Autosegmental Representations in Zigula and Shambaa

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September 19, 2016

This chapter provides computational analyses of two common patterns in tone, unbounded tone shift and unbounded tone spreading, using autosegmental representations (Goldsmith, 1976). These patterns, exemplified here by data from two Bantu languages, illustrate two common characteristics of tone (see Yip, 2002). Unbounded tone shift in Zigula (Kenstowicz and Kisseberth, 1990) exemplifies the 'mobility' of tonal units, or their ability to move long distances. Unbounded tone spreading, exemplified by data from Shambaa (Odden, 1982), illustrates the ability of a single tonal unit to be associated to multiple vowels. This chapter shows how MSO-definable transductions over autosegmental representations can insightfully capture these phenomena.

We first turn to the distribution of tones in Zigula verbs (also known as Zigua or Chizigula; Kenstowicz and Kisseberth, 1990), and argue that the correct generalization is that a single underlying tone shifts to the penultimate vowel. Zigula verb roots come in two flavors: toned and toneless, as can be seen in the infinitive forms in Table 1. The following data are due to Kenstowicz and Kisseberth (1990). Surface high tones are marked with an acute accent on the vowel ([á]); low-toned vowels are unmarked. In these and all examples in this chapter, the data have been converted to IPA from their original sources.

ku-gulus-a	'to chase'	ku-lombéz-a	'to ask'
ku-damaɲ-a	'to do'	ku-bindilíz-a	'to finish'
ku-songoloz-a	'to avoid	ku-hangalasáɲ-a	'to carry many things at once'

Table 1: Verb roots in Zigula

The verbs in the left column in Table 1 are pronounced entirely with a low tone, whereas the verbs in the right column all have a high tone on the penultimate vowel. As the affixes are the same, we must conclude that the roots on the right have an underlying high tone. However, there is a restriction on the position of the tone: roots where a high tone appears elsewhere in the infinitive form, such as the hypothetical *[ku-lómbez-a], are not attested.

Furthermore, in toned roots a single high tone appears on the penultimate vowel when the verb is extended to the right with toneless suffixes. Table 2 shows two forms from Table

1 extended with verbal suffixes [ez]/[iz] 'for' and [an] 'each other'.[1]

ku-damaɲ-a	'to do'	ku-lombéz-a	'to ask'
ku-damaɲ-iz-a	'to do for'	ku-lombez-éz-a	'to ask for'
ku-damaɲ-iz-an-a	'to do for each other'	ku-lombez-ez-án-a	'to ask for each other'

Table 2: Suffixes in Zigula

The verb [ku-damaɲ-a] 'to do', which is pronounced with all low tones in the plain infinitive, also shows no high tones in the suffixed forms [ku-damaɲ-iz-a] 'to do for' and [ku-damaɲ-iz-an-a] 'to do for each other'. In contrast, the verb [ku-lombéz-a] 'to ask', which has a high tone on the penultimate vowel in the plain infinitive, also has a single high tone on the penultimate vowel when the infinitive is suffixed: [ku-lombez-éz-a] 'to ask for' and [ku-lombez-ez-án-a] 'to ask for each other'. As these suffixes do not induce a tone for the toneless root [damaɲ] 'do', we can reasonably assume that they do not carry a tone underlyingly. Thus, the single high tone in the forms in the right column must originate from the root [lombez]/[lombéz] 'ask'. However, this tone always appears on the penultimate vowel, regardless of whether it must shift from its underlying root to a suffix vowel.

That this generalization extends to high tones from other morphemes can be seen in toned prefixes. Table 3 gives data showing how the pronunciation of toneless roots changes depending on their prefix.

ku-gulus-a	'to chase'	ku-songoloz-a	'to avoid'
na-gulus-a	'I am chasing'	na-songoloz-a	'I am avoiding'
a-gulús-a	'He/she is chasing'	a-songolóz-a	'He/she is avoiding'

Table 3: Prefixes in Zigula

As seen in the second and third rows, finiteness and person are indicated by replacing te infinitive [ku] prefix with other prefixes, here [na] for the first person and [a] for the second person. As established in Table 1 and repeated here in Table 3, the roots [gulus] 'chase' and [songoloz] 'to avoid' are not pronounced with any tone in the infinitive. This is also true with the first person suffix: [na-gulus-a] 'I am chasing' and [na-songoloz-a] 'I am avoiding'.

