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ABSTRACT

*Research within the framework of constraint-based grammar formalisms such as Head-driven Phrase Structure Grammar (*HPSG*) has focussed on syntax and semantics, largely to the exclusion of phonology. In return, current developments in phonology have generally ignored the technical and linguistic innovations offered by constraint-based grammar formalisms. This paper focusses on those modifications to* HPSG *and to non-linear phonology which we believe are necessary in order to bring both sides together into a happy marriage.*

This process consists of three stages. First, we explore the application of typed feature logic to phonology, and propose a system of prosodic types. Second, the phonology attribute of HPSG *is enriched, so that it can encode multi-tiered, hierarchical phonological representations. Finally, we exemplify the approach in some detail for the languages Terêna, Sierra Miwok and French. The approach taken in this paper lends itself particularly well to capturing phonological generalisations in terms of high-level prosodic constraints.*[1]

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1 Phonology in Constraint-Based Grammar

Classical generative phonology is couched within the same set of assumptions that dominated standard transformational grammar. Despite some claims that "derivations based on ordered rules (that is, external ordering) and incorporating intermediate structures are essential to phonology" (Bromberger & Halle, 1989:52), much recent work has tended towards a new model, frequently described in terms of constraints on well-formedness (Paradis, 1988; Goldsmith, 1993; McCarthy & Prince, 1993; Prince & Smolensky, 1993). While this work has an increasingly declarative flavour, most versions retain procedural devices for repairing representations that fail to meet certain constraints, or for constraints to override each other. This view is in marked contrast to the interpretation of constraints in grammar frameworks like LFG, GPSG, and HPSG.[2] In such approaches, constraints cannot be circumvented, there are no 'intermediate structures', and the well-formedness constraint (Partee, 1979:276) is observed (i.e. ill-formed representations can never be created). The advantage of these frameworks is that they allow interesting linguistic analyses to be encoded while remaining computationally tractable.

Here, we are interested in the question of what a theory of phonology ought to look like if it is to be compatible with constraint-based grammar framework, specifically HPSG.[3] This issue has already received attention (Bach & Wheeler, 1981; Wheeler, 1981; Bird, 1990; Cahill, 1990; Coleman, 1991; Scobbie, 1991; Bird, 1992; Broe, 1993), although a thoroughgoing integration of phonology into HPSG is yet to be attempted. In this article we take some steps towards this goal, identifying key phonological requirements on the HPSG formalism by examining nasalisation in Terêna, templatic morphology in Sierra Miwok and schwa in French. Before embarking on this enterprise, however, we present an overview of those aspects of phonology that present a challenge to the standard assumptions about phonology taken in HPSG. Then we describe a (simplified) version of HPSG that will make it possible to illustrate the approach without irrelevant technical machinery.

1.1 The challenge of phonology

Given that the dominant focus of HPSG has been syntax and semantics, it is not surprising that the phonological content of words and phrases has been largely limited to orthographic strings, supplemented with a concatenation operation. How far would such representations have to be enriched if we wanted to accommodate a more serious treatment of phonology?

As remarked earlier, recent work in theoretical phonology has apparently moved closer to a constraint-based perspective, and is thus a promising starting point for our investigation. Yet there are at least three challenges that confront anyone looking into theoretical phonology with the viewpoint of computational linguistics. Most striking perhaps is the relative informality of the language in which theoretical statements are couched. Bird & Ladd (1991) have catalogued several examples of this informality: notational ambiguity (incoherence), definition by example (informality), variable interpretation of notation depending on subjective criteria (inconsistency), and uncertainty about empirical content (indeterminacy). When a clear theoretical statement can be found, it is usually

[2] Lexical Functional Grammar (Kaplan & Bresnan, 1982), Generalised Phrase Structure Grammar (Gazdar, Klein, Pullum & Sag, 1985), and Head-Driven Phrase Structure Grammar (Pollard & Sag, 1987).

[3] There are a number of grammar environments which implement large fragments of HPSG. Notable examples are the TFS system developed at Stuttgart by Emele and Zajac, and the ALE system developed at Carnegie Mellon University by Carpenter.

expressed in procedural terms, which clouds the empirical ramifications making a theory difficult to falsify. Finally, even when explicit and non-procedural generalisations are found, they are commonly stated in a non-linear model, which clearly goes beyond the assumptions about phonology made in HPSG as it currently stands.

We approach these challenges by adopting a formal, non-procedural, non-linear model of phonology and showing how it can be integrated into HPSG, following on the heels of recent work by the authors (Bird & Klein, 1990; Bird, 1992; Klein, 1992). One of the starting assumptions of this work is that phonological representations are intensional, i.e. each representation is actually a *description* of a class of utterances. Derivations progress by refining descriptions, further constraining the class of denoted objects. Lexical representations are likewise partial, and phonological constraints are cast as generalisations in a lexical inheritance hierarchy or in a prosodic inheritance hierarchy. When set against the background of constraint-based grammar this approach is quite natural (Johnson, 1988). Moreover, some recent thinking on the phonology-phonetics interface supports this view (Pierrehumbert, 1990). However, it represents a fundamental split with the generative tradition, where rules do not so much refine descriptions as alter the objects themselves (Keating, 1984:286–287).

While it is clearly possible to integrate an essentially generative model into the mould of constraint-based grammar (Krieger et al., 1993), it is less clear that this is the approach most phonologists would wish to take nowadays. It is becoming increasingly apparent that rule-based relationships between surface forms and hypothetical lexical forms are unable to capture important generalisations about surface forms. This concern was voiced early in the history of generative phonology, when Kisseberth (1970) complained that such rules regularly *conspire* to achieve particular surface configurations, but are unable to express the most elementary observations about what those surface configurations are. As a criticism of rule-based systems, Kisseberth's complaint remains valid. However, recent work in phonology has moved away from models involving rules that relate lexical and surface forms towards models involving general systems of interacting constraints, where this problem has been solved.

Accordingly, we avoid the theoretical framework of early generative phonology, focussing instead on encoding phonological *constraints* in a *constraint-based* grammar framework. We present an overview of the grammar framework in the next section.

1.2 Theoretical framework

Typed feature structures (Carpenter, 1992) impose a type discipline on constraint-based grammar formalisms. A partial ordering over the types gives rise to an inheritance hierarchy of constraints. As Emele & Zajac (1990) point out, this object-oriented approach brings a number of advantages to grammar writing, such as a high level of abstraction, inferential capacity and modularity.

On the face of it, such benefits should extend beyond syntax, to phonology for example. Although there have been some valuable efforts to exploit inheritance and type hierarchies within phonology, e.g. (Bird, 1990; Reinhard & Gibbon, 1991), the potential of typed feature structures for this area has barely been scratched so far. In this section, we present a brief overview of HPSG (Pollard & Sag, 1987), a constraint-based grammar formalism built around a type system which suits our purposes in phonology.

In order to formulate the type system of our grammar, we need to make two kinds of TYPE DECLARATION.

The first kind contains information about the subsumption ordering over types. For example, the basic grammar object in HPSG is the feature structure of type *sign*. The type *sign* has some SUBTYPES. If σ is a subtype of τ, then σ provides at least as much information as τ. A type declaration for *sign* defines it as the following disjunction of subtypes:[4]

(1) $$sign \Rightarrow morph \vee stem \vee word \vee phrase$$

The second kind of declaration is an APPROPRIATENESS CONDITION. That is, for each type, we declare (all and only) the attributes for which it is specified, and additionally the types of values which those attributes can take.[5] For example, objects of type *sign* could be constrained to have the following features defined:

(2) $$\begin{bmatrix} \text{PHON}: & phon \\ \text{SYNSEM}: & synsem \end{bmatrix}_{sign}$$

That is, feature structures of type *sign* must contain the attributes PHON (i.e. phonology) and SYNSEM (i.e. syntax/semantics),[6] and these attributes must take values of a specific type (i.e., *phon* and *synsem* respectively). A further crucial point is that appropriateness conditions are inherited by subtypes. For example, since *morph* is a subtype of *sign*, it inherits all the constraints obeyed by *sign*. Moreover, as we will see in §3.2, it is subject to some further appropriateness conditions which are not imposed on any of its supertypes.

Continuing in the same vein, we can assign appropriateness conditions to the types *synsem* and *phon* which occurred as values in (2), (simplifying substantially from standard HPSG). Here we give the constraints for *synsem*. The type *phon* will be discussed in §2.

(3) $$\begin{bmatrix} \text{CAT}: & cat \\ \text{AGR}: & agr \\ \text{SUBCAT}: & list \\ \text{DTRS}: & list \\ \text{SEM}: & semantics \end{bmatrix}_{synsem}$$

Later, we will see more examples of how types are declared and constrained.

1.3 Overview of Paper

The structure of the paper is as follows. In the next section, we present our assumptions about phonological representations and phenomena, couched in the framework of typed feature logic. In

[4] The constraints proposed here deviate in various respects from the standard version of HPSG.

[5] We are using what Carpenter (1992) calls TOTAL WELL-TYPING. That is, (i) the only attributes and values that can be specified for a given feature structure of type τ are those which are appropriate for τ; and (ii) every feature structure of type τ must be specified for all attributes that are appropriate for τ.

[6] Earlier versions of HPSG kept syntax and semantics as separate attributes, and we will sometimes revert to the latter when borrowing examples from others' presentations.

§3 we discuss our view of the lexicon, borrowing heavily on HPSG's lexical type hierarchy, and developing some operations and representations needed for morphology. The next three sections investigate various applications of the approach to three widely differing phenomena, namely Terêna nasalisation, Sierra Miwok templatic morphology, and French schwa. The paper concludes with a summary and a discussion of the future prospects.

2 String-Based Phonology

In this section we present two varieties of string-based phonology, one based on finite-state automata (FSAs) and one based on the HPSG list notation. The former has computational advantages over the latter, while the latter represents a more conservative extension to HPSG than the former. We do not attempt to resolve the tension between these two approaches, since we feel both represent useful ways of thinking about the linguistic problems we address. We begin by presenting the FSA approach in §2.1, followed by the list-based approach in §2.2 and §2.3. The section concludes with a discussion of prosodic constituency.

2.1 Finite-State Phonology

Over the last decade much has been written on the application of finite-state transducers (FSTs) to phonology, centering on the TWO-LEVEL MODEL of Koskenniemi (1983). Antworth (1990) gives a comprehensive introduction to the field. The two-level formalism is an attractive computational model for 1960's generative phonology. However, as has already been noted, phonologists have since moved away from complex string rewriting systems to a range of so-called nonlinear models of phonology. The central innovation of this more recent work is the idea that phonological representations are not strings but collections of strings, synchronised like an orchestral score.

