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Declarative Syllabification with Applications to German*

Markus Walther

1 Introduction

Recognizing the syllables in a word is one of the most basic phonological abilities any human speaker can master with ease. Abstracting away from fast speech phenomena and a number of other complications, it is a demonstratable fact that German speakers unambiguously divide a word like **Wodka** as **[vɔt.kaː]** in careful speech. This ability is put into perspective by the observation that the seemingly equally simple task of identifying the individual sounds which compose a word usually cannot be mastered by either children or adult illiterates. Apart from the mere grouping of sounds in a word the syllable functions as a natural reference for the description of many phonological processes in language. Note that e.g. the syllable-final /d/ of the Russian loanword cited above appears as [t] by a process known as Final Devoicing (to be described in more detail in section 4). Thus it appears that any phonological description of human language should attempt to capture this basic ability, which exhibits crosslinguistic universal tendencies but nevertheless has been shown to be of a non-phonetic and language-particular nature. Surprisingly though, few attempts to capture syllabification exist, which attempt to pay attention to adequate linguistic description and are at the same time formulated in a precise and formally sound way. Such an attempt is highly desirable given that the consistency of a usually complex language-particular syllabification theory may then be mechanically evaluated with the help of computers. Successfully formulating such a theory would also be beneficial for computational theories of grammar such as HPSG, which at present lack a serious treatment of phonology [1] as well as for speech technology applications, as demonstrated e.g. by the YORKTALK text-to-speech system (Coleman(1991)). We attempt to present such a theory below, concentrating on relevant data for German in an initial section before explaining the main model. It can be characterised as a modular approach, identifying a basic sonority-driven syllabification algorithm supplemented by

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[1] But see Bird(1992) for a first sketch of how one might integrate phonology within the HPSG framework.

language-particular instantiations of syllable length-restricting constraints and formal phonotactics. The basic algorithm avoids extrinsic ordering and structure-changing operations, as we work in a monotonic unification-based feature-constraint formalism enriched with a type system. It is based on partially specified subsyllabic functions modelled as types which are assigned on the basis of elementary sonority differences, leading to the more familiar syllabic roles by means of standard constraint combination. In the last section we explore some consequences of our approach for the description of syllable-dependent phonological processes, taking German Final Devoicing as our primary example. A novel non-feature-changing analysis is proposed. Also we touch upon questions of how to model phonetic interpretation of phonological structure in parallel with the building of phonological representations proper, showing that a certain class of constraints, arithmetic constraints, is particularly useful for that purpose. The overall phonological paradigm is that of Declarative Phonology (henceforth DP), whose general aims are summarised in Scobbie(1991).

2 German Syllabification: The Data

In this section we want to summarize very briefly the main facts about German syllable structure. We concentrate on the range of shapes found and incorporate aspects of phonotactics, the domain-bounded nature of syllabification and ambisyllabicity into this overview.

Empirically, we find the following possibilities with respect to the number of consonants allowed in onset (1.a) and coda position (1.b) of monomorphemic monosyllables. Note that consonants may be lacking altogether in both positions.

(1) a. Aal *eel*, oh *oh!*, Maus *mouse*, Luft *air*, grau *grey*, Flug *flight*, Stroh *straw*, Sprung *jump(n.)*
b. Schnee *snow*, blau *blue*, Ball *ball*, rot *red*, Wurm *worm*, Milch *milk*, Faust *fist*, Helm *helmet*, Worms *(town name)*, Mumps *(disease name)*, Herbst *autumn*, Dienst *service*

Consistent with the syllable patterns in many other languages we find that obstruents precede sonorants in the onset, with matters being reversed in the coda. Moreover, if we have consonant clusters of length greater than two in either onset or coda, then the extra peripheral consonants can only be coronal obstruents. Onsets tolerate one of these, whereas in codas we have up to two extra segments.

Now consider the monomorphemic forms listed under (2). All forms shown are maximal in the sense that only coronal obstruents may follow, e.g. in the form of inflections. Whereas short vowels tolerate two coda consonants (2.c), long vowels (2.a) and diphthongs (2.b) pattern alike in only allowing for one coda consonant proper. Thus there exists a kind of trading relation between the number of vowels and coda consonants within a syllable.

(2) a. viel [fiːl], doof [doːf], schön [ʃϕːn], Stab [ʃtaːp]
b. fein [faIn], drauf [dʁauf], neun [nɔyn], Raub [ʁaup]
c. Film [film], darf [daʁf], gern [gɛʁn],] gelb [gɛlp]

The data under (3) show, moreover, that there is an absolute constraint on the number of vowel 'positions' per syllable: Assuming that long vowels count as two positions we can summarize the data by stating that no more than two vowel positions are allowed in a syllable, as evidenced by the obligatory syllable boundaries intervening below.