However, with the third person suffix, a high tone appears on the penultimate vowel: [a-gulús-a] 'He/she is chasing' and [a-songolóz-a] 'He/she is avoiding'. We could analyze this as a complex morphological process, in which affixation of /a-/ 'FINITE-3SG' also induces a high tone in the penultimate vowel of the word. However, a more parsimonious explanation is that /a-/ 'FINITE-3SG', like toned verb roots, carries with it a high tone, which is then subject to the same penultimate-tone shift generalization as root tones. Of course, because affixes can carry tones, is possible to have more than one underlying high tone in a word, and

[1] The [ez]/[iz] allomorphy is due to vowel harmony, and will not be analyzed here.

Kenstowicz and Kisseberth (1990) give a complete picture of the complex interactions which occur among multiple underlying tones. For expositional purposes, the discussion here will be restricted to at most one underlying high tone.

The Zigula data above are thus most generally explained by the following two propositions. One, morphemes may be toneless or they may carry a high tone. Two, an underlying high tone shifts to the penultimate vowel.

PENULTIMATE SHIFT: An underlying high tone shifts to the penultimate vowel in the word. (1)

We can most directly express these generalizations with *autosegmental representations* (Goldsmith, 1976), in which different kinds of phonological units are arranged on different *tiers*, or distinct strings. Units on different tiers can be *associated* with one another. In the particular case of Zigula, we can posit that high tones exist on a tonal tier independent of the segments in the word, and that in the output of the phonology they are then associated to the penultimate vowel, as in the diagrams in Table 4.

		H
Underlying Form	ku - gulus - a	ku - lombez - a
		H
Surface Form	ku - gulus - a	ku - lombez - a
	'to chase'	'to ask'
	H	H
Underlying Form	a - gulus - a	ku - lombez - ez - an - a
	H	H
Surface Form	a - gulus - a	ku - lombez - ez - an - a
	'he/she is chasing'	'to ask for each other'

Table 4: Autosegmental representations in Zigula

For example, the underlying form of [ku-lombez-ez-án-a] 'to ask for each other' is thus /ku-lombez^{H}-ez-an-a/, to use the superscript H to indicate in-line that the root /lombez^{H}/ 'ask' contains an underlyingly unassociated H tone.As this H resides on a tier by itself, it is to move outside of its originating morpheme. Why, then, does it shift to the penultimate vowel? Kenstowicz and Kisseberth (1990) offer a metrical story: the final vowel is extrametrical, leaving the penultimate vowel in a metrically prominent position. This prominent position thus attracts the tone. We shall not dwell on this aspect of the analysis, except to to later note how extrametricality can be referred to using MSO.

Autosegmental representations can similarly be invoked to insightfully account for the patterning of verbs in Shambaa (Odden, 1982). Verbs in Shambaa, like verbs in Zigula, can be either 'toned' or 'toneless'. However, in toned verbs in Shambaa, unlike those in Zigula, all vowels from the beginning of the root to the penult are pronounced with a high tone.

Table 5 contrasts toneless verbs, illustrated with examples in the left column, with toned verbs on the right.

ku-ʃunt^{h}-a	‘to wash’	ku-táɣ-a	‘to buy’
ku-ɣoʃo-a	‘to do’	ku-táhík-a	‘to vomit’
ku-hand-a	‘to plant’	ku-fúmbátíʃ-a	‘to tie securely’

Table 5: Verb roots in Shambaa

That the correct generalization is that all vowels up to the penult are pronounced high, and not just all the vowels on the root, can be seen in suffixed forms. When affixed to toneless roots, the suffixes ‘for each other’ are pronounced [ij-an], with a low tone. When affixed to toned roots, they are pronounced [íj-án], with a high tone.

ku-hand-a	‘to plant’	ku-fúmbátíʃ-a	‘to tie securely’
ku-hand-ij-an-a	‘to plant for each other’	ku-fúmbátíʃ-íj-án-a	‘to tie securely for each other’

Table 6: Suffixes in Shambaa

The best explanation in difference in pronunciation of the tone in suffixes in [ku-hand-ij-an-a] ‘to plant for each other’ and [ku-fúmbátíʃ-án-a] is thus that it due to the contrast between [ku-hand-a] ‘to plant’ and [ku-fúmbátíʃ-a] ‘to tie securely’—that is, the difference between toned and toneless verb roots.