There have been some notable recent attempts to rescue the FST model from its linearity in order to encompass nonlinear phonology (Kay, 1987; Kornai, 1991; Wiebe, 1992). However, from our perspective, these refinements to the FST model still admit unwarranted operations on phonological representations, rule conspiracies and the like. Rather, we believe a more constrained and linguistically appealing approach is to employ FSAs in preference to FSTs, since it has been shown how FSAs can encode autosegmental representations and a variety of constraints on those representations (Bird & Ellison, 1992). The leading idea in this work is that each tier is a partial description of a string, and tiers are put together using the intersection operation defined on FSAs.

Apart from being truer to current phonological theorising, this one-level model has a second important advantage over the two-level model. Since the set of FSAs forms a boolean lattice under intersection, union and complement, we can safely conjoin ('unify'), disjoin and negate phonological descriptions. Such a framework is obviously compatible with constraint-based grammar formalisms, and there is no reason in principle to prevent us from augmenting HPSG with the data type of regular expressions. In practice, we are not aware of any existing implementations of HPSG (or other feature-based grammars) which accommodate regular expressions. In their work mentioned above, Krieger et al. (1993) propose to encode FSAs as typed feature terms. However, since such terms will presumably still be handled by a general constraint solver, there seems to be no computational benefit in such an encoding. Ideally, we would envisage a computational interpretation of typed feature structures where operations on regular expression values are delegated to a specialised engine which manipulates the corresponding FSAs, and returns regular expression results.

2.2 List Notations

As a concession to existing practice in HPSG, we have taken the step of using lists in place of strings. We will use angle bracket notation as syntactic sugar for the standard FIRST/REST encoding.

We will assume that the type system allows parametrised types of the form *list(α)*, where α is an atomic type. This would be cashed out in the following declarations:

(4) $list(\alpha) \Rightarrow e\text{-}list(\alpha) \vee ne\text{-}list(\alpha)$

$$_{ne\text{-}list(\alpha)}\left[\begin{array}{ll} \text{FIRST}: & \alpha \\ \text{REST}: & list(\alpha) \end{array}\right]$$

We can now treat α^* and α^+ as abbreviations for *list(α)* and *ne-list(α)* respectively.

Another useful abbreviatory notation is parenthesised elements within lists. We will interpret $\langle a(b)\rangle \frown L$ as the following disjunction of constraints:

(5)
$$_{list}\left[\begin{array}{ll} \text{FIRST}: & a \\ \text{REST}: & _{list}\left[\begin{array}{ll} \text{FIRST}: & b \\ \text{REST}: & \boxed{1}list \end{array}\right] \vee \boxed{1} \end{array}\right]$$

A third useful notation assigns a type τ to each position in a list. This notation is defined recursively, as given in (6), where *map(τ)* is a parameterised type (a subtype of *list*), and τ is a variable ranging over types.

(6)
$$map(\tau) \equiv {}_{\tau}\left[\text{REST}: \; map(\tau)\right] \vee \langle\rangle$$

If a list $\langle a\ b\ c\rangle$ has type *map(seg-list)*, it will appear as follows:

(7)
$$_{seg\text{-}list}\left[\begin{array}{ll} \text{FIRST}: & a \\ \text{REST}: & _{seg\text{-}list}\left[\begin{array}{ll} \text{FIRST}: & b \\ \text{REST}: & _{seg\text{-}list}\left[\begin{array}{ll} \text{FIRST}: & c \\ \text{REST}: & \langle\rangle \end{array}\right] \end{array}\right] \end{array}\right]$$

We shall see applications of these list notations in the next section.

2.3 A prosodic type hierarchy

A PROSODIC TYPE HIERARCHY is a subsumption network akin to the lexical hierarchy of HPSG (Pollard & Sag, 1987:191ff). The type constraints we have met so far can be used to define a type hierarchy, which for our purposes will be a boolean lattice. In this section we present in outline form a prosodic hierarchy which subsequent analyses will be based on. Example (8) defines the upper reaches of the hierarchy.

(8) $\quad phon \Rightarrow utterance \vee phrase \vee foot \vee syl \vee segment$

Each of these types may have further structure. For example, following Clements (1985:248) we may wish to classify segments in terms of their place and manner of articulation, using the following appropriateness declaration.

(9)

$$\begin{bmatrix} \text{LARYNGEAL}: & \begin{bmatrix} \text{SPREAD}: & boolean \\ \text{CONSTRICTED}: & boolean \\ \text{VOICED}: & boolean \end{bmatrix} \\ \text{SUPRALARYNGEAL}: & \begin{bmatrix} \text{MANNER}: & \begin{bmatrix} \text{NASAL}: & boolean \\ \text{CONTINUANT}: & boolean \\ \text{STRIDENT}: & boolean \end{bmatrix} \\ \text{PLACE}: & \begin{bmatrix} \text{CORONAL}: & boolean \\ \text{ANTERIOR}: & boolean \\ \text{DISTRIBUTED}: & boolean \end{bmatrix} \end{bmatrix} \end{bmatrix}_{segment}$$

Suppose now that we wished to use these structures in a constraint for English homorganic nasal assimilation. This phenomenon does not occur across phrase boundaries and so the constraint will be part of the definition of the type *phrase*. Let us assume that a *phrase* is equivalent to $segment^*$, i.e. a list of *segments*. Informally speaking, we would like to impose a negative filter which bars any nasal whose value for place of articulation differs from that of the segment that immediately follows. Here, we use SL as an abbreviation for SUPRALARYNGEAL and CONT for CONTINUANT.

(10) $$hna \equiv \neg \left\langle \cdots \begin{bmatrix} \text{SL}: \begin{bmatrix} \text{MANNER}|\text{NASAL}: & + \\ \text{PLACE}: & \boxed{1} \end{bmatrix} \end{bmatrix}_{segment} \begin{bmatrix} \text{SL}: \begin{bmatrix} \text{MANNER}|\text{CONT}: & - \\ \text{PLACE}: & \neg\boxed{1} \end{bmatrix} \end{bmatrix}_{segment} \cdots \right\rangle_{phrase}$$

While a filter of this kind might appear suspicious, it is straightforwardly translated into the following constraints. First, we define *hna* in (11a), using the *map* type introduced in (6). The type *hom-nas*, used in (11a), is defined in (11b). This type constrains the first and second members of a list.

(11) a. *hna* $\equiv$ *map(hom-nas)*

b. $$hom\text{-}nas \equiv \neg \begin{bmatrix} \text{FIRST}|\text{SL}: & \begin{bmatrix} \text{MANNER}|\text{NASAL}: & + \\ \text{PLACE}: & \boxed{1} \end{bmatrix} \\ \text{REST}|\text{FIRST}|\text{SL}: & \begin{bmatrix} \text{MANNER}|\text{CONT}: & - \\ \text{PLACE}: & \neg\boxed{1} \end{bmatrix} \end{bmatrix}$$

Standard techniques can now be used to move the negation in (11b) inwards.[7] Since constraints on adjacent list elements generally seem to be more intelligible in the format exhibited by (10), we shall stick to this notation in the remainder of the paper.

2.4 Prosodic Constituency

One standard phonological approach assumes that prosodic constituency is like phrase structure (Selkirk, 1984). For example, one might use a rewrite rule to define a (phonological) phrase as a sequence of feet, and a foot as sequence of syllables:

(12) a. *phrase* $\rightarrow$ *foot*$^+$

b. *foot* $\rightarrow$ *syl*$^+$

Within the framework of HPSG, it would be simple to mimic such constituency by admitting a feature structure of type *phrase* whose DTRS (i.e. daughters) are a list of feature structures of type *foot*, and so on down the hierarchy. However, there appears to be no linguistic motivation for building such structure. Rather, we would like to say that a *phrase is* just a non-empty list of feet. But a foot is just a list of syllables, and if we abandon hierarchical structure, we seem to be stuck with the conclusion that phrases are also just lists of syllables. In a sense this is indeed the conclusion that we want. However, not any list of syllables will constitute a phrase, and not every phrase will be a foot. That is, although the data structure may be the same in each case, there will be additional constraints which have to be satisfied. For example, we might insist that elements at the periphery of phrases are exempt from certain sandhi phenomena; and similarly, that feet have no more than three syllables, and only certain combinations of heavy and light syllables are permissible. Thus, we will arrive at a scheme like the following, where the C_i indicate the extra constraints:

[7] These techniques employ the following equivalences:

$$\neg\begin{bmatrix} \text{A}: \phi \\ \text{B}: \psi \end{bmatrix} \equiv \neg\begin{bmatrix} \text{A}: \phi \end{bmatrix} \vee \neg\begin{bmatrix} \text{B}: \psi \end{bmatrix}$$

$$\neg\begin{bmatrix} \text{A}: \phi \end{bmatrix} \equiv \begin{bmatrix} \neg(\text{A}: \top) \end{bmatrix} \vee \begin{bmatrix} \text{A}: \neg\phi \end{bmatrix}$$

Here $\neg(\text{A}:\top)$ indicates that the attribute A is not appropriate for this feature structure.

(13) a. $\textit{phrase} \equiv \textit{foot}^{+} \wedge C_1 \wedge \ldots \wedge C_k$

b. $\textit{foot} \equiv \textit{syl}^{+} \wedge C_l \wedge \ldots \wedge C_n$

This concludes our discussion of string-based phonology. We have tried to show how a phonological model based on FSAs is compatible with the list notation and type regime of HPSG. Next we move onto a consideration of morphology and the lexicon.

3 Morphology and the Lexicon

3.1 Linguistic Hierarchy

The subsumption ordering over types can be used to induce a hierarchy of grammatically well-formed feature structures. This possibility has been exploited in the HPSG analysis of the lexicon: lexical entries consist of the idiosyncratic information particular to the entry, together with an indication of the minimal lexical types from which it inherits. To take an example from (Pollard & Sag, 1987), the base form of the English verb *like* is given as (14).

(14)
$$\left[\begin{array}{ll} \text{PHON}: & \langle \text{l a ɪ k} \rangle \\ \text{SYN|LOC|SUBCAT}: & \langle \boxed{2}[\,]\ \boxed{1}[\,] \rangle \\ \text{SEM|CONT}: & \left[\begin{array}{ll} \text{RELN}: & \textit{like} \\ \text{LIKER}: & \boxed{1} \\ \text{LIKEE}: & \boxed{2} \end{array}\right] \end{array}\right]_{\textit{main} \wedge \textit{base} \wedge \textit{strict-trans}}$$

Since *main* is a subtype of *verb*, the entry for *like* will inherit the constraint that its major class feature is *V*; by virtue of the type *strict-trans*, it will inherit the constraint that the first element in the SUBCAT list is an accusative *NP*, while the second element is a nominative *NP*, and so on for various other constraints. Figure 1 shows a small and simplified portion of the lexical hierarchy in which the verb *like* is a leaf node.

Along the phonological dimension of signs, lexical entries will have to observe any morpheme or word level constraints that apply to the language in question. When words combine as syntactic phrases, they will also have to satisfy all constraints on well-formed phonological phrases (which is not to say that phonological phrases are isomorphic with syntactic ones). In the general case, we may well want to treat words in the lexicon as unsyllabified sequences of segments. It would then follow that, for example, the requirement that syllable-initial voiceless obstruents be aspirated in English would have to be observed by each syllable in a phrase (which in the limiting case, might be a single word), rather than lexical entries *per se*.