(3) Theater [teː.aː.tɐ] *theatre*, Oase [oː.aː.zə] *oasis*,
larmoyant [laʁ.mɔy.jant]

Summarizing what we have found so far we formulate the syllable template in (4), which is to be taken as a purely descriptive statement:

(4) (C)(C)(C) V X (C)(C)(C)

As usual, optional elements go in brackets and X generalizes over V and C, thereby allowing us to capture the trading relation mentioned above. Note that the formulation in (4) entails the claim (Wiese(1988:67ff)'s 'Kernbedingung', nucleus constraint) that final full vowels must be phonologically long . This is indeed the case as contrasts like **Zoo [tsoː] *[tsɔ]** *zoo* show. The reference to full vowels is not superfluous, as schwa and syllabic sonorants, which usually result from schwa-zero alternations, *do* appear in final position. However, schwa has a very special status in German phonology, as documented in several studies (e.g. Giegerich(1987),Wiese(1988)). Apart from clear evidence that schwa functions as a default vowel, its special status is also evidenced by the predictability of its distribution in terms of general regularities and the fact that no schwa-initial words exist in German.[2]

Turning now to monomorphemic polysyllables, let us have a look at the cases under (5).

(5)
a. Aorta [aː.ɔʁ.taː], Eosin [eː.oː.ziːn]
b. Aroma [aː.ʁoː.maː], Kabine [kaː.biː.nə]
c. Alkohol [al.koː.hoːl], Tablett [taː.blɛt]
d. Ernte [ɛʁn.tə], Elster [ɛls.tɐ]
e. extra [ɛks.tʁaː], extrem [ɛks.tʁeːm], *[ɛʁks.tʁeːm]

These forms display the range of zero to four medial consonants, which cannot be extended as the illformed example in (5.e) shows. Note that with regard to the syllabification of medial obstruent clusters only one prominent pattern is shown, yet others are attested depending on speaker dialect and other factors.

Of course there is much more to be said about the precise phonotactic restrictions which go with individual segments cooccurring in either onset or coda. Some are dealt with in section 3.2, but lack of space precludes a fuller treatment here.[3]

Syllabification in German is a *domain-sensitive process*. While the domains of autonomous syllabification are induced by morphological information, the precise domain description nevertheless cuts across morphologically motivated boundaries. This can be seen in the examples under (6), where derivational prefixes (6.a), compound members (6.b) and C-initial

[2] Note the contrast to English, where schwa-initial cases like **anoint, award, about** are indeed attested.

[3] See Walther(1992:11-13) for a fairly exhaustive description of the distributions found in word-peripheral clusters.

derivational suffixes (6.c) all form separate syllabification domains, independent of phonotactic wellformedness considerations of the boundary-adjacent elements which would otherwise force final consonants to go with the syllable to their right. In the case of minimal pairs like **Tauchen** versus **tauchen [taʊ.xən]** *to dive(inf.)* we have independent evidence for the autonomous status of these domains, as the palatal fricative in **-chen** fails to assimilate in backness to the preceding vowel, as predicted by the German ich/ach alternation. In other words, with respect to syllabification and phonological processes these items act like stand-alone words.

In contrast inflectional and V-initial derivational suffixes (6.d) amalgamate with their respective stems to form larger domains of syllabification.[4]

(6) a. Ur.ur.oma {Ur-}{Ur-}{Oma} *grand-grandmother*,
be.vor.mun.den {be-}{vor-}{mund+n}

b. Va.ter.un.ser {Vater}{unser} *Lord's prayer*,
Klapp.fahr.rad {Klapp}{fahr}{rad} *foldable bike*,
Herbst.anfang {Herbst}{anfang} *beginning of autumn*

c. frag.los {frag}{-los} *unquestionably*, gelb.lich {gelb}{-lich} *yellowish*,
Tau.chen [taʊ.çən] {Tau}{-chen} *little rope*

d. At.mung {Atm+ -ung} *breath(n.)*, far.big {farb+ -ig} *coloured*, For.ma.lis.ten
{form+ -al + -ist + -n} *formalists*

We conclude this overview by pointing to the data in (7), which show some clear cases of *ambisyllabicity*.

(7) a. Mitte [mɪt̄ə] *middle*, lachen [laχ̄ən] *to laugh*,