typology. In most binary plus lapse systems involving an internal lapse, the lapse occurs immediately adjacent to the primary stressed foot. Thus, in Garawa, which stresses even-numbered syllables from the right and places primary stress on the initial syllable, the stress lapse follows the initial foot in odd parity words: (ˈσσ)σ(ˌσσ)(ˌσσ). In Piro (Matteson 1965), which stresses odd-numbered syllables counted from the left and places primary stress on the penult, the lapse precedes the final foot: (ˌσσ)(ˌσσ)σ(ˈσσ). Kager proposes that these systems result form a constraint requiring that lapses occur adjacent to a primary stressed foot: LAPSE-AT-PEAK. This constraint ensures that lapses adjacent to the main stressed foot will be preferred over those in other positions.

Kager also finds that stress clashes in binary plus clash stress systems involve two secondary stresses rather than a primary plus a secondary stress. For example, in South Conchucos Quechua, the stress clash in odd parity words involves the initial and peninitial syllables both of which have secondary stress, at least in words produced in isolation. Furthermore, stress clashes in binary plus clash systems invariably involve a foot at the word periphery, as in South Conchucos Quechua. To account for these two observations, Kager posits two constraints: *CLASH-AT-PEAK bans stress clashes involving a primary stress and CLASH-AT-EDGE requires a clash be restricted to a word edge.

A prediction made by this approach is that there should not be any binary plus internal lapse systems where the lapse is not adjacent to the primary stressed foot. Apparent cases where the lapse does not occur adjacent to the primary stressed foot must thus be reanalyzed in different terms. Such cases involve initial dactyls where primary stress falls on the penult and secondary stress is on even-numbered syllables counting from the right plus the initial syllable, e.g. (ˌσσ)σ(ˌσσ)(ˈσσ). Alber (2005) argues that most of these cases (Polish, German, Indonesian) of initial dactyls involve loan words where the stress patterns of the donor language have been preserved.

4. Quantity-sensitive stress

In many languages, an alternating binary stress pattern is interrupted by certain "heavy" syllables, which attract stress themselves even if they are immediately adjacent to a stressed syllable. After the heavy syllable, the normal binary stress count resumes. For example, stress in Chickasaw (Munro and Ulrich 1984, Munro and Willmond 1994, Gordon 2004) falls on even-numbered syllables counting from the left and on heavy syllables, which are CVC and CVV in Chickasaw. In addition, the final syllable is stressed as well. (Primary stress falls on the rightmost long vowel, otherwise on the final syllable in words without long vowels.)

(14) Chickasaw stress

ˌissoˈba	'horse'
ˌtʃonˈkaʃ	'heart'
ˌbaʃˈpo	'knife'
aˈboːkoˌʃiʔ	'river'
ˈbaːˌtamˌbiʔ	name
ˈʃiːˌˈki	'buzzard'
tʃaˈlakˈkiʔ	'Cherokee'
ˈokˈfokˈkol	'type of snail'
ˈnaːɬtoˈkaʔ	'policeman'
ˈaːˈtʃomˈpaʔ	'store'

The attraction of stress by heavy syllables in quantity-sensitive stress systems means that several stressed syllables may occur in succession, thereby creating multiple violations of *CLASH, as in words like ˈokˈfokˈkol and ˈbaːˌtamˌbiʔ. An additional constraint is thus necessary to account for the stress-attracting property of heavy syllables.

4.1. Quantity-sensitive in a foot-based framework

In a foot-based theory, quantity-sensitivity is typically incorporated directly into the foot type constraint. Hayes (1995) suggests that all iambic stress systems are quantity-sensitive and proposes three basic foot types. Some languages parse syllables into quantity-insensitive trochees, while quantity-sensitive stress systems may be either trochaic or iambic. In quantity-sensitive systems, the binary stress count is calculated at the level of the mora rather than the syllable. Heavy syllables consist of two moras, while light syllables have one mora. Feet are minimally bimoraic, consisting of one heavy syllable or two light syllables. Thus, the Chickasaw word ˌissoˈba 'horse' would have the moraic and foot structure in (15), where moras are indicated by the Greek letter μ.