In some languages we may require there to be a special kind of interaction between the lexical and the prosodic hierarchy. For example, Archangeli & Pulleyblank (1989) discuss the tongue root harmony of Yoruba which is restricted to nouns. If *atr* (i.e. advanced tongue root) was the type of harmonic utterances, then we could express the necessary constraint thus:

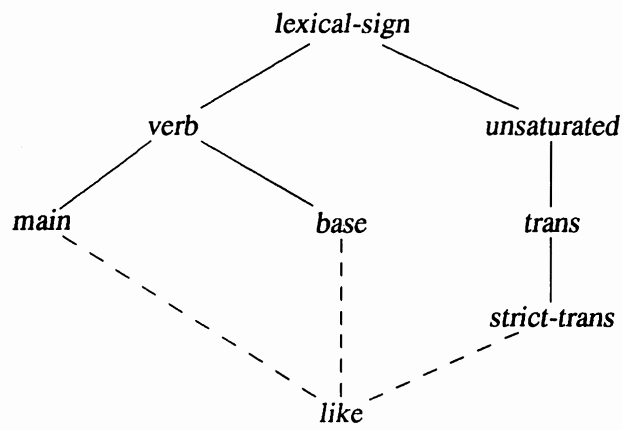


Figure 1: A portion of the lexical hierarchy

(15)
$$\left[\begin{array}{ll} \text{PHON}: & \textit{phon} \wedge \textit{atr} \\ \text{SYN}|\text{LOC}|\text{HEAD}: & \left[\begin{array}{l} \text{MAJ}: \textit{noun} \\ \text{LEX}: + \end{array}\right] \end{array}\right]_{\textit{noun}}$$

This kind of constraint is known as a morpheme structure constraint, and phonologists have frequently needed to have recourse to these (Kenstowicz & Kisseberth, 1979:424ff). Another example of the interaction between prosody and morphology is the phenomenon of prosodic morphology, an example of which can be found in §5.

3.2 Morphological complexity

Given the syntactic framework of HPSG, it seems tempting to handle morphological complexity in an analogous manner to syntactic complexity. That is, morphological heads would be analysed as functors which subcategorise for arguments of the appropriate type, and morphemes would combine in a Word-Grammar scheme.[8] Simplifying drastically, such an approach would analyse the English third person singular present suffix *-s* in the manner shown in (16), assuming that affixes are taken to be heads.

(16)
$$\left[\begin{array}{ll} \text{PHON}: & \langle \text{s} \rangle \\ \text{SYNSEM}|\text{SUBCAT}: & \langle \textit{verb-stem} \rangle \end{array}\right]_{\textit{affix}}$$

By adding appropriately modified versions of the Head Feature Principle, Subcategorisation Principle and linear order statements, such a functor would combine with a verb stem to yield a tree-structured sign for *walks*.

[8] See (Krieger & Nerbonne, 1991) for an analysis of this sort.

(17)
$$\left[\begin{array}{ll}\text{PHON}: & \boxed{1} \frown \boxed{2} \\ \text{SYNSEM|DTRS}: & \left\langle {}_{\textit{verb-stem}}\left[\text{PHON}: \boxed{1}\langle \text{w ɔː k}\rangle\right]_{\textit{affix}}\left[\text{PHON}: \boxed{2}\langle \text{s}\rangle\right]\right\rangle\end{array}\right]_{\textit{verb}}$$

However, a more economical treatment of inflectional morphology is obtained if we analyse affixes as partially instantiated word forms.[9] Example (18) illustrates this for the suffix *-s*.

(18)
$$\left[\begin{array}{ll}\text{PHON}: & \boxed{1} \frown \boxed{2} \\ \text{MORPH}: & \left[\begin{array}{ll}\text{STEM}: & {}_{\textit{verb-stem}}\left[\text{PHON}: \boxed{1}\right] \\ \text{AFFIX}: & {}_{\textit{suffix}}\left[\text{PHON}: \boxed{2}\langle \text{s}\rangle\right]\end{array}\right]_{\textit{affix-morph}}\end{array}\right]_{\textit{3ps}}$$

Note that we have added to *sign* a new attribute MORPH, with a value *morph*. The latter has two subtypes, *affix-morph* and *basic-morph*, depending on whether the value contains a stem and affix or just a stem.

(19) $\textit{morph} \Rightarrow \textit{affix-morph} \vee \textit{basic-morph}$

While both of these types will inherit the attribute STEM, *affix-morph* must also be defined for the attribute AFFIX:

(20) a. ${}_{\textit{morph}}\left[\text{STEM}: \textit{stem}\right]$

b. ${}_{\textit{affix-morph}}\left[\text{AFFIX}: \textit{affix}\right]$

Moreover, *affix* has two subtypes:

(21) $\textit{affix} \Rightarrow \textit{prefix} \vee \textit{suffix}$

Thus, (18) is a 3rd person singular verb form whose stem is unspecified.

Let us assume that the interpretation of a complex type is equivalent to the disjunction of all of its subtypes. Now, suppose that our lexicon contained only two instances of *verb-stems*, namely *walk* and *meet*. Then (18) would evaluate to exactly two fully specified word forms, where *verb-stem* was expanded to the signs for *walk* and *meet* respectively. Example (22) illustrates the first of these options.

[9] See (Riehemann, 1992) for a detailed working out of this idea for German derivational morphology.

(22)

$$
{}_{\mathit{3ps}}\begin{bmatrix}
\text{PHON}: & \boxed{1} \frown \boxed{2} \\
\text{MORPH}: & {}_{\mathit{affix\text{-}morph}}\begin{bmatrix}
\text{STEM}: & {}_{\mathit{verb\text{-}stem}}\begin{bmatrix}
\text{PHON}: & \boxed{1}\langle \text{w ɔː k} \rangle \\
\text{SYNSEM}: & \begin{bmatrix}\text{CAT}: \mathit{verb}\end{bmatrix}
\end{bmatrix} \\
\text{AFFIX}: & {}_{\mathit{suffix}}\begin{bmatrix}\text{PHON}: \boxed{2}\langle s \rangle\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

Of course, this statement of suffixation would have to be slightly enriched to allow for the familiar allomorphic alternation. -s∼z∼Iz. The first pair of allomorphs can be handled by treating the suffix as unspecified for voicing, together with a voicing assimilation rule similar to the homorganic nasal rule in (10). The third allomorph would admit an analysis similar to that which we propose for French schwa in §6.

A second comment on (22) is that the information about ordering of affixes relative to the stem should be abstracted into a more general pair of statements (one for prefixes and one for suffixes) which would apply to all morphologically complex lexical signs (e.g. of type *affixed*); this is straightforward to implement:

(23) a.

$$
{}_{\mathit{affixed}}\begin{bmatrix}
\text{PHON}: & \boxed{2} \frown \boxed{1} \\
\text{MORPH}: & \begin{bmatrix}
\text{STEM}|\text{PHON}: & \boxed{1} \\
\text{AFFIX}: & {}_{\mathit{prefix}}\begin{bmatrix}\text{PHON}: \boxed{2}\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

b.

$$
{}_{\mathit{affixed}}\begin{bmatrix}
\text{PHON}: & \boxed{1} \frown \boxed{2} \\
\text{MORPH}: & \begin{bmatrix}
\text{STEM}|\text{PHON}: & \boxed{1} \\
\text{AFFIX}: & {}_{\mathit{suffix}}\begin{bmatrix}\text{PHON}: \boxed{2}\end{bmatrix}
\end{bmatrix}
\end{bmatrix}
$$

Given this constraint, it is now unnecessary to specify the phonology attribute for feature structures like (22).

Additionally, it is straightforward to prevent multiple copies of the plural suffix from being attached to a word by ensuring that *3ps* and *verb-stem* are disjoint.

3.3 Morphophonological Operations

In and of itself, HPSG imposes no restrictions on the kind of operations which can be performed in the course of composing morphemes into words, or words into phrases. As an illustration, consider the data from German verb inflections considered by (Krieger et al., 1993). As they point out, the second person singular present inflection *-st* has three different allomorphs, phonologically conditioned by the stem:

(24)	sag+st	arbaIt+əst	mIks+t
	'say'	'work'	'mix'

Although the main thrust of their paper is to show how a FST treatment of this allomorphy can be incorporated into an HPSG-style morphological analysis, from a purely formal point of view, the FST is redundant. Since the lexical sign incorporates the phonologies of both stem and affix, segments can be freely inserted or deleted in constructing the output phonology. This is exemplified in (25) for *arbeitest* and *mixt* respectively.

(25) a.

$$
{}_{2ps}\left[\begin{array}{ll}
\text{PHON}: & \boxed{1} \frown \text{ə} \frown \boxed{2} \\
\text{MORPH}: & \left[\begin{array}{ll}\text{STEM}: & \boxed{1}\langle \ldots \{t, d\}\rangle \\ \text{SUFFIX}: & \boxed{2}\langle s\ t\rangle\end{array}\right] \\
\text{SYN|LOC|HEAD|AGR}: & \left[\begin{array}{ll}\text{NUM}: & sg \\ \text{PER}: & 2\end{array}\right]
\end{array}\right]
$$

b.

$$
{}_{2ps}\left[\begin{array}{ll}
\text{PHON}: & \boxed{1} \frown \boxed{2} \\
\text{MORPH}: & \left[\begin{array}{ll}\text{STEM}: & \boxed{1}\langle \ldots \{s, z, x\}\rangle \\ \text{SUFFIX}: & \langle s\rangle \frown \boxed{2}\langle t\rangle\end{array}\right] \\
\text{SYN|LOC|HEAD|AGR}: & \left[\begin{array}{ll}\text{NUM}: & sg \\ \text{PER}: & 2\end{array}\right]
\end{array}\right]
$$

That is, we can easily stipulate that ə is intercalated in the concatenation of stem and suffix if the stem ends with a dental stop (i.e either *t* or *d*); and that the *s* of the suffix is omitted if the stem ends with alveolar or velar fricative. Although an actual analysis along these lines would presumably be stated as a conditional, depending on the form of the stem, the point remains that all the information needed for manipulating the realisation of the suffix (including the fact that there is a morpheme boundary) is already available without resorting to two level rules. Of course, the question which this raises is whether such operations should be permitted, given that they appear to violate the spirit of a constraint-based approach. The position we shall adopt in this paper is that derivations like (25) should in fact be eschewed. That is, we will adopt the following restriction:

Phonological Compositionality:

The phonology of a complex form can only be produced by either unifying or concatenating the phonologies of its parts.

We believe that some general notion of phonological compositionality is methodologically desirable. The specific formulation of the principle given above is intended to ensure that information-combining operations at the phonological level are monotonic, in the sense that all the information in the operands is preserved in the result. As we have just seen, the constraint-based approach does not guarantee this without such an additional restriction.