Furthermore, like in Zigula, verb roots are not the only class of morpheme that can carry a tone. Table 7 shows how the pronunciation of toneless verb roots changes when affixed with the object marker prefixes [t͡ʃí] ‘it’ and [ví] ‘them’.

ku-ʃunt^{h}-a	‘to wash’
ku-t͡ʃí-ʃúnt^{h}-a	‘to wash it’
ku-ɣoʃo-a	‘to do’
ku-ví-ɣóʃó-a	‘to do them’
ku-ɣoʃo-a-ɣoʃo-a	‘to do repeatedly’
ku-t͡ʃí-ɣóʃó-á-ɣóʃó-a	‘to do it repeatedly’

Table 7: Prefixes in Shambaa

When prefixed only with the infinitive prefix [ku], [ku-ʃunt^{h}-a] ‘to wash’ and [ku-ɣoʃo-a] ‘to do’ are pronounced with all low-toned vowels, as previously established. However, when prefixed with one of these object markers, the forms exhibit the familiar pattern of all high-toned vowels up to the penult, such as in [ku-ví-ɣóʃó-a] ‘to do them’. This is illustrated most dramatically in the contrast between the reduplicated form [ku-ɣoʃo-a-ɣoʃo-a] ‘to do repeatedly’ and the same form with an object prefix, [ku-t͡ʃí-ɣóʃó-á-ɣóʃó-a] ‘to do it repeatedly’.

The generalizations in the Shambaa data are thus as follows. Like in Zigula, morphemes may be toneless or they may carry a high tone. In contrast with Zigula, however, this tone manifests on every vowel from its originating morpheme to the penultimate vowel in the word. Let us call this *unbounded spreading.*

UNBOUNDED SPREADING: An underlying high tone spreads to the penultimate vowel in the word. (2)

Again, autosegmental representations present us with a direct way to express this generalization. Morphemes which carry a tone can be analyzed with a H tone underlyingly associated to their initial vowel. Unbounded spreading (2) then associates this H tone with all vowels up to the penult.

Underlying Form	ku - ɣoʃo - a	H ku - fumbatiʃ- a
Surface Form	ku - ɣoʃo - a 'to do'	H ku - fumbatiʃ- a 'to tie securely'
Underlying Form	H ku - vi - ɣoʃo - a	H ku - fumbatiʃ- ij - an - a
Surface Form	H ku - vi - ɣoʃo - a 'to do them'	H ku - fumbatiʃ- ij - an - a 'to tie for each other'

Table 8: Autosegmental representations in Shambaa

This multiple association of a single tonal autosegment to multiple vowels directly captures the generalization that, for example, all of the high toned vowels in [ku-fúmbátíʃ-íj-án-a] 'to tie for each other' are the result of the single H tone underlyingly associated to the root /fúmbatiʃ/ 'tie' (where the accented /ú/ marks the underlying position of the H tone, as is usual).

We have now seen two patterns from tonal phonology which are directly captured through a change in autosegmental representations: penultimate tone shift in Zigula, in which an H tone is unassociated in the underlying form but associated to the penultimate vowel in the surface, and unbounded tone spread in Shambaa, in which a H tone is associated to a single vowel in the underlying representation but associated to multiple vowels in the surface representation. The following shows how this change can be analyzed using MSO transductions over relational models.