(15)

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( x )(.  x)
(μμ)(μ  μ)
 ˌi s soˈba
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4.2. Quantity-sensitivity in non-binary stress systems

Quantity-sensitivity also plays a role in a number of languages with non-binary stress systems. For example, many single stress languages display quantity-sensitivity. Thus, in Yana (Sapir and Swadesh 1960), stress falls on the initial syllable in words with only light (CV) syllables (16a), but on the leftmost heavy syllable (CVV or CVC) if any are present (16b)

(16) Yana stress (Sapir and Swadesh 1960)
  a. ˈp'udiwi 'women'
  b. siˈbumk'ai 'sandstone'
     suˈk'oːniyaː, 'name of Indian tribe'
     tsiniˈjaː 'no'

Single stress systems displaying quantity-sensitivity, sometimes called “unbounded” stress systems (Hayes 1995), like that of Yana have been treated in different ways in the theoretical literature. One approach assumes that all heavy syllables in unbounded stress systems carry at least secondary stress, which can be difficult to hear, and that an edgemost stress is promoted to primary stress by ER-L or ER-R (McCarthy 2003). For example, the Yana word siˈbumˌk’ai ‘sandstone’ would have two stresses, of which the leftmost one is primary. In words consisting of only light syllables, ALIGN-PRWD-LEFT would position stress on the initial syllable. Under this approach, heavy syllables are assumed to constitute monosyllabic feet and words with only light syllables are treated as having a disyllabic foot at the word edge feet (Bakovic 1998, McCarthy 2003). One potential drawback to this analysis, however, is its assumptions about secondary stress, which would ideally find support from instrumental studies and/or other phonological diagnostics. An alternative that still assumes a single stress per word is to posit a constraint against heavy syllables in pretonic syllables, in the case of leftward orientation, or posttonic syllables, in the case of rightward orientation.

4.3. Scalar quantity-sensitivity

In some languages, quantity-sensitivity is scalar such that more than two degrees of weight are distinguished with stress seeking out the heaviest syllable in the hierarchy (see Davis this volume for further discussion of syllable weight). In the simpler type of these scalar weight systems, all degrees of weight are operative within the same window. For example, in the variety of Hindi described by Kelkar (1968) there are three degrees of weight: superheavy (CVVC and CVCC), heavy (CVV and CVC), and light (CV). Stress falls on the heaviest syllable within a word (17a) and, in the case of a tie, stress falls on the rightmost non-final of the tied syllables (17b).

(17) Hindi stress (Kelkar 1968)

a. ˈʃoːx.dʒa.baː.niː ‘talkative’
mu.sal.ˈmaːn ‘Muslim’
ru.pi.ˈaː ‘rupee’
ki.ˈdʰar ‘which way’

b. ˈaːs.mãː.dʒaːh ‘highly placed’
   kaː.ˈriː.ga.riː ‘craftsmanship’

The Hindi weight hierarchy can be analyzed moraically (Hayes 1995, Broselow et al. 1997) if superheavy syllables are treated as trimoraic, heavy syllables as bimoraic, and light syllables as monomoraic. A constraint, PK-PROM (Prince and Smolensky 1993, Walker 1996) selects the heaviest syllable in the hierarchy to be stressed, while a rightward alignment constraint working in conjunction with NONFINALITY derive the correct results in case of a tie in weight.

In some languages, scalar weight is sensitive to vowel quality rather than syllable structure. For example, in Kobon (Davies 1980), stress falls on the heavier of the final two syllables, where weight is defined by the scale: Low Vowels > Mid Vowels > High Vowels > Centralized Vowels; in case of a tie, the data are less clear in showing which of the final two syllables is stressed. Kenstowicz (1997) proposes a series of prominence constraints referring to vowel quality to account for the Kobon facts. One constraint bans stress on low vowels, *P/a, another on mid vowels, *P/e,o, another on high vowels, *P/i,u, and another on central vowels, *P/ə,ɨ. The ranking of these constraints is fixed on a universal basis where constraints banning stress on less sonorous vowels are ranked above constraints banning stress on more sonorous vowels, i.e. *P/ə >> *P/i,u >> *P/e,o >> *P/a. Kenstowicz adopts a foot-based approach in which FT-BIN and a rightward alignment constraint ensure that a binary foot is constructed at the right edge of a word, where the type of foot, iambic or trochaic, is determined by the relative weight of the final two syllables.