4 Terêna nasalisation

4.1 Introduction

Terêna is an Arawakan language spoken in Brazil, described by Bendor-Samuel (1970). The category of first person is marked by a phenomenon of nasalisation, effecting both nouns and verbs, as the data in (26) illustrates.

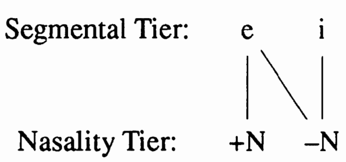
(26)

3rd person		1st person	
e'moʔu	*his word*	ẽ'mõʔũ	*my word*
'ayo	*his brother*	'ãỹõ	*my brother*
'owoku	*his house*	'õw̃õ^{ŋ}gu	*my house*
'piho	*he went*	'^{m}biho	*I went*
a'ɥaʔaʃo	*he desires*	ã'^{n}ʒaʔaʃo	*I desire*

Observe that the segments of the first person words in (26) are all nasalised until the first (oral) obstruent. If there is no such obstruent then the whole word is nasalised. We shall ignore the voicing alternation going on here (e.g. p∼b) since it is not contrastive in the language.

Before proceeding to the analysis, we introduce the autosegmental notation (Goldsmith, 1990) in which the analysis is couched. Consider the autosegmental representation in (27).

(27)



Bird & Ellison (1992) have given a procedure for interpreting such a diagram as the set of "surface" forms that are compatible with the diagram, where lines indicate temporal overlap (Bird & Klein, 1990). Diagram (27) describes a nasalised *e*, followed by non-nasalised *e* and *i*. Under the interpretation procedure, this diagram denotes a set of strings, including ⟨ẽ e i⟩.[10] The next step is to define the concatenation of diagrams like (27) in terms of our feature structure notation.

(28) **Concatenation of Autosegmental Diagrams:**
Suppose that TIER_1 and TIER_2 are two attributes (corresponding to autosegmental tiers),

[10] Although two copies of the *e* have been produced, this carries no implication for the relative durations of the *e* and the *i*, as explained in (Bird & Ellison, 1992).

and that a_i and b_j are autosegments on these tiers (respectively). Then concatenation of diagrams is defined in terms of list concatenation as follows:

$$\begin{bmatrix} \text{TIER}_1 : & \langle a_1 \cdots a_k \rangle \\ \text{TIER}_2 : & \langle b_1 \cdots b_{k'} \rangle \end{bmatrix} \frown \begin{bmatrix} \text{TIER}_1 : & \langle a_l \cdots a_s \rangle \\ \text{TIER}_2 : & \langle b_{l'} \cdots b_{s'} \rangle \end{bmatrix} = \begin{bmatrix} \text{TIER}_1 : & \langle a_1 \cdots a_k \rangle \frown \langle a_l \cdots a_s \rangle \\ \text{TIER}_2 : & \langle b_1 \cdots b_{k'} \rangle \frown \langle b_{l'} \cdots b_{s'} \rangle \end{bmatrix}$$

4.2 Analysis

Equiped with the autosegmental notation of (27) and the concatenation of (28), we are now able to give part of the lexical entry for the first person marker in Terêna.[11] Note that the type *nasal-spreading* will be defined in (33).

(29)

$$_{1ps}\begin{bmatrix} \text{PHON}: & (\boxed{1} \frown \boxed{2}) \wedge \textit{nasal-spreading} \\ \text{MORPH}: & _{\textit{affix-morph}}\begin{bmatrix} \text{ROOT}: & _{\textit{root}}\begin{bmatrix} \text{PHON}: \boxed{2} \end{bmatrix} \\ \text{AFFIX}: & _{\textit{prefix}}\begin{bmatrix} \text{PHON}: \boxed{1} \; _{\textit{phon}}\begin{bmatrix} \text{SEG}: & \langle\rangle \\ \text{NAS}: & \langle +N \rangle \end{bmatrix} \end{bmatrix} \end{bmatrix} \\ \text{SYNSEM}|\text{AGR}: & _{\textit{agr}}\begin{bmatrix} \text{NUM}: & \textit{sg} \\ \text{PER}: & 1 \end{bmatrix} \end{bmatrix}$$

Given (23), the feature structure in (29) actually simplifies to the following (where *1ps* is assumed to be a subtype of *affixed*):

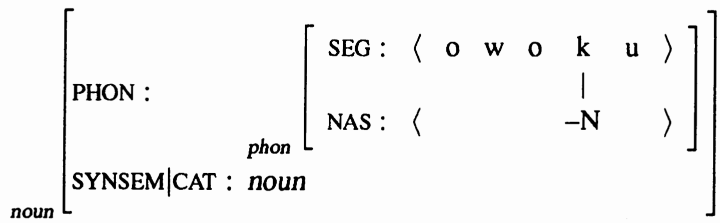
(30)

$$_{1ps}\begin{bmatrix} \text{PHON}: & \textit{nasal-spreading} \\ \text{MORPH}|\text{AFFIX}: & _{\textit{prefix}}\begin{bmatrix} \text{PHON}: \; _{\textit{phon}}\begin{bmatrix} \text{SEG}: & \langle\rangle \\ \text{NAS}: & \langle +N \rangle \end{bmatrix} \end{bmatrix} \\ \text{SYNSEM}|\text{AGR}: & _{\textit{agr}}\begin{bmatrix} \text{NUM}: & \textit{sg} \\ \text{PER}: & 1 \end{bmatrix} \end{bmatrix}$$

[11] We assume that the SYNSEM of the root will be transferred to the SYNSEM of the overall sign by a constraint like (49). We also assume that roots are unspecified for agreement.

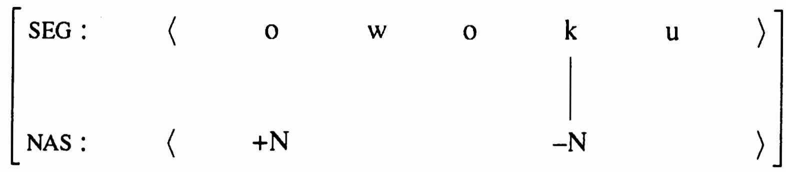
The phonology attribute of the prefix specifies a floating +*N* autosegment which is prefixed to the phonology of the root morpheme. Here then is part of the lexical entry for the noun *house*.

(31)



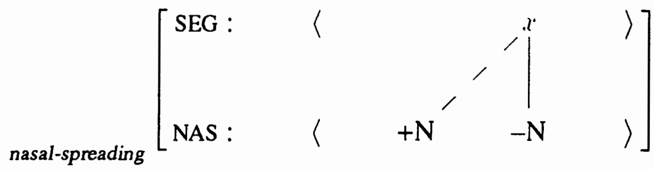
When the ROOT attribute of (29) is specialised to the sign in (31), the resulting sign has the following phonology attribute:

(32)



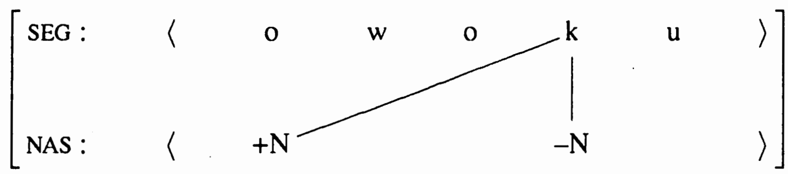
Now we need to adopt an association rule. Let the prosodic type *nasal-spreading* be defined as follows:

(33)



Under the semantics defined by Bird & Ellison (1992), (33) corresponds to a regular expression describing all forms licensed by the rule. For present purposes, it suffices to state that the type *nasal-spreading* denotes all linguistic forms compatible with the association rule, i.e. all forms that do not match its structural description, along with all forms that match its structural change. The effect of the rule on (32) is shown below:[12]

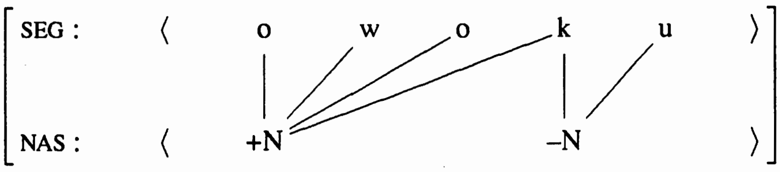
(34)



Again, under the semantics defined by Bird & Ellison (1992), both tiers are forced to occupy the same temporal extent. This follows from the fact that both tiers are taken to describe the same speech interval. Consequently, the temporal overlaps required by (34) are actually those given in (35).

[12]The way that a rule like (33) is applied to (32) is shown by Bird & Ellison (1992) to involve the automaton operation of intersection.

(35)

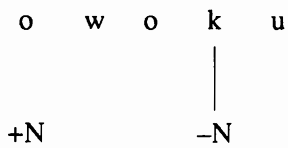


This same approach will work for the other words in our dataset which have a blocking obstruent, such as ['piho] and [a'ɥaʔaʃo]. The remaining two forms, [e'moʔu] and ['ayo], are straightforward. They have no lexical specification of a nasal autosegment, and so do not meet the requirements of the nasal assimilation rule. When these morphemes are assigned +*N* by the first person morpheme, this autosegment automatically has the whole word as its domain.

4.3 Discussion

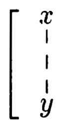
It is perhaps interesting to compare the analysis presented above with a more traditional autosegmental analysis. Recall that for the word ['õw̃õ^{ŋ}gu] we had the following representation prior to application of the association rule:

(32)

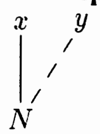


In a standard autosegmental analysis we would require the following two rules, where x and y denote arbitrary autosegments.

(36) a. **Initial association**

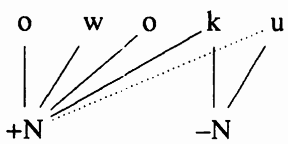


b. **Nasal spreading**



The first rule adds an association line between the first two elements of each tier, while the second rule adds further associations, so long as each new line does not cross an existing line. The difficulty with this approach is that rule (36b) must be defeasible. It is not allowed to add the association line (represented as a dotted line) below, even though its structural description is met.

(37)



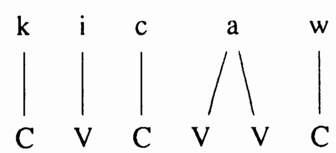
Therefore, associating the floating nasal autosegment to the leftmost *o* and then spreading associations rightwards is not the best option in the current context. Rather, we have chosen instead to associate the nasal autosegment to the lexically associated obstruent (creating a contour segment), and then allowing our principles of temporal interpretation to do the spreading automatically. This approach applies more generally to autosegmental spreading and blocking.