A relational model for autosegmental representations is much like a string model, except that in addition to a relation indicating linear order there is a binary relation $\circ$ for association. Equation (3) gives such a model, where the standard set of segmental features $\mathcal{F}$ is augmented with a set T of tones.

$$\langle \mathcal{D}, \triangleleft, \circ, \tau \ (\forall \tau \in T), \texttt{feature} \ (\forall \texttt{feature} \in \mathcal{F}) \rangle \tag{3}$$

For simplicity, the following examples consider a singleton set of tones $T = \{\mathrm{H}\}$ and only the segmental features $\mathcal{F} = \{\texttt{voc}, \texttt{cons}\}$ identifying vowels and consonants, respectively. However, the following definitions are more general. We assume that tones cannot carry features; i.e. that for all $\tau \in T$ and $\texttt{feature} \in \mathcal{F}$, $\tau(x) \rightarrow \neg\texttt{feature}(x)$ and $\texttt{feature}(x) \rightarrow \neg\tau(x)$.

The model in (3) is still too general; we need to establish that tones and segments appear on separate tiers. It is thus necessary to restrict (3) to the set of autosegmental structures which adhere to this basic well-formedness constraint through the domain formula φ_{dom}. To do this, we first define predicates which isolate tones from the segments. We define

$$\varphi_{\texttt{tone}}(x) \stackrel{\text{def}}{=} \tau_1(x) \vee \tau_2(x) ... \vee \tau_n(x) \tag{4}$$

for $\{\tau_1, \tau_2, ..., \tau_n\} = T$, i.e, that x is some tone in T), and

$$\varphi_{\texttt{segment}}(x) \stackrel{\text{def}}{=} \texttt{feature}_1(x) \vee \texttt{feature}_2(x) \vee ... \vee \texttt{feature}_m(x) \tag{5}$$

for $\{\texttt{feature}_1, \texttt{feature}_2, ..., \texttt{feature}_m\} = \mathcal{F}$, i.e., that x has some segmental feature. We can then write a predicate $\varphi_{\texttt{tier}}(x, y)$ which is true if and only if x and y are both tones or both segments.

$$\varphi_{\texttt{tier}}(x, y) \stackrel{\text{def}}{=} (\varphi_{\texttt{tone}}(x) \wedge \varphi_{\texttt{tone}}(y)) \vee (\varphi_{\texttt{segment}}(x) \wedge \varphi_{\texttt{segment}}(y)) \tag{6}$$

Note that it would be straightforward to extend $\varphi_{\texttt{tier}}(x, y)$ to any finite number of such tier groupings. The following sentence then constrains tier structure such that only like units can appear on a tier together:

$$\texttt{good-tiers} \stackrel{\text{def}}{=} (\forall x, y)[x \leq y \rightarrow \varphi_{\texttt{tier}}(x, y)] \tag{7}$$

This ensures that the tiers are homogenous, and excludes structures in which, for example, a consonant precedes a tone.

The following formulas then define a well-formed association as being between a tone and a *tone-bearing unit*, or TBU. In Zigula and Shambaa, the phonological generalizations referred to the tones of vowels, and not consonants. We thus specify that vowels are the TBUs.

$$\varphi_{\texttt{TBU}}(x) \stackrel{\text{def}}{=} \texttt{vocalic}(x) \tag{8}$$

It should be noted that, while this definition of TBU is satisfactory for the current discussion, other units have been proposed as TBUs, such as syllables and moras, and some researchers claim what counts as a TBU to be language specific (for in-depth discussion see Yip 2002). Note, however, that identifying a different TBU in the logical framework simply requires replacing $\texttt{vocalic}(x)$ in the definition for $\varphi_{\texttt{TBU}}(x)$ with a different predicate.

Regardless of the definition of TBU, the following defines well-formed associations (WFAs) as those in which a tone is matched with a TBU:[2]

$$\varphi_{\mathtt{WFA}}(x, y) \stackrel{\text{def}}{=} x \circ y \wedge \mathtt{tone}(x) \wedge \mathtt{TBU}(y) \tag{9}$$

The formula in (10) then requires that all associations are of this type.

$$\mathtt{good\text{-}associations} \stackrel{\text{def}}{=} (\forall x, y)[x \circ y \rightarrow \varphi_{\mathtt{WFA}}(x, y)] \tag{10}$$

For completeness, we will also define one further constraint on well-formed autosegmental representations, although it is not relevant to the current discussion. The oft-posited No-Crossing Constraint (NCC; Goldsmith, 1976; Hammond, 1988; Coleman and Local, 1991) states that pairs of associated elements must precede each other; in other words, that association lines cannot cross. Formally,

$$\mathtt{NCC} \equiv (\forall x_1, x_2, y_1, y_2)[(x_1 \circ x_2 \wedge y_1 \circ y_2 \wedge x_1 \leq y_1) \rightarrow x_2 \leq y_2] \tag{11}$$

This constraint is usually defined as a universal constraint on autosegmental representations (beginning with their initial definition in Goldsmith 1976). However, as the example tonal patterns given above only involve a single tone, the NCC will not come into play in the examples below. For a thorough discussion of the nature of the NCC, the reader is referred to Coleman and Local (1991).