More problematic for a coherent metrical stress theory are cases in which different parts of the weight hierarchy have different spheres of influence. For example, in Klamath (Barker 1964), stress falls on the penultimate syllable if it is either CVV(C) or CVC(C) (18a) and otherwise on the antepenult (18b). However, a long vowel in final position or to the left of the antepenult attracts stress away from both a CVC penult and the antepenult (18c):

(18) Klamath stress (Barker 1964)

a. saˈɢapd͡ʒol ‘to play cat’s cradle’
   seˈsadwi ‘to sell’
   gaːˈmoːla ‘finishes grinding’
b. ˈt͡ʃ’aw̰iga ‘is crazy’
c. gaˈbaːtambli ‘goes back to shore’
   gaˈw̰iːnapbabli ‘is going among again’
   sak’amsiˈneːʔ ‘to be lonesome’
   n̰isˈq’aːk ‘little girl’

The stress facts suggest a three-way weight hierarchy with CVV being heaviest, since it can attract stress in any position, CVC being intermediate in weight, since it can attract stress in penultimate position, and CV being lightest, since it does not attract stress in either penultimate or final syllables. The complication posed by this system is that CVV can attract in contexts where CVC cannot, namely word-finally and to the left of the antepenult. Thus, there is no single footing algorithm or alignment principle that will account for the distribution of stress involving both CVV and CVC.

Working within a rule-based paradigm, Hayes (1995) proposes that the attraction of stress by both CVV and CVC in the penult reflects a right aligned trochaic foot with the proviso that final syllables are not footed, i.e. sa(ˈɢap)d͡ʒol, (ˈt͡ʃ’aw̰i)ga. A separate prominence tier treats CVV as heavier than both CVC and CV, thereby capturing the attraction of stress by final CVV and CVV to the left of the antepenult. An undesirable feature of this analysis is that it assumes a separation between footing and prominence without offering a principled explanation for why two formally distinct devices should be invoked to account for the superficially uniform phenomenon of stress. On the other hand, Hayes (1995) notes that long vowels attract high tones in the intonation system prompting him to suggest that the attraction of stress by long vowels may be tonally rather than stress-driven.

5. Metrical stress theory and intonational prominence

The interaction between stress and intonation in Klamath ties into a broader issue in metrical stress theory that has received relatively little attention in the Optimality-theoretic literature compared to stress typology: the interaction between word-level stress and intonational prominence at higher prosodic levels (see Gussenhoven 2004, 2007 for an overview of this literature). While typological knowledge of the range of variation in stress systems appears to be relatively robust, it is unclear from most published descriptions of stress whether the described patterns reflect those found in words uttered in isolation or in a phrasal context. If the former case is true, then word-level stress is confounded with phrase-level prominence. Fortunately, the body of literature discussing differences between phrase-level and word-level prominence is increasing.

One observation that appears to hold for most languages is that prominence is constructed bottom-up in such a way that phrase-level prominence patterns are overlaid on top of word-level stress (see Ladd 1996 for an overview). For example, in the English sentence *The elephants attacked the alligator*, the first syllable of *alligator* is the most prominently stressed syllable of the sentence when uttered under neutral declarative intonation. Contrastive focus on one of the other words can change the location of phrasal prominence. For example, if *elephants* is focused, as in the sentence *The elephants attacked the alligator, the birds didn't attack it*, the primary phrasal stress falls on the first syllable of *elephants*. If *attacked* is focused, as in *The elephants attacked the alligator, they didn't feed it*, the phrasal stress falls on the second syllable of *attacked*. Regardless of focus, phrasal stress selects the primary stress in the word for promotion. Thus, one would not say *The elephants attacked the alligator* with phrasal stress on the second, third, or fourth syllables of *alligator* or the second or third syllables of *elephants* or the first syllable of *attacked*. Phrasal accent is typically phonetically manifested tonally in the form of a pitch accent, where the type of pitch accent, e.g. H* or L* or a combination of the two, varies depending on the language and semantic properties of the utterance (Goldsmith 1978, Pierrehumbert 1980). Though an utterance may have multiple pitch accents, there is characteristically one, the "nuclear pitch accent", that is stronger than others.

In an Optimality-theoretic analysis, alignment constraints capture the attraction of the pitch accent by the primary stressed syllable of the phrase. One of these constraints captures the docking of the nuclear pitch accent on the rightmost content word in the default case. This constraint, formulated by Gussenhoven (2000) as ALIGN (T*, R, IP), requires the pitch accent to align with the right edge of an Intonation Phrase, a large prosodic constituent associated with a number of phonetic properties, including a final pitch excursion and final lengthening (Pierrehumbert 1980). Another constraint, ALIGN (T*, HEADσ_{IP}) (Gordon 2003), requires that the pitch accent falls on the main stressed syllable of the phrase.