5 Sierra Miwok templatic morphology

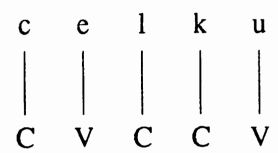
5.1 Descriptive overview

Goldsmith (1990:83–95) uses data involving Sierra Miwok verb stems to illustrate morphologically determined alternations in skeletal structure. He discusses three of the four types of stem, where the division into types depends primarily on the syllable structure of the basic form, which is the form used for the present tense. The three types are given the following autosegmental representations by Goldsmith:

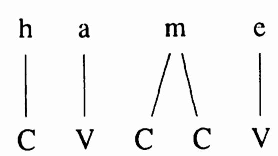
(38) a. Type I



b. Type II



c. Type III



As shown in (39), each type has forms other than the basic one, depending on the morphological or grammatical context; these additional forms are called second, third and fourth stems.

Although the associations of vowels and consonants exhibited above are taken as definitional for the three stem Types, from the data in (39), it appears that the distinction is only relevant to so-called Basic stem forms.

(39)

Gloss	Basic stem	Second stem	Third stem	Fourth stem
Type I				
bleed	kicaaw	kicaww	kiccaw	kicwa
jump	tuyaaŋ	tuyaŋŋ	tuyyaŋ	tuyŋa
take	patɨɨt	patɨtt	pattɨt	pattɨ
roll	huteel	hutell	huttel	hutle
Type II				
quit	celku	celukk	celluk	celku
go home	woʔlu	woʔull	woʔʔul	woʔlu
catch up with	nakpa	nakapp	nakkap	nakpa
spear	wimki	wimikk	wimmik	wimki
Type III				
bury	hamme	hameʔʔ	hammeʔ	hamʔe
dive	ʔuppi	ʔupiʔʔ	ʔuppiʔ	ʔupʔi
speak	liwwa	liwaʔʔ	liwwaʔ	liwʔa
sing	mɨlli	mɨliʔʔ	mɨlliʔ	mɨlʔi

5.2 Segmental Analysis

Goldsmith (1990:84ff) has shown just how complex a traditional segmental account of Sierra Miwok would have to be, given the assumption that all of the stem forms are derived by rule from a single underlying string of segments. Here, we simplify Goldsmith's analysis so that it just works for Type I stems. The left hand column of (40) contains four rules, and these are restricted to the different forms according to the second column.

(40)

Rules	Form	Second	Third	Fourth
		k i c a a w	k i c a a w	k i c a a w
$V_i \rightarrow \emptyset / C — V_i C]$	all	k i c a w	k i c a w	k i c a w
$C_i \rightarrow C_i C_i / —]$	2	k i c a w w	—	—
$C_i \rightarrow C_i C_i / [CV — V$	3	—	k i c c a w	—
$VC] \rightarrow CV$	4	—	—	k i c w a
		k i c a w w	k i c c a w	k i c w a

Thus, the first rule requires that a vowel V_i is deleted if it occurs after a consonant and immediately before an identical vowel V_i which in turn is followed by a stem-final consonant.

Goldsmith soundly rejects this style of analysis in favour of an autosegmental one. As Bird & Ladd (1991) have also noted, Goldsmith's discussion strongly favours a declarative approach.

> This analysis, with all its morphologically governed phonological rules, arbitrary rule ordering, and, frankly, its mind-boggling inelegance, ironically misses the most basic point of the formation of the past tense in Sierra Miwok. As we have informally noted,

all the second stem forms are of the shape CVCVCC, with the last consonant a geminate, and the rules that we have hypothetically posited so far all endeavor to achieve that end without ever directly acknowledging it. (Goldsmith, 1990:87)

5.3 Analysis

We shall not attempt here to give a general encoding of association, although the technique used in §4 and §6 could be applied to achieve this end. Moreover, like Goldsmith we shall ignore the role of syllable structure in the data, though it clearly does play a role. Instead, we will confine our attention to the manner in which skeletal slots are linked to the consonant and vowel melodies. Consider again the skeletal structure of Type I verb stems shown above in (38a). As Goldsmith (1990) points out, there is a closely related representation which differs only in that the *CV* information is split across two tiers (and which allows a much more elegant account of metathesis and gemination):

(41)

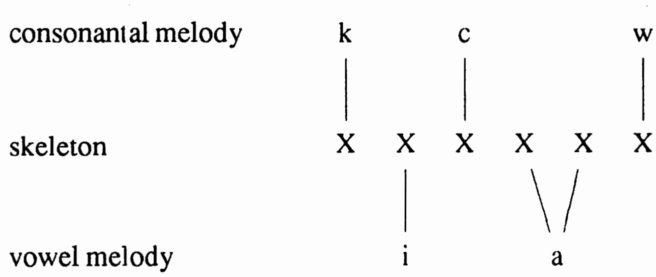


Diagram (41) can be translated into the following feature structure:

(42)

$$\begin{bmatrix} \text{CON}: & \langle \boxed{1}\,\text{k}\,\boxed{3}\,\text{c}\,\boxed{5}\,\text{w}\rangle \\ \text{VOW}: & \langle \boxed{2}\,\text{i}\,\boxed{4}\,\text{a}\rangle \\ \text{SKEL}: & \langle \boxed{1}\;\boxed{2}\;\boxed{3}\;\boxed{4}\;\boxed{4}\;\boxed{5}\rangle \end{bmatrix}_{\textit{phon}}$$

That is, since association in (41) consists of slot-filling (rather than the more general temporal interpretation), it can be adequately encoded by coindexing.

5.4 Basic Stem Forms

The analysis starts from the assumption that the Sierra Miwok lexicon will contain minimally redundant entries for the three types of verb root. Let us consider the root corresponding to the basic stem form *kicaaw*. We take the unpredictable information to be the consonantal and vowel melodies, the valency, the semantics, and the fact it is a Type I verb stem. This is stated as (43), together with the declaration that *lex-bleed* is a subtype of *v-root-I*.

(43) $$\left[\begin{array}{ll} \text{PHON}: & {}_{\textit{phon}}\left[\begin{array}{ll} \text{CON}: & \langle \text{k c w} \rangle \\ \text{VOW}: & \langle \text{i a} \rangle \end{array}\right] \\ \text{SYNSEM}: & {}_{\textit{synsem}}\left[\begin{array}{ll} \text{SUBCAT}: & \langle \mathit{NP} \rangle \\ \text{SEM}: & \mathit{bleed} \end{array}\right] \end{array}\right]_{\textit{lex-bleed}}$$

Notice that we have said nothing about how the melodies are anchored to a skeleton—this will be a task for the morphology. Additionally, this entry will inherit various properties by virtue of its type *v-root-I*. The three types of verb root share at least one important property, namely that they are all verbs. This is expressed in the next two declarations:

(44) a. $\mathit{v\text{-}root} \Rightarrow \mathit{v\text{-}root\text{-}I} \vee \mathit{v\text{-}root\text{-}II} \vee \mathit{v\text{-}root\text{-}III}$

b. $${}_{\textit{v-root}}\left[\text{SYNSEM}|\text{CAT}: \ \mathit{verb}\right]$$

We will also assume, for generality, that every *v-root* is a *root*, and that every *root* is a *morph*.

The next step is to show how a *v-root-I* like (43) undergoes morphological modification to become a basic verb stem; that is, a form *with* skeletal structure. Our encoding of the morphology will follow the lines briefly sketched in Section 3.2.

We begin by stating types which encode the patterns of skeletal anchoring associated with the three types of basic stem.

(45) $\mathit{phon} \Rightarrow \mathit{template\text{-}I} \vee \mathit{template\text{-}II} \vee \mathit{template\text{-}III}$

The appropriateness constraints on these types are given in (46). As an aid to readability, the numerical tags are supplemented with a C or V to indicate the type of value involved.

(46) a. $${}_{\textit{template-I}}\left[\begin{array}{ll} \text{CON}: & \langle \boxed{1}C\ \boxed{3}C\ \boxed{5}C \rangle \\ \text{VOW}: & \langle \boxed{2}V\ \boxed{4}V \rangle \\ \text{SKEL}: & \langle \boxed{1}C\ \boxed{2}V\ \boxed{3}C\ \boxed{4}V\ \boxed{4}V\ \boxed{5}C \rangle \end{array}\right]$$

b. $${}_{\textit{template-II}}\left[\begin{array}{ll} \text{CON}: & \langle \boxed{1}C\ \boxed{3}C\ \boxed{5}C \rangle \\ \text{VOW}: & \langle \boxed{2}V\ \boxed{4}V \rangle \\ \text{SKEL}: & \langle \boxed{1}C\ \boxed{2}V\ \boxed{3}C\ \boxed{4}V\ \boxed{5}C \rangle \end{array}\right]$$

c. $${}_{\textit{template-III}}\left[\begin{array}{ll} \text{CON}: & \langle \boxed{1}C\ \boxed{3}C \rangle \\ \text{VOW}: & \langle \boxed{2}V\ \boxed{4}V \rangle \\ \text{SKEL}: & \langle \boxed{1}C\ \boxed{2}V\ \boxed{3}C\ \boxed{3}C\ \boxed{4}V \rangle \end{array}\right]$$

Each of these types specialises the constraints on the type *phon*, and each can be unified with the *phon* value which was earlier assigned to the root form of *kicaaw* in (43). In particular, the conjunction of constraints given in (47) evaluates to (42), repeated here:

(47)
$$\left[\begin{array}{ll} \text{CON}: & \langle \text{k c w}\rangle \\ \text{VOW}: & \langle \text{i a}\rangle \end{array}\right]_{phon} \wedge \textit{template-I}$$

(42)
$$\left[\begin{array}{ll} \text{CON}: & \langle \boxed{1}\,\text{k}\,\boxed{3}\,\text{c}\,\boxed{5}\,\text{w}\rangle \\ \text{VOW}: & \langle \boxed{2}\,\text{i}\,\boxed{4}\,\text{a}\rangle \\ \text{SKEL}: & \langle \boxed{1}\ \boxed{2}\ \boxed{3}\ \boxed{4}\ \boxed{4}\ \boxed{5}\rangle \end{array}\right]_{phon}$$

However, we also need to specify the dependency between the three types of verb root, and the corresponding phonological exponents which determine the appropriate basic stem forms (cf. Anderson (1992:133)). As a first attempt to express this, let us say that *stem* can be either *basic* or *affixed*:

(48) $\textit{stem} \Rightarrow \textit{affixed} \vee \textit{basic}$

Type declaration (48) ensures that *basic* will inherit from *stem* the following constraint, namely that its SYNSEM value is to be unified with its MORPH's ROOT's SYNSEM value:

(49)
$$\left[\begin{array}{ll} \text{SYNSEM}: & \boxed{1} \\ \text{MORPH}|\text{ROOT}|\text{SYNSEM}: & \boxed{1} \end{array}\right]_{stem}$$

We could now disjunctively specify the following three sets of constraints on *basic*:

(50) a.
$$\left[\begin{array}{ll} \text{PHON}: & \textit{phon} \wedge \textit{template-I} \\ \text{MORPH}: & \left[\text{ROOT}: \ \textit{v-root-I}\right] \end{array}\right]_{basic}$$

b.
$$\left[\begin{array}{ll} \text{PHON}: & \textit{phon} \wedge \textit{template-II} \\ \text{MORPH}: & \left[\text{ROOT}: \ \textit{v-root-II}\right] \end{array}\right]_{basic}$$

c.
$$\left[\begin{array}{ll} \text{PHON}: & \textit{phon} \wedge \textit{template-III} \\ \text{MORPH}: & \left[\text{ROOT}: \ \textit{v-root-III}\right] \end{array}\right]_{basic}$$

Although the example in question does not dramatise the fact, this manner of encoding morphological dependency is potentially very redundant, since *all* the common constraints on *basic* have to be repeated each time.[13] In this particular case, however, it is easy to locate the dependency in the *phon* value of the three subtypes of *v-root*, as follows:

(51)
$$\begin{array}{l} {}_{\textit{v-root-I}}\left[\text{PHON}: \ \textit{template-I}\right] \\ {}_{\textit{v-root-II}}\left[\text{PHON}: \ \textit{template-II}\right] \\ {}_{\textit{v-root-III}}\left[\text{PHON}: \ \textit{template-III}\right] \end{array}$$

We then impose the following constraint on *basic*:

(52)
$${}_{\textit{basic}}\left[\begin{array}{ll} \text{PHON}: & \boxed{1} \\ \text{MORPH}|\text{ROOT}: & {}_{\textit{v-root}}\left[\text{PHON}: \ \boxed{1}\right] \end{array}\right]$$

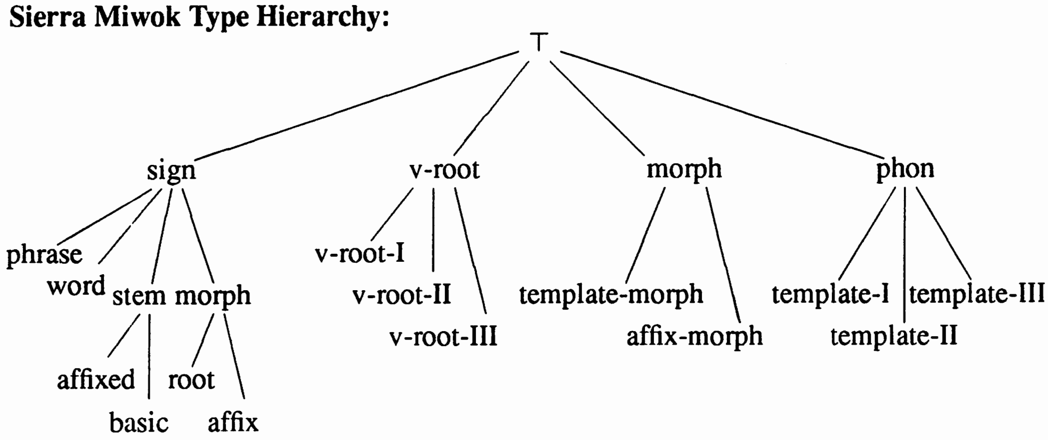
By iterating through each of the subtypes of *v-root*, we can infer the appropriate value of PHON within MORPH's ROOT, and hence infer the value of PHON at the top level of the feature structure. Example (53) illustrates the result of specialising the type *v-root* to *lex-bleed*:

(53)
$${}_{\textit{basic}}\left[\begin{array}{ll} \text{PHON}: & \boxed{6}\ {}_{\textit{phon}}\left[\begin{array}{ll} \text{CON}: & \langle \boxed{1}\text{k}\ \boxed{3}\text{c}\ \boxed{5}\text{w}\rangle \\ \text{VOW}: & \langle \boxed{2}\text{i}\ \boxed{4}\text{a}\rangle \\ \text{SKEL}: & \langle \boxed{1}\ \boxed{2}\ \boxed{3}\ \boxed{4}\ \boxed{4}\ \boxed{5}\rangle \end{array}\right] \\ \text{SYNSEM}: & \boxed{7}\ {}_{\textit{synsem}}\left[\begin{array}{ll} \text{CAT}: & \textit{verb} \\ \text{SUBCAT}: & \langle NP\rangle \\ \text{SEM}: & \textit{bleed} \end{array}\right] \\ \text{MORPH}: & {}_{\textit{template-morph}}\left[\text{ROOT}: \ {}_{\textit{v-root-I}}\left[\begin{array}{ll} \text{PHON}: & \boxed{6} \\ \text{SYNSEM}: & \boxed{7} \end{array}\right]\right] \end{array}\right]$$

Exactly the same mechanisms will produce the basic stem for the other two types of verb root. For an account of the other alternations presented in Goldsmith's paradigm, see (Klein, 1993). We conclude with a display of the type hierarchy proposed for Sierra Miwok:

[13] In an attempt to find a general solution to this problem in the context of German verb morphology, Krieger et al. (1993) adopt the device of 'distributed disjunction' to iteratively associate morphosyntactic features in one list with their corresponding phonological exponents in another list.

(54) **Sierra Miwok Type Hierarchy:**



6 French Schwa

6.1 Descriptive Overview

Unlike schwa in English, the French schwa (or mute *e*) is a full vowel, usually realised as the low-mid front rounded vowel œ (and sometimes as the high-mid front rounded vowel ø in certain predictable environments). Its distinctive characteristic is that under certain conditions, it fails to be realised phonetically.[14] From now on, we will use the term 'schwa' to refer to the vowel with this characteristic, rather than to the segment ə.

Although schwa is associated with orthographic *e*, not all *e*s will concern us here. For example, the orthographic *e* of *samedi* [sam.di] 'Saturday' can be taken to indicate that the previous vowel should not be nasalised, while the final *e* of *petite* [pœ.tit] indicates that the final *t* should be pronounced. In morphology, orthographic *e* marks feminine gender, first-conjugation verbs and subjunctive mood.

Instead, we shall be concerned with the pattern of realisation and non-realisation exhibited by schwa—a pattern which we interpret as grounded in the alternation of two allophones of schwa: œ and ∅ (zero). This alternation is manifested in forms like (55),[15] where the dots indicate syllable boundaries.

(55) a. six melons [si.mœ.lɔ̃] ~ [sim.lɔ̃]

b. sept melons [sɛt.mœ.lɔ̃], *[sɛtmlɔ̃]

Observe that while *six melons* can be pronounced with or without the schwa, *sept melons* requires the schwa in order to break up the *tml* cluster that would otherwise be formed. Unfortunately, the conditions on the distribution of schwa are not as simple (and purely phonological) as this example

[14]The data used in this section is drawn primarily from the careful descriptive work of Morin (1978) and Tranel (1987b). The particular approach to French schwa described in the following paragraphs most closely resembles the analysis of Tranel (1987a). We are grateful to Bernard Tranel for helpful discussions on French schwa, although any empirical or formal shortcomings in this section remain our own responsibility.

[15]We shall not be concerned with another œ~∅ alternation known as elision. This is a phonologically conditioned allomorphy involving alternations such as *le~l'*, for example, *le chat* [lœ.ʃa], *l'ami* [la.mi].

implies. As we shall see, schwa alternation in French is governed by an interesting mixture of lexical and prosodic constraints.

In the remainder of this section, we dispel the initial hypothesis that arises from (55), namely that schwa alternation is to be treated as a general epenthesis process[16]. Consider the following data (Morin, 1978:111).

(56)

Cluster	Requires Schwa		Schwa Impossible	
rdr	bordereau	[bɔr.dœ.ro]	perdrix	[pɛr.dri]
rʃ	derechef	[dœ.rœ.ʃɛf]	torchon	[tɔr.ʃɔ̃]
skl	squelette	[skœ.lɛt]	sclérose	[skle.roz]
ps	dépecer	[de.pœ.se]	éclipser	[ek.lip.se]

The table in (56) gives data for the clusters [rdr], [rʃ], [skl] and [ps]. In the first column of data, the œ is obligatory, while in the second column, it is absent. Thus, we see that the location of œ cannot be predicted on phonotactic grounds alone. Consequently, we shall assume that schwa must be encoded in lexical representations. Note that it is certainly not the case that a lexical schwa will be posited wherever there is an orthographic *e*. Consider the data in (57), where these orthographic *e*s are underlined.

(57)

Orthography	With Schwa	Without Schwa
bordereau	[bɔr.dœ.ro]	—
fais-le	[fɛ.lø]	—
six melons	[si.mœ.lɔ̃]	[sim.lɔ̃]
pelleterie	—	[pɛl.tri]

In a purely synchronic analysis there is no basis for discussing an alternating vowel for *bordereau*, *fais-le* and *pelleterie.*

Accordingly, we begin our analysis with three background assumptions: the alternating schwa is (i) prosodically conditioned, (ii) lexically conditioned, and (iii) not in direct correspondence with orthographic *e*. In the next section we present a generative analysis of schwa due to Dell, followed by an autosegmental analysis due to Tranel. We conclude with our own, syllable-based analysis.

6.2 A traditional generative analysis

The traditional approach to vowel-zero alternations is to employ either a rule of epenthesis or a deletion rule. Dell discusses the case of the word *secoue*, whose pronunciation is either [sku] or [sœku], in a way that parallels (55).

> In order to account for alternations such as that between [sku] and [sœku] there are two possibilities: the first consists of positing the underlying representation /sku/ where no vowel appears between /s/ and /k/, and to assume that there exists a phonological rule

[16]This epenthesis hypothesis was advanced by Martinet (1972).

of epenthesis that inserts a vowel œ between two consonants at the beginning of a word when the preceding word ends in a consonant. ... The second possibility is preferable: the vowel [œ] that appears in *Jacques secoue* is the realisation of an underlying vowel /ə/ which can be deleted in certain cases. We will posit the VCE_1 rule, which deletes any /ə/ preceded by a single word-initial consonant when the preceding word ends in a vowel.

$$VCE_1: \quad ə \rightarrow \emptyset \,/\, V \,\#_1\, C \,—$$

(Dell, 1980:161f).

Suppose we were to begin our analysis by asking the question: how are we to express the generalisation about schwa expressed in the above rule? Since our declarative, monostratal framework does not admit deletion rules, we would have to give up. As we shall see below, however, we begin with a different question: how are we to express the *observation* about the distribution of schwa which Dell encodes in the above rule?

There is another good reason for taking this line. As it happens, there is an empirical problem with the above rule, which Dell addresses by admitting a potentially large number of lexical exceptions to the rule (Dell, 1980:206), and by making *ad hoc* stipulations (Dell, 1980:234f). However, adding diacritics to lexical entries to indicate which rules they undergo and employing rules that count # boundaries would seem to complicate a grammar formalism unnecessarily. As we saw above for the discussion of the word *bordereau*, in the approach taken here, we have the choice between positing a stable œ or one which alternates with zero (i.e. a schwa) in the lexicon, whereas Dell must mark lexical items to indicate which rules they must not undergo. There is also some evidence for a distinction between the phonetic identity of the œ allophone of schwa and the phonetic identity of a non-alternating lexical œ in some varieties of French, requiring that the two be distinguished phonologically (Morin, 1978:102f).