We can now define φ_{dom} using the above axioms of autosegmental well-formedness:

$$\varphi_{dom} = \mathtt{good\text{-}tiers} \wedge \mathtt{good\text{-}associations} \wedge \mathtt{NCC} \tag{12}$$

An example autosegmental model that conforms to φ_{dom} is given in Figure 1. This model corresponds to the autosegmental representation of the underlying form of Shambaa /ku-ví-ɣoʃo-a/ 'to do them' (c.f. Table 8). (Note that morpheme boundaries are ignored.)

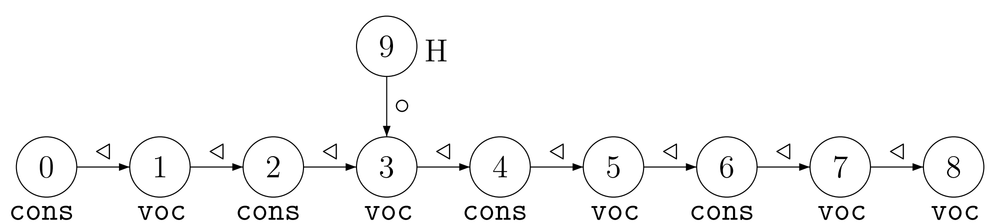

Figure 1: A graph representing the autosegmental model of Shambaa /ku-ví-ɣoʃo-a/ 'to do them'. Note both the edges representing successor ◁ and association ∘.

[2]This defines association as inherently directional; that is, a tone is associated to a TBU, but not vice-versa. Association is often thought of as unordered (see, ex., Kornai, 1995). However, it will simplify the formulas in our transduction to treat them as directional, as any binary predicate referring to association between x and a y will only need to consider the case in which x is a tone and y is a TBU (and not vice versa). This choice has no effect on the function of the association relation.

The graph in Figure 1 has the usual directed edges representing the successor relation $\triangleleft$ among segments. Additionally, there is an associatoin $\circ$ edge between node 9, the H node, and node 3, the second vowel.

We can then define transductions that operate on these representations. We begin with Zigula. Recall that in Zigula, a high tone shifts to the penultimate vowel in the word, as is illustrated for /a$^{\text{H}}$-gulus-a/→[a-gulús-a] 'he/she is chasing' in Figure 2.

H   H
a - gulus - a → a - gulus - a
'he/she is chasing'

Figure 2: An example of high tone shift in Zigula

As there is no epenthesis, we set our copy set $C \stackrel{\text{def}}{=} \{1\}$ to a singleton set. Furthermore, we shall not need to change any feature or tone values for any of the nodes. Thus,

$$(\forall \texttt{feature} \in \mathcal{F})\ \varphi_{\texttt{feature}}(x) \stackrel{\text{def}}{=} \texttt{feature}(x) \tag{13}$$

$$(\forall \tau \in \mathcal{T})\ \varphi_{\tau}(x) \stackrel{\text{def}}{=} \tau(x) \tag{14}$$

This is because, with autosegmental representations, we are not changing the featural representations of single nodes, but rather the associations between them.