Despite the strong cross-linguistic tendency for pitch accents to be associated with stressed syllables in bottom-up fashion, there is one phonetic property of utterance-final position that creates counterexamples to this tendency. Because phrase-final position is associated with a final pitch fall in the unmarked case, stress on phrase-final syllables is avoided in many languages (cf. Hyman 1977, Gordon 2000). This incompatibility between lowered pitch and stress creates mismatches in some languages, e.g. Cayuga (Chafe 1977, Foster 1982, Michelson 1988), Onondaga (Chafe 1970, 1977, Michelson 1988), Seneca (Chafe 1977, Michelson 1988), Hill Mari (Ramstedt 1902), Central Alaskan Yupik (Leer 1985, Miyaoka 1985, Woodbury 1987), Tiberian Hebrew (Prince 1975, McCarthy 1979, Dresher 1980, Rappaport 1984, Churchyard 1989, 1999), Chickasaw (Gordon 2003), between stress patterns of phrase-medial words where stress falls on final syllables, and prominence patterns in phrase-final words where stress is rejected by final syllables. These cases potentially represent instances of top-down assignment of phrasal prominence, since word-level stress conventions that place stress on final syllables are overridden by considerations specific to phrase-final position. This positionally governed asymmetry can be formally modeled by assuming a context sensitive NONFINALITY constraint specific to phrase-final position in addition to a generic NONFINALITY constraint relevant for all words regardless of prosodic context. Alternatively, the intonational motivation behind final syllable avoidance at the phrase-level can be modeled with direct reference to tones adopting Pierrehumbert's (1980) autosegmental/metrical model of intonation in which phrase-final position is associated with a boundary tone, an idea originally proposed in Liberman and Sag (1975). Pursuing this approach, final stress avoidance in phrase-final position is captured, following Gussenhoven (2000) and Gordon (2003), by a constraint against crowding of two tones, the boundary tone and the pitch accent, onto a single syllable. If this constraint, *CROWD Gussenhoven (2000), is ranked above ALIGN (T*, R, IP), then the pitch accent, and stress along with it, retracts onto the penult. If the opposite ranking of *CROWD and ALIGN (T*, R, IP) obtains, then the pitch accent (and stress) is free to fall on the final syllable. This account assumes that the rightmost stress in a phrase receives a pitch accent.

The tonal account of final stress avoidance finds support from Chickasaw (Gordon 2003). In Chickasaw, the nuclear pitch accent falls on the final syllable of statements which lack a final boundary tone but on a pre-final syllable under most circumstances in questions, which are marked by a final low boundary tone. This split between utterance types differing in their boundary properties is exactly the type of asymmetry predicted by a metrical account based on tonal factors.

Certain syllable weight distinctions operative in final position are also consistent with a tonal account of final stress avoidance. The attraction of stress by final CVV but not final CVC or CV in Klamath is plausibly due to the superior ability of a long vowel to support tonal crowding. Evidence for this position comes from tone languages that allow contour tones on long vowels but not short vowels (see Zhang 2002 for typology). Barker's (1964) description provides several pieces of evidence that an intonationally based analysis of final stress avoidance is appropriate for Klamath. First, Barker's account of Klamath stress and intonation suggests that the reported stress patterns reflect the pronunciation of words in isolation. With this in mind, consider the following facts reported by Barker. Stressed vowels are realized with higher pitch than unstressed vowels. Furthermore, the unmarked intonation contour ends in a final fall. Based on these facts, it seems likely that final stress avoidance on syllables not containing long vowels is driven by tonal crowding avoidance. Stressing the final syllable necessitates a rapid excursion from high to low tone if both the high pitch accent associated with stress and the boundary tone are to be realized. A final syllable containing a short vowel is particularly disadvantaged when it comes to realizing a tonal contour; thus, final CVC(C) resists stress.

Further support for the tonal basis of final stress avoidance in Klamath comes from Barker's report (p. 40) that, under certain semantic conditions involving "emphasis, strong emotion, command, etc." final long vowels may be realized with even higher pitch than that typically associated with primary stress. As a concomitant of this increased pitch range, the long vowel may be "stylistically lengthened by several morae". While it is possible that this lengthening is itself expressive, the additional length may also plausibly be viewed as a response to the higher pitch associated with the final stress: the higher pitch creates a more precipitous fall to the low boundary tone which requires additional length on the vowel to be effectively realized.

Chickasaw questions provide further evidence that an intonational account of final stress avoidance is on the right track. Final CVV in questions does attract the pitch accent whereas final CVC and CV do not in Chickasaw (Gordon 2003). Of course, the extent to which a tone-based analysis can be extended to other languages hinges on a better cross-linguistic understanding of the relationship between stress and intonation.