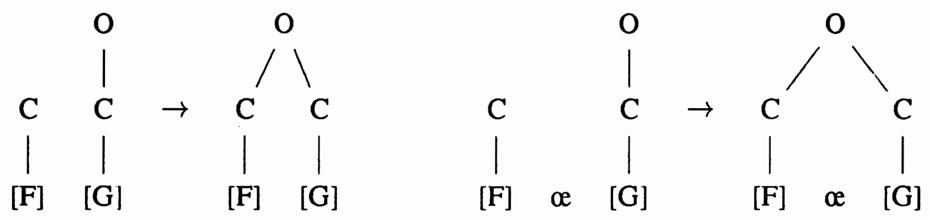
Thus, the fact that Dell's analysis involves deletion does not provide a significant stumbling block to our approach. However, Dell employs another procedural device, namely rule ordering, in the application of the rule. In discussing the phrase *vous me le dites* [vu.m(œ).l(œ).dit], in which either schwa (but not both) may be omitted, Dell writes:

> VCE_1 begins on the left and first deletes the schwa of *me*, producing /vu#m#lə#dit/. But VCE_1 cannot operate again and delete the schwa of *le*, for, although this schwa was subject to the rule in the original representation, it no longer is once the schwa of *me* has been dropped. In other words, the first application of VCE_1 creates new conditions that prevent it from operating again in the following syllable (Dell, 1980:228).

Again, we are not interested in encoding Dell's particular generalisation, and in fact we are unable to. Rather, it is necessary to look at the underlying observation about the distribution of schwa. The observation is that schwa does not appear as its zero allophone in consecutive syllables. This observation is problematic for us, in that it refers to two levels of representation, an underlying (or lexical) level involving a schwa segment, and a surface level involving a zero allophone. We cannot formulate this observation monostratally. However, we can come up with a different observation, namely that the vowel is never omitted if the omission results in unacceptable syllable structure. In the case of Dell's example, *vous me le dites*, if both schwas are omitted the result is a [vml] cluster, which cannot be broken up into a valid coda-onset sequence. This new observation makes a different

Tranel gives two additional syllable formation rules, shown in (64).

(64) a. Onset accretion — b. Onset accretion across schwa



Restriction: must create a valid onset — Restriction: [F] must be word-initial

Rule (64a) incorporates as many consonants as possible into an onset, so long as the onset conforms to the phonotactic constraints of the language. Rule (64b), of most interest here, allows for a consonant to be incorporated into a following onset even if there is an intervening schwa, provided that the consonant is word-initial (and that the resulting onset is allowable). The intervening schwa remains unpronounced. Rule (64b), which is optional, correctly captures the alternations displayed in (63). This rule is restricted to apply word-initially "so as to avoid the generation of word-internal triliteral consonant clusters from underlying /CCəC/ sequences (compare *marguerite* /margərit/ [margərit] *[margrit] and *margrave* /margrav/ [margrav] *[margərav])" (Tranel, 1987a:852). Thus, although many CCC sequences are acceptable phonologically, they are not permitted if a schwa is available to break up the cluster.

We also note that Tranel's analysis (Tranel, 1987a) gives the correct result for cases of deletion of schwa in consecutive syllables. Consider the following data.

(65) a. *on ne se moque pas* [õn.smɔk.pɑ] (Valdman, 1976:120)
b. *sur le chemin* [syl.ʃmɛ̃] (Morin, 1978:82)

For both of these cases we observe an "underlying" C_1œC_2œ pattern, but where both œs are omitted and where C_1 syllabifies into the preceding coda and C_2 syllabifies into the following onset.

To conclude, we can summarise the empirical content of Tranel's analysis as follows:

(a) Every consonant must be syllabified.

(b) Schwa must be realised if it provides the syllable nucleus for an immediately preceding consonant which:

(i) cannot be sullabified into a coda, and

(ii) cannot form a permissible (word) onset with an immediately following consonant.

6.4 A constraint-based analysis

Given our formal semantics for the autosegmental notation, it would be a relatively straightforward matter to implement Tranel's analysis directly, especially since the rules only involve the building of structure, and there is no use of destructive processes. Tranel's analysis is fully declarative.

However, as it happens, there is no need for us to adopt the rich representation Tranel employs. We can simulate his analysis using a single tier (rather than two) while retaining a representation of syllable structure. Observe that the use of the CV tier and the melody tier was motivated solely by the need to have a floating autosegment, the œ. It is equivalent to collapse these two tiers, using the alternation œ$\sim\emptyset$ in place of the floating œ. However, we follow Tranel in representing syllable structure. We shall represent syllables as shown in (66).[17]

(66)
$$_{syl}\begin{bmatrix} \text{ONS}: & \textit{onset} \\ \text{NUC}: & \textit{nucleus} \\ \text{CODA}: & \textit{coda} \end{bmatrix}$$

An independent tier which represents syllable structure will be encoded as a sequence of such syllables, where the segmental constituents of the syllable structure are coindexed with a separate segmental tier, as defined in (67). Note that the indices in (67) range over lists which may be empty in the case of onsets and codas.

(67) a.
$$_{phrase}\begin{bmatrix} \text{SYLS}: \left\langle {}_{syl}\begin{bmatrix} \text{ONS}: & \boxed{1} \\ \text{NUC}: & \boxed{2} \\ \text{CODA}: & \boxed{3} \end{bmatrix} \right\rangle \frown \boxed{4} \\ \text{SEGS}: \boxed{1} \frown \boxed{2} \frown \boxed{3} \frown \boxed{5} \end{bmatrix} \quad :- \quad {}_{phrase}\begin{bmatrix} \text{SYLS}: & \boxed{4} \\ \text{SEGS}: & \boxed{5} \end{bmatrix}$$

b.
$$_{phrase}\begin{bmatrix} \text{SYLS}: & \langle\rangle \\ \text{SEGS}: & \langle\rangle \end{bmatrix}$$

The notation of (67) states that in order for something to be a well-formed phrase, its sequence of segments must be parsed into a sequence of well-formed syllables. In more familiar terms, one could paraphrase (67) as stating that the domain of syllabification in French is the phrase.

As a simple illustration of the approach, consider again the word *melons*. The proposed lexical representation for the phonology attribute of this word is [SEGS : ⟨m (œ) l ɔ̃⟩]. When we insist that any phrase containing this word must consist of a sequence of well-formed syllables, we can observe the following pattern of behaviour for *six melons*.

(68) a.
$$_{phrase}\begin{bmatrix} \text{SYLS}: \left\langle {}_{syl}\begin{bmatrix} \text{ONS}: & \langle \text{s} \rangle \\ \text{NUC}: & \langle \text{i} \rangle \\ \text{CODA}: & \langle\rangle \end{bmatrix} {}_{syl}\begin{bmatrix} \text{ONS}: & \langle \text{m} \rangle \\ \text{NUC}: & \langle \text{œ} \rangle \\ \text{CODA}: & \langle\rangle \end{bmatrix} {}_{syl}\begin{bmatrix} \text{ONS}: & \langle \text{l} \rangle \\ \text{NUC}: & \langle \tilde{\text{ɔ}} \rangle \\ \text{CODA}: & \langle\rangle \end{bmatrix} \right\rangle \\ \text{SEGS}: \langle \text{s i m œ l } \tilde{\text{ɔ}} \rangle \end{bmatrix}$$

[17]Our analysis is not crucially tied to this particular version of syllable structure, which is most closely related to the proposals of (Kahn, 1976; Clements & Keyser, 1983).

b.
$$\left[\begin{array}{l} \text{SYLS}: \left\langle {}_{syl}\left[\begin{array}{ll}\text{ONS}: & \langle \text{s}\rangle \\ \text{NUC}: & \langle \text{i}\rangle \\ \text{CODA}: & \langle \text{m}\rangle\end{array}\right] {}_{syl}\left[\begin{array}{ll}\text{ONS}: & \langle \text{l}\rangle \\ \text{NUC}: & \langle \tilde{\text{ɔ}}\rangle \\ \text{CODA}: & \langle\rangle\end{array}\right]\right\rangle \\ \text{SEGS}: \langle \text{s i m l } \tilde{\text{ɔ}}\rangle \end{array}\right]_{phrase}$$

Observe in the above example that the syllabic position of *m* is variable. In (68a) *m* is in an onset while in (68b) it is in a coda. Therefore, it is inappropriate to insist that the syllabic affiliation of segments is determined lexically. Rather, we have opted for the prosodic type *phrase*, insisting that anything of this type consists of one or more well-formed syllables (cf. (12)).

Now consider the case of the phrase *sept melons*. This is similar to the situation in (68), except that we must find a way of ruling out the *tml* cluster as a valid coda-onset sequence. We are not aware of any exhaustive study of possible french consonant clusters, although one can find discussions of particular clusters (e.g. Tranel (1987b:95ff) shows that CLj onset clusters are not tolerated). Consequently, the following proposals are necessarily preliminary, and are made more for the sake of being explicit than for their precise content.[18]

(69)
a. *onset* ⇒ *word-internal-onset* ∨ *word-initial-onset*
b. *word-internal-onset* ⇒ *(cons) (glide)* ∨ *obstruent liquid*
c. *word-initial-onset* ⇒ *word-internal-onset* ∨ *obstruent sonorant* ∨ *s stop liquid* ∨ *p n*
d. *coda* ⇒ *word-internal-coda* ∨ *word-final-coda*
e. *word-internal-coda* ⇒ *(cons)*
f. *word-final-coda* ⇒ *word-internal-coda* ∨ *(s) stop (liquid)*

Note that parentheses indicate optionality, so, for example, both onsets and codas are allowed to be null. Additional stipulations will be necessary to ensure that an intervocalic consonant is syllabified with the material to its right. We can do this by preventing an onsetless syllable from following a closed syllable, with the type *onset-max-1*.

(70)
$$\textit{onset-max-1} \equiv \neg\; {}_{phrase}\left\langle \ldots\; {}_{syl}\left[\text{CODA}: \textit{ne-list}\right] {}_{syl}\left[\text{ONS}: \textit{e-list}\right] \ldots \right\rangle$$

Now consider again the phrase *six melons*. The syllabification *[si.mœl.ɔ̃] would be represented as follows:

(71)
$$* \left\langle {}_{syl}\left[\begin{array}{ll}\text{ONS}: & \langle \text{s}\rangle \\ \text{NUC}: & \langle \text{i}\rangle\end{array}\right] {}_{syl}\left[\begin{array}{ll}\text{ONS}: & \langle \text{m}\rangle \\ \text{NUC}: & \langle \text{œ}\rangle \\ \text{CODA}: & {}_{ne\text{-}list}\langle \text{l}\rangle\end{array}\right] {}_{syl}\left[\begin{array}{ll}\text{ONS}: & \textit{e-list} \\ \text{NUC}: & \langle \tilde{\text{ɔ}}\rangle\end{array}\right]\right\rangle$$

[18]Note that some disjuncts in (69) are not simple types but lists, such as *s stop liquid*. We take this to be shorthand for a complex type (say, *s-stop-liquid*), defined as follows: ${}_{s\text{-}stop\text{-}liquid}\langle \textit{s stop liquid}\rangle$

Observe that this list of syllables contains a violation of (70), so [si.mœl.ɔ̃] is ruled out. Now that we have considered vowel-consonant-vowel (VCV) sequences, we shall move on to more complex intervocalic consonant clusters.