Finally, as neither the Zigula or Shambaa generalizations involves deletion, both transformations preserve the successor relation.

$$\varphi_{\triangleleft}(x) \stackrel{\text{def}}{=} x \triangleleft y \tag{15}$$

This leaves us with $\varphi_{\circ}(x, y)$, the predicate which determines when the copies of x and y are associatied in the output. In Zigula, informally, this is when x is a H tone and y is the penultimate vowel in the word. We must first, then, define predicates identifying the penultimate vowel. The predicate in (18) defines relative order $\triangleleft_V$ of vowels, ignoring consonants.

$$x \triangleleft_V y \stackrel{\text{def}}{=} \texttt{voc}(x) \wedge \texttt{voc}(y) \wedge x \leq y \wedge (\forall z)[(x \leq z \wedge z \leq y) \rightarrow \neg\texttt{voc}(z)] \tag{16}$$

In other words, $x \triangleleft_V y$ iff x precedes y and no other vowels intervene. The final vowel can then be defined as the vowel for which no other vowel follows in the order $\triangleleft_V$.

$$\varphi_{\texttt{finalV}}(x) \stackrel{\text{def}}{=} \texttt{voc}(x) \wedge (\forall y)[\neg x \triangleleft_V y] \tag{17}$$

The penultimate vowel is then the vowel that precedes the final vowel with respect to $\triangleleft_V$.

$$\varphi_{\texttt{penultV}}(x) \stackrel{\text{def}}{=} (\exists y)[x \triangleleft_V y \wedge \varphi_{\texttt{finalV}}(y)] \tag{18}$$

The final definition for the penultimate shift transduction is then simple: a H tone associates to the penultimate vowel.

$$\varphi_{\circ}(x,y) \stackrel{\text{def}}{=} \text{H}(x) \wedge \varphi_{\texttt{penultV}}(y) \tag{19}$$

To illustrate how this obtains the correct output autosegmental representation for penultimate shift in Zigula, Figure 3 gives the graphs for the autosegmental transformation in Figure 2 for the form /a$^{\text{H}}$-gulus-a/→[a-gulús-a] 'he/she is chasing'.

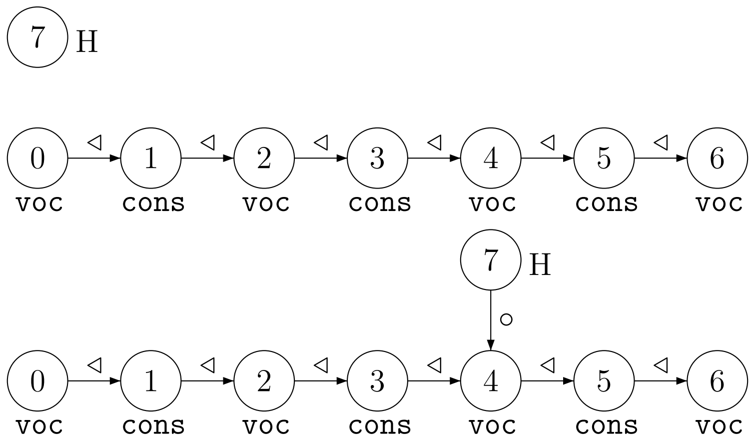

Figure 3: Graphs for the transduction of the autosegmental representation of Zigula /a$^{\text{H}}$-gulus-a/ → a-gulús-a 'he/she is chasing'.

All of the work in the transduction is done by $\varphi_{\circ}(x,y)$: it identifies nodes 7 and 4 as the nodes whose copies are to be associated in the output because 7 is a H tone and 4 is the penultimate vowel. In this way, the MSO transduction defines the transduction entirely by identifying the well-formed associations in the output graph.

This is also the case for unbounded spreading in Shambaa. Recall that in Shambaa, an underlying H tone spreads up to the penultimate vowel, as Figure 4 recalls for /ku-ví-ɣoʃo-a/→[ku-vi-ɣoʃó-a] 'to do them'.

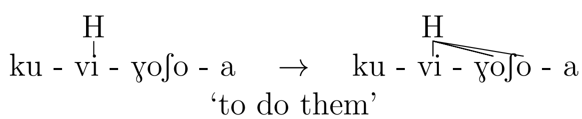

Figure 4: An example of unbounded spreading in Shambaa

The analysis for this as a MSO transduction is almost identical for that in Zigula, save the predicate $\varphi_{\circ}(x,y)$. Instead, the predicate $\varphi_{\circ}(x,y)$ as defined below in (20) creates surface associations between the H tone and all vowels—save the extrametrical final vowel—to the right of the vowel associated to this H in the input. Note that it uses several predicates defined previously for φ_{dom} and the transduction in Zigula.