6. Foot-based vs. grid-based theories of stress

An alternative to foot-based theories of stress is to model prominence as a rhythmic grid structure (e.g. Liberman and Prince 1977, Prince 1983, Selkirk 1984) involving sequences of strong, i.e. stressed, and weak, i.e. unstressed, syllables without any word-internal constituent structure larger than the syllable. Under this approach, distinctions in degree of stress, i.e. primary vs. secondary stress, are captured in terms of differences in level of prominence. For example, the representation of the Maranungku word ˈjaŋarˌmata 'the Pleiades', in a grid-based approach to stress would be as in (19).

(19)

Level 1 (Primary stress)	x			
Level 2 (Secondary stress)	x	.	x	.
	ˈja	ŋar	ˌma	ta

The lower level of stress reflects the secondary stress, where any syllable dominated by an "x" only on the lower grid level has secondary stress, e.g. the third syllable in (19). The higher grid level captures primary stress, which falls on the first syllable of the word.

Grid-based theories and foot-based accounts largely overlap in their empirical coverage of stress systems, though their predictions differ in some ways. As a departure point for our comparison of the two approaches, let us briefly consider Gordon's (2002) grid-based Optimality-theoretic account of stress, which builds on earlier grid-based approaches couched within a derivational framework (Prince 1983, Selkirk 1984). As in the foot-based OT theory, leftward and rightward alignment constraints play an important role in accounting for the location of stress in all types of stress systems. In a grid-based theory, these two constraints, formalized here simply as ALIGN-L and ALIGN-R, refer directly to stress rather than to feet. Binary stress is attributed to two rhythmic constraints ensuring that stress falls on alternating syllables: *LAPSE bans adjacent unstressed syllables, while *CLASH prohibits a sequence of stressed syllables. Ternary stress is attributed to the high ranking of a constraint banning sequences of three unstressed syllables, *EXTENDED LAPSE, and the low ranking of *LAPSE. The directionality of the parse in binary and ternary stress systems depends on the relative ranking of the alignment constraints as in the foot-based theory.

In a grid-based theory, the relevant constraint needed to capture weight-sensitive stress like that observed in Chickasaw is the OT counterpart to Prince's (1990) Weight-to-Stress Principle, which requires that heavy syllables be stressed. WEIGHT-TO-STRESS PRINCIPLE (abbreviated WSP) is violated by a heavy syllable that is not stressed. WSP dominates *CLASH as well as the right alignment constraint that accounts for the normal unstressed-stressed alternating pattern found in words without heavy syllables. This is illustrated for a Chickasaw form in (20).

(20) Weight-sensitive stress in Chickasaw

tʃonkaʃ 'heart'	WSP	ALIGN-R	*CLASH
☞ ˌtʃonˈkaʃ		*	*
tʃonˈkaʃ	*!		

A difference between Gordon's grid-based theory and the foot-based analysis emerges in the treatment of peninitial, penultimate and antepenultimate stress. In the foot-based account, these three patterns reflect a foot aligned either with a word edge in the case of penultimate and peninitial stress or one syllable removed from the right edge in the case of antepenultimate stress. Penultimate and antepenultimate stress are attributed to a trochaic foot and peninitial stress to an iambic foot. In Gordon's grid-based approach, penultimate, peninitial, and antepenultimate stress result from competition between alignment constraints and three anti-lapse constraints localized to the edge of words. *LAPSE RIGHT bans adjacent unstressed syllables at the right edge of a word, *EXTENDED LAPSE RIGHT prohibits three consecutive unstressed syllables at the right edge, and *LAPSE LEFT militates against a sequence of two unstressed syllables at the left edge of a word. For example, ranking *EXTENDED LAPSE RIGHT above ALIGN-L yields the antepenultimate stress pattern of Macedonian, as illustrated in (21).

(21) Antepenultimate stress in Macedonian

vodenicari 'miller (pl.)'	*EXT LAPSE RIGHT	ALIGN-L
☞ vode'nicari		**
'vodenicari	*!	

Similarly, ranking *LAPSE LEFT above ALIGN-R produces the peninitial stress system of Koryak, and ranking *LAPSE RIGHT above ALIGN-L creates the penultimate stress pattern of Nahuatl.