Although the constraints in (69) produce the desired result for VLLV clusters (L=liquid), by assigning each liquid to a separate syllable (Tranel, 1987b:97), there is still ambiguity with VOLV clusters (O=obstruent) which are syllabified as V.OLV according to Tranel. We can deal with this and similar ambiguities by further enriching the classification of syllables and imposing suitable constraints on syllable sequences. Here is one way of doing this, following the same pattern that we saw in (70).

(72) $$\textit{onset-max-2} \equiv \neg_{phrase}\left\langle \ldots\ {}_{syl}\!\left[\text{CODA}: \langle \cdots \textit{obs} \cdots \rangle\right]\ {}_{syl}\!\left[\text{ONS}: \neg\langle \cdots \textit{obs} \cdots \rangle\right] \ldots \right\rangle$$

This constraint states that it is not permissible to have an obstruent in a syllable coda if the following onset lacks an obstruent. Equivalently, we could say that if a syllable coda contains an obstruent then the following onset must also contain an obstruent. To see why these constraints are relevant to schwa, consider the case of *demanderions*, (also discussed by Tranel (1987b:97f)). The type declaration in (69b) rules out *[dœ.mɑ̃.drjɔ̃], since the underlined onset cluster is too complex. The constraint in (72) rules out *[dœ.mɑ̃d.rjɔ̃], where the obstruent *d* is assigned to the preceding syllable to leave an *rj* onset. The remaining two possible pronunciations are [dœ.mɑ̃.dœ.rjɔ̃], and [dœ.mɑ̃.dri.jɔ̃], as required. (Note that the *ions* suffix has the two forms [jɔ̃] and [ijɔ̃].)

Now let us consider the case of h-aspiré words. These vowel-initial words do not tolerate a preceding consonant being syllabified into the word-initial onset. What happens to the V.CV and V.OLV constraints when the second vowel is in the first syllable of an h-aspiré word, as we find in *sept haches* [sɛt.aʃ], *[sɛ.taʃ] and *quatre haches* [katr.aʃ], *[kat.raʃ], *[ka.traʃ]? Here, it would appear that Tranel's analysis breaks down. Our conjecture is that the constraints in (70) and (72) should only apply when the second syllable is not an h-aspiré syllable. So we need to introduce a further distinction in syllable types, introducing *ha-syl* for h-aspiré syllables and *nha-syl* for the rest.

(73) $$\textit{syl} \Rightarrow \textit{ha-syl} \vee \textit{nha-syl}$$

Now, *ha-syl* is defined as follows:

(74) $${}_{ha\text{-}syl}\!\left[\text{ONSET}: \textit{e-list}\right]$$

Accordingly, the constraints (70) and (72) are refined, so that the second syllable is of the type *nha-syl*. The revised constraints are given in (75).

(75) a. $$\textit{onset-max-1'} \equiv \neg_{phrase}\left\langle \ldots\ {}_{syl}\!\left[\text{CODA}: \textit{ne-list}\right]\ {}_{nha\text{-}syl}\!\left[\text{ONS}: \textit{e-list}\right] \ldots \right\rangle$$

b. $$\textit{onset-max-2'} \equiv \neg_{phrase}\left\langle \ldots\ {}_{syl}\!\left[\text{CODA}: \langle \cdots \textit{obs} \cdots \rangle\right]\ {}_{nha\text{-}syl}\!\left[\text{ONS}: \neg\langle \cdots \textit{obs}, \cdots \rangle\right] \right\rangle$$

Now, h-aspiré words will be lexically specified as having an initial *ha-syl*. However, we must not specify any more syllable structure than is absolutely necessary. Example (76) displays the required constraint for the word *haut*.

(76)
$$\left[\begin{array}{ll} \text{PHON}: & \left[\begin{array}{ll} \text{SYLS}: & \left\langle {}_{\textit{ha-syl}}\left[\text{NUC}: \langle \boxed{1}\ \text{o}\rangle\right]\right\rangle \\ \text{SEGS}: & \langle \boxed{1}\ \text{o}\rangle \end{array}\right]_{\textit{phon}} \\ \text{SYNSEM}|\text{CAT}: & \textit{noun} \end{array}\right]_{\textit{lexical-sign}}$$

It remains to show how this treatment of h-aspiré bears on schwa. Fortunately Tranel (1987b:94) has provided the example we need. Consider the phrase *dans le haut* [dɑ̃.lœ.o]. This contains the word *le* [l(œ)] which is lexically specified as having an optional œ, indicated by parentheses. There are three possible syllabifications, only the last of which is well-formed.

(77)

a. $$*\left\langle {}_{\textit{syl}}\left[\begin{array}{ll} \text{ONS}: & \langle \text{d}\rangle \\ \text{NUC}: & \langle \tilde{\text{ɑ}}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right] {}_{\textit{ha-syl}}\left[\begin{array}{ll} \text{ONS}: & \langle \text{l}\rangle \\ \text{NUC}: & \langle \text{o}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right]\right\rangle$$

b. $$*\left\langle {}_{\textit{syl}}\left[\begin{array}{ll} \text{ONS}: & \langle \text{d}\rangle \\ \text{NUC}: & \langle \tilde{\text{ɑ}}\rangle \\ \text{CODA}: & \langle \text{l}\rangle \end{array}\right] \left({}_{\textit{syl}}\left[\begin{array}{ll} \text{ONSET}: & \langle\rangle \\ \text{NUC}: & \langle \text{œ}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right]\right) {}_{\textit{ha-syl}}\left[\begin{array}{ll} \text{ONSET}: & \langle\rangle \\ \text{NUC}: & \langle \text{o}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right]\right\rangle$$

c. $$\left\langle {}_{\textit{syl}}\left[\begin{array}{ll} \text{ONS}: & \langle \text{d}\rangle \\ \text{NUC}: & \langle \tilde{\text{ɑ}}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right] {}_{\textit{syl}}\left[\begin{array}{ll} \text{ONSET}: & \langle \text{l}\rangle \\ \text{NUC}: & \langle \text{œ}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right] {}_{\textit{ha-syl}}\left[\begin{array}{ll} \text{ONSET}: & \langle\rangle \\ \text{NUC}: & \langle \text{o}\rangle \\ \text{CODA}: & \langle\rangle \end{array}\right]\right\rangle$$

The syllabification in (77a) is unavailable since the syllable corresponding to the word *haut* is lexically specified as *ha-syl*, which means that its onset must be an *e-list* from (74). The syllabification in (77b) is likewise unavailable since this consists of a syllable with a coda followed by a syllable without an onset, in contravention of (75a). This only leaves (77c), which corresponds to the attested form [dɑ̃.lœ.o].

We conclude this section with an example derivation for the phrase *on ne se moque pas* [õn.sm.ɔk.pɑ], which was presented in (65). We assume that at some stage of a derivation, the PHON attribute of a sign is as follows:

(78)
$$\left[\text{SEGS}: \langle \tilde{\text{o}}\rangle \frown \langle \text{n}\ (\text{œ})\rangle \frown \langle \text{s}\ (\text{œ})\rangle \frown \langle \text{m}\ \text{ɔ}\ \text{k}\rangle \frown \langle \text{p}\ \text{ɑ}\rangle\right]_{\textit{phon}}$$

When the appropriate grammatical conditions are met, this phonology attribute will be given the type *phrase*. The definition in (67) will accordingly specialise the SYLS attribute. One possible specialisation is given in (79).

(79)

$$\left[\begin{array}{l} \text{SYLS} : \left\langle \left[\begin{array}{ll}\text{ONS} : & \langle\rangle \\ \text{NUC} : & \langle\tilde{\text{o}}\rangle \\ \text{CODA} : & \langle\text{n}\rangle\end{array}\right]_{syl} \left[\begin{array}{ll}\text{ONSET} : & \langle\text{s m}\rangle \\ \text{NUC} : & \langle\text{ɔ}\rangle \\ \text{CODA} : & \langle\text{k}\rangle\end{array}\right]_{syl} \left[\begin{array}{ll}\text{ONSET} : & \langle\text{p}\rangle \\ \text{NUC} : & \langle\text{ɑ}\rangle \\ \text{CODA} : & \langle\rangle\end{array}\right]_{syl} \right\rangle \\ \text{SEGS} : \langle\tilde{\text{o}}\text{ n s m ɔ k p ɑ}\rangle \end{array}\right]_{phrase}$$

The reader can check that the onset and coda sequences comply with the constraints in (69), that the first syllable can have an empty onset because there is no preceding syllable which could have a coda that matches the requirements of (75a), and that the obstruent *k* is permitted by constraint (75b) to appear in the coda of the second syllable because there is another obstruent *p* in the following onset.

This concludes our discussion of French schwa. We believe our treatment of schwa is empirically equivalent to that of Tranel (1987a), except for the analysis of h-aspiré. Several empirical issues remain, but we are optimistic that further refinements to our proposals will be able to take additional observations on board. Notwithstanding such further developments, we hope to have demonstrated that the procedural devices of deletion and rule ordering are unnecessary in a typed feature-based grammar framework, and that constraints represent a perspicuous way of encoding linguistic observations.

7 Conclusion

In this paper, we have tried to give the reader an impression of how three rather different phonological phenomena can be given a declarative encoding in a constraint-based grammar. Although we have focussed on phonology, we have also placed our analyses within a morphological context as befits the multi-dimensional perspective of HPSG.

The formal framework of HPSG is rather powerful; certainly powerful enough to capture many analyses in the style of classical generative phonology in which arbitrary mappings are allowed between underlying and surface representations. We have limited ourselves further by allowing only one phonological stratum in the grammar, and by adopting a notion of phonological compositionality which supports monotonicity. These restrictions make it much harder to carry over generalisations which depended on a procedural rule format. This is not a handicap, we contend, since it is heuristically valuable to view the data in a new light rather than just coercing traditional analyses into a modern grammar formalism.

So what is a constraint-based style of phonological analysis? An important key, we claim, is the use of generalisations expressed at the level of prosodic types. Coupled with a systematic underspecification of lexical entries and a regime of type inheritance, this allows us to have different levels of linguistic abstraction while maintaining a 'concrete' relation between lexical and surface representations of phonology.

We hope to have given enough illustration to show that our approach is viable. In future, we wish to extend these same techniques to a typologically diverse range of other linguistic phenomena. A second important goal is to show how the technology of finite state automata can be invoked to deal with phonological information in HPSG. For although we have placed phonology withing a general framework of linguistic constraints, the analyses we have presented only involve manipulation of regular expressions.

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