$$\varphi_{\circ}(x,y) \stackrel{\text{def}}{=} \phi_{\texttt{WFA}}(x,y) \wedge (\exists x_1)[x \circ x_1 \wedge x_1 \leq y] \wedge (\exists y_2)[\varphi_{\texttt{penultV}}(y_2) \wedge y \leq y_2] \tag{20}$$

The reference to $\varphi_{\texttt{WFA}}(x, y)$ ensures that any surface association is well-formed (i.e. between a tone and TBU). The next part of the conjunct, $(\exists x_1)[x \circ x_1 \wedge x_1 \leq y]$, specifies that y must be equal to, or to the right of, the x_1 to which x was originally associated. Finally, $(\exists y_2)[\varphi_{\texttt{penultV}}(y_2) \wedge y \leq y_2]$ specifies that y is either equal to, or is to the left of, the penultimate vowel.

That this obtains the correct transduction is illustrated in Figure 5 corresponding to the mapping between the autosegmental representations for /ku-ví-ɣoʃo-a/→[ku-ví-ɣóʃó-a] 'to do them'.

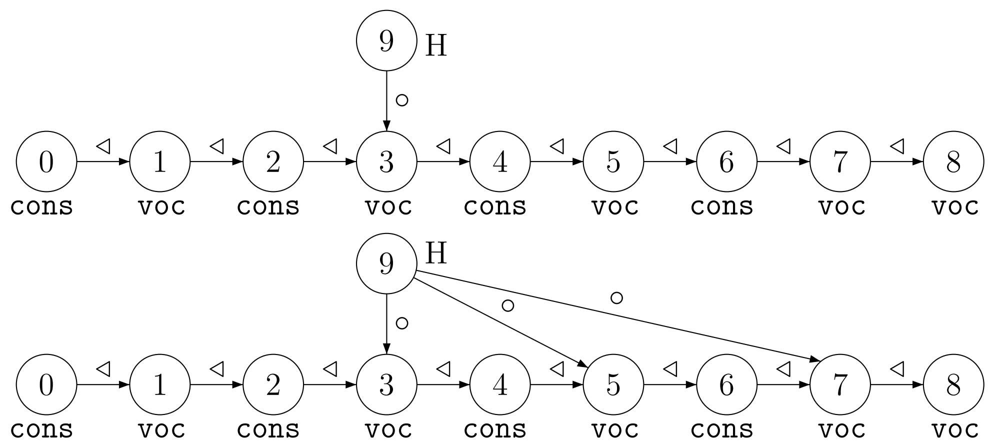

Figure 5: Graphs for the transduction of the autosegmental representation of Shambaa 'he/she is chasing'/ku-ví-ɣoʃo-a/→[ku-ví-ɣóʃó-a] 'to do them'.

The associations are built as follows. That node 9, as the only tone, satisfies the role of x in $\varphi_{\texttt{WFA}}(x, y)$ is clear. The potential TBU nodes are 1, 3, 5, 7, and 8 (i.e., the `vocalic` nodes). Out of these, only 3, 5, and 7 satisfy the role of y in the other conjunctions in $\varphi_\circ$. Node 3 satisfies the other conditions on y as it is the node to which 9 is associated, and it is to the left of the penult vowel. So an association between 9 and 3 is drawn. Node 5 also satisfies these conditions because it is to the right of 3 but to the left of the penult 7; node 7 satisfies them because it is to the right of 3 and it is the penultimate vowel. So associations between 9 and 5 and between 9 and 7 are drawn. Associations are *not* drawn to nodes 1 and 8, because 1 is to the left of 3 (the originally associated vowel) and 8 is to the right of 7 (the penultimate vowel).