6.1. Degenerate foot effects in foot-based and grid-based theories

In a foot-based metrical theory, monosyllabic or "degenerate" feet, are predicted to arise only if there is a stray syllable remaining after all other syllables have been parsed into disyllabic feet. For example, in the five syllable Maranungku word (ˈŋalti)(ˌriti)(ˌri) 'tongue', the final syllable forms a monosyllabic foot since there are no other unparsed syllables with which it can be grouped into a canonical disyllabic foot. Constructing a degenerate foot constitutes a violation of the requirement that feet be binary but has the virtue of ensuring that a foot occurs at a word edge, thereby honoring either ALIGN-PRWD-LEFT or ALIGN-PRWD-RIGHT. However, because ALIGN-PRWD-LEFT and ALIGN-PRWD-RIGHT refer to feet rather than directly to stress, they cannot ensure that stresses occur at a word-edge. This means that stress systems that have stress on both the initial and final syllables are problematic for the foot-based theory. For example, the hammock stress systems with initial and final stress in Armenian (Vaux 1998), some dialects of Udihe (Kormushin 1998), and Canadian French (Gendron 1966) involve stress on both syllables in disyllabic words. This pattern necessitates a parse into two monosyllabic feet, i.e. (ˈσ)(ˈσ), which are always dispreferred to a single disyllabic foot. The initial plus final stress pattern is also problematic for the foot-based theory for another reason. In words of at least four syllables, a trochaic foot must be assumed at the left edge of the word and an iambic foot at the right edge; it is unclear how this split type of foot system could be generated.

There are also at least two binary stress languages that consistently stress both the initial and final syllable across words of different lengths. In Tauya (MacDonald 1990), stress falls on odd-numbered syllables from the right plus the initial syllable. In foot-based terms, this system entails an iambic pattern from right to left plus two degenerate feet at the left edge of even parity words: (ˈσ)(ˈσ)(σˈσ)(σˈσ). The sequence of two monosyllabic feet at the left edge of the word parse cannot readily be generated by the proposed constraints, which predict that a parse into a single binary foot is always preferable to one into two degenerate feet. A similar difficulty arises for the foot-based approach in generating the Gosiute Shoshone (Miller 1996) pattern, which differs minimally from the Tauya pattern in employing a binary pattern starting from the left edge and displaying a clash at the right edge in even parity words: (ˈσσ)(ˈσσ)(ˈσ)(ˈσ).

Because they refer directly to stress rather than feet, grid-based accounts have the potential to capture stress systems with both initial and final stress. Gordon (2002) posits a constraint, ALIGN EDGES, that requires the initial and final syllable to be stressed. This constraint competes with others, including NONFINALITY (Prince and Smolensky 1993), but is unviolated in languages with both initial and final stress, including those with hammock patterns, i.e. Canadian French, Armenian, and Udihe, and those with binary patterns, i.e. Tauya and Gosiute Shoshone.

6.2. Segmental correlates of metrical structure

Despite the grid-based account's success in deriving stress at word peripheries, the absence of feet in the grid-based theory may also be a shortcoming, as there is evidence that certain segmental processes are sensitive to the foot as a constituent. One such phenomenon considered in section 6.2.1 involves a well-documented asymmetry between the prosodic profile of trochaic feet and iambic feet that emerges in the examination of quantity-sensitive stress. Another piece of evidence for foot structure that is discussed in section 6.2.2 comes from segmental alternations that are predictable from feet rather than stress.

6.2.1 The Iambic/Trochaic Law

There is an interesting feature of iambic systems that differentiates them from trochaic systems. Many iambic stress languages lengthen stressed syllables in a foot, thereby creating feet consisting of a light syllable followed by a heavy syllable. Chickasaw is one such language, with its pattern of lengthening vowels in stressed non-final open syllables (Munro and Ulrich 1984, Munro and Willmond 1994). Thus, the second and fourth vowels in the word /tʃipisa**li**tok/ 'I looked at you' undergo lengthening to produce the surface form (tʃiˌpiː)(saˌliː)(ˈtok) 'I looked at you'. Patterns of rhythmic lengthening of stressed syllables are less prevalent in quantity-sensitive trochaic systems (Mellander 2001), particularly those applying to all stressed syllables in a word and not just the primary stress. This apparent difference between trochaic and iambic stress systems supports an asymmetric foot inventory in which iambs are inherently biased in favor of quantity-sensitivity (Prince 1990). In fact, certain trochaic stress languages display shortening of stressed syllables, which creates durationally balanced feet consisting of a light stressed syllable followed by a light unstressed syllable. For example, in Fijian (Schütz 1985), phrases that underlyingly end in a heavy penult (one containing a long vowel) followed by a light ultima shorten the long vowel in the penult; thus, underlying /m͡buːŋ͡gu/ 'my grandmother' surfaces as ˈm͡buŋ͡gu (Schütz 1985:528). Hayes (1995), following the spirit of a proposal advanced by Schütz (1985), offers an explanation for this a priori anomalous process of stressed syllable shortening in terms of the rhythmic principles underlying the trochaic foot. In Hayes' analysis, the penult and the final syllable initially form a trochaic foot, which then shortens in order to create a trochaic foot (ˈm͡buːŋ͡gu) consisting of two syllables of equivalent weight. By shortening the stressed syllable of the foot the pressure for balanced trochaic feet is satisfied.

Interestingly, a bias toward durationally unbalanced light plus heavy iambs in contrast to durationally balanced light plus light trochees finds support from not only stress systems, but also psycholinguistic experiments, music and poetry (see Hayes 1995:79-81 for overview). In the non-foot-based theories of stress proposed thus far, any asymmetry between the durational patterns observed in trochaic stress systems and those found in iambic systems is an accident. The iambic/trochaic asymmetry may thus constitute one of the strongest pieces of evidence for the foot.

6.2.2. Mismatches between stress and metrical structure

Another piece of evidence for the foot comes from segmental processes that are predictable from constituent structure rather than stress. The existence of segmental fortition in stressed syllables and lenition in unstressed contexts is well known. For example, Dutch (Booij 1995) inserts an intervocalic glottal stop as an onset to stressed vowels; epenthesis does not interrupt vowel sequences in which the second vowel is unstressed. We thus have pairs such as ˈxa.ɔs 'chaos' and a.ˈʔɔr.ta 'aorta' in which the presence of glottal stop is predictable based on stress. Similarly, English reduces most vowels to schwa in unstressed syllables.

Interestingly, there are also segmental alternations that are not predictable from stress but that fall out from analyses assuming metrical constituency distinct from stress. Vaysman (2009) documents several cases of this type, one of which we consider here. In Nganasan (Tereshchenko 1979, Helimski 1998, Vaysman 2009), a Uralic language, primary stress is confined to a three syllable window at the right edge of a word. Stress falls on a final long vowel (22a), and on the penult if it contains a full, i.e. non-central, vowel (22b). If the penult contains a central vowel and the antepenult contains a non-central vowel, stress falls on the antepenult (22c). Secondary stress falls on heavy (CVV) syllables and odd-numbered syllables counting from the left edge of a word except if this would entail a clash with another stress (22d).

(22) Nganasan stress (Vaysman 2009)
a. kyˈmaː 'knife'
   leˈhua 'board'
b. baˈkunu 'salmon'

tɨˈrimi ‘caviar’
c. kuˈbutənu ‘skin, fur (prol., non-possessive)’
ˈhʷaːtənu ‘tree (prol., non-possessive)’
d. ˌkitaˈraː ‘only cup’
ˌbakuˌnuməˈnumə ‘my salmon (prol.)’
ˌkaðarməˈnumə ‘my light (prol.)’
suːˈðəːðu ‘his/her/its lung’

Nganasan also displays an alternation between intervocalic consonants, termed “consonant gradation”, whereby strong consonants, typically either voiceless or prenasalized obstruents, alternate with weak consonants, which are in most cases voiced or not prenasalized. The appearance of strong and weak pairs of consonants, indicated by boldface in the examples below, is predictable from syllable count (23). In the onset of even-numbered non-initial syllables, the strong grade appears, while the weak grade appears in the onset of odd-numbered syllables. Long vowels interrupt the alternating syllable count and, as long as they are not word-initial, are always preceded by weak consonants.

(23) Nganasan consonant gradation (Vaysman 2009)
ˌjamaˈða-**t**u ‘his/her/its animal’
ˌŋoruˈmu-**t**u ‘his/her/its copper’
ˌsuuˈðəː-**ð**u ‘his/her/its lung’
ŋuˈhu-**ð**u ‘his/her/its mitten’

As Vaysman shows, this pattern is explained if one assumes that words are parsed into binary feet starting at the left edge of words with long vowels forming monosyllabic feet and degenerate feet allowed word-finally. Strong consonants occur foot-medially and weak consonants occur in foot-initial syllables that are not also word-initial (24).

(24) Nganasan consonant gradation and foot structure (Vaysman 2009)
(ˌjama)(ˈða-**t**u) ‘his/her/its animal’
(ˌŋoru)(ˈmu-**t**u) ‘his/her/its copper’
(suː)(ˈðəː)-(**ð**u) ‘his/her/its lung’
(ŋuˈhu)-(**ð**u) ‘his/her/its mitten’

The interesting feature of the Nganasan data is that stress does not always fall on syllables predicted to be stressed by the metrical structure diagnosed by consonant gradation. For example, the final foot in the last two words in (24) and the first foot in the third word have no stress, while the first foot in the last word is iambic rather than trochaic unlike the other bisyllabic feet in the words illustrated here.