Thus, in the analyses for both Zigula and Shambaa, the transduction is defined in terms of well-formed surface associations. In Zigula, this involved specifying that the only valid surface association is between a tone and the penultimate vowel. In Shambaa, this involved specifying a range of vowels in between the underlyingly associated vowel and the penult. In some ways, this is similar to Yip (2002)'s Optimality-Theoretic analyses for similar tonal processes, which also motivate the mapping between underlying and surface autosegmental structures through the well-formedness of surface associations. However, in OT, well-formedness is implemented through competition among individual constraints. For example, both spreading and shift to a penultimate vowel can be analyzed in OT through the interaction of a ALIGN-R constraint motivating the association of a H tone to as close to the word as possible with a NON-FINALITY constraint barring association to the final vowel. The difference between spreading and shift is whether or not a highly-ranked *ASSOC constraint bans the addition of new association lines. In contrast, in the MSO transductions defined in the present chapter, these conditions on the creation of surface associations are stated directly in the definition of $\varphi_\circ$.

There is one aspect of previous analyses we have not yet discussed with respect to MSO. Recall that Kenstowicz and Kisseberth (1990) explain the attraction of the tone to the penult via the extrametricality of the final vowel, whereas the MSO definitions above refer directly refer to the penultimate vowel. However, it is just as possible to create predicates which reference whether or not vowels are extrametrical. First, the following formula defines the 'metrical' vowels; i.e., those excluding the extrametrical final vowel.

$$\varphi_{\texttt{metrical}}(x) \stackrel{\text{def}}{=} \texttt{voc}(x) \wedge \neg\varphi_{\texttt{finalV}}(x) \tag{21}$$

Note that the above formula simply lists the conditions for being metrical—to implement other language-specific conditions for extrametricality, one only needs to add formula of the form $\neg\varphi(x)$ (where $\varphi(x)$ inidcates the property that qualifies a unit as extrametrical).

We can then rewrite the final definition given in (19) for the Zigula penultimate shift transduction as the following: a H tone associates to the last metrical vowel.

$$\varphi_\circ(x,y) \stackrel{\text{def}}{=} \mathrm{H}(x) \wedge \varphi_{\texttt{metrical}}(y) \wedge (\forall z)[\varphi_{\texttt{metrical}}(z) \rightarrow \neg y \triangleleft_V z] \tag{22}$$

The reader can confirm with the graphs in Figure 3 that this has the same effect as the previous definition. A single association is drawn between nodes 7 and 4 because node 7 is a H tone and node 4 is the last vowel to satisfy $\varphi_{\texttt{metrical}}(x)$.

We can similarly recruite $\varphi_{\texttt{metrical}}(x)$ to define the surface association relation in Shambaa unbounded spreading. Recall that in Shambaa, the goal of the predicate $\phi_\circ(x,y)$ was to define the range of vowels to which the H tone should associate. We can recast the definition in (20) in metrical terms in the following way: the H tone associates to all metrical vowels to the right of the originally associated vowel:

$$\varphi_\circ(x,y) \stackrel{\text{def}}{=} \phi_{\texttt{WFA}}(x,y) \wedge (\exists x_1)[x \circ x_1 \wedge x_1 \leq y] \wedge \varphi_{\texttt{metrical}}(y)] \tag{23}$$

The definition for $\varphi_\circ$ in (23) differs only from that in (20) in the final conjunct. The original definition in (20) referred directly to the penult and all vowels to the left of it. In (23), however, we simply need only state that y is metrical. The reader can confirm that this defines the same transduction by referring back to Figure 5: nodes 3, 5, and 7 are the only metrical vowels to the right (or equal to) the originally associated node 3. Node 8, by the defintion of $\varphi_{\texttt{metrical}}(x)$, is extrametrical, and so is not associated.

To conclude, this chapter has reviewed two tonal phenomena, penultimate tone shift in Zigula and unbounded tone spreading in Shambaa, in which the correct generalizations referred not to the changing of features and segments, but to associations between units on independent tiers in autosegmental representations. Specifically, these autosegmental representations placed tonal units on a separate tier from segmental units. These autosegmental representations were then defined as relational structures with an additional association relation, and constraints on well-formed autosegmental representations were defined in MSO. Finally, we saw how MSO transductions could specify change from underlying form to surface form by directly stating the conditions on association from tonal units to segmental units in the surface form. This chapter could not possibly cover the vast range of tonal phenomena that has been observed (see, e.g., Yip, 2002), but the analyses given here have shown how some fundamental properties of tone can be captured with MSO transductions.

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