In order to account for this mismatch between metrical structure and stress in Nganasan, Vaysman adopts a hybrid approach employing both feet and grid-based prominence representations. The reader is referred to Vaysman (2009) for the details of her analysis.

7. Metrical stress theory and formal acquisition models

The constraint-based paradigm of Optimality Theory offers the opportunity for developing computational algorithms designed to model the language acquisition process. Some of these models have been applied to simulate the learning of stress systems systems (Tesar and Smolensky 2000, Tesar 2004, 2007, Heinz et al. 2005, Heinz 2006, Hayes and Wilson 2008). One such model is the maximum entropy model of phonotactic learning employed by Hayes and Wilson (2008). In their model, constraints are weighted in their relative strength rather than operating within a strict dominance hierarchy as in classical OT. The weightings of each constraint are constantly reassessed by comparing the number of expected violations of that constraint given the current weightings with the observed number of violations in a corpus of data. Hayes and Wilson also implement a model of constraint learning which discovers the constraints that account for the observed data. They submit their model of constraint learning and weighting to several empirical tests including the acquisition of two types of stress systems. Stress systems are of particular interest as a test of a learning algorithm since they represent a type of non-local phonotactics where positioning of stress requires examination of strings larger than adjacent syllables. First, they tackle the default-to-opposite subtype of unbounded stress system, in which stress falls on the heavy syllable closest to one edge of words with at least one heavy syllable, but on the light syllable at the opposite edge in words lacking heavy syllables. For example, stress in Chuvash (Krueger 1961; but see Dobrovolsky 1999 for an alternative account) is reported to fall on the rightmost heavy syllable, i.e. syllable containing a non-central vowel, otherwise on the initial syllable in words with only light syllables. Hayes and Wilson make the assumption that all heavy syllables (see section 4.2) and all initial syllables in a language with this type of stress system are stressed and that End Rule Right promotes the rightmost stress in a word to primary stress. Employing a set of six predicates capturing the dimensions of syllable weight and stress (L, ˌL, ˈL, H, ˌH, ˈH), their training data consist of all combinations of symbols conforming to the stress description for words consisting of up to five syllables. Given this data, their grammar discovered five constraints each with a weighting: one requiring every word to have a single primary stress, another requiring that the rightmost stress be the main one, another banning unstressed heavy syllables, another requiring the initial syllable to be stressed, and one banning stress on non-initial light syllables. Given these constraints and their weightings, various stress patterns can be assigned grammaticality scores that are calculated as a function of the number and weighting of constraint violations. In testing their model, Hayes and Wilson find that all of the legal forms for their sample default-to-opposite stress pattern received perfect grammaticality scores, whereas other illegal forms received substantial penalties. In a separate test, Hayes and Wilson feed the 33 quantity-insensitive stress systems in Gordon's (2002) typology to their learner, which discovered 6 constraints. They test the 33 learned stress grammars by submitting all possible strings of 8 or fewer syllables to their model. In support of their algorithm, they find that all licit stress patterns received perfect scores whereas the illicit ones incurred substantial penalties. Similarly successful results obtained in the acquisition of the weight-sensitive stress system (as well as other phonotactic properties) of the Australian language, Wargamay.

A key feature of Hayes and Wilson's tests of the acquisition of metrical structure is their adoption of a grid-based rather than a foot-based approach to stress. This avoids the burden of having to model the learning of the hidden structure implicit in a foot-based theory. Whereas a language learner can hear stresses, an additional leap is required to infer the foot structure behind the stresses. Indeed, a single stress pattern can reflect multiple foot parses. For example, the Maranungku pattern with stress on odd-numbered syllables counting from the left could reflect the following foot structures in a four syllable word even if one constrains the number of possible parsings by assuming a ban on feet larger than two syllables: (ˈσσ)(ˌσσ), (ˈσ)(σˌσ)σ, (ˈσσ)(ˌσ)σ,(ˈσ)σ(ˌσ)σ. The learner must choose the correct parse that is also consistent with the footing in words with differing numbers of syllables. Though this is not an insurmountable difficulty for a learning model, it presents challenges, as it presumably would for a child as well (see Tesar and Smolensky 2000, Tesar 2004, 2007 for approaches to the acquisition of hidden structure).

8. Conclusions

The formal analysis of stress systems has provided fertile ground for phonologists working within both rule-based and constraint-based frameworks. Several issues remain unresolved, however, independent of the paradigm one assumes, including the role of the foot in stress systems and the interaction between word-level stress and intonational prominence. The advent of Optimality Theory has also raised issues of direct relevance to metrical stress theory, such as the formal modeling of the acquisition of stress.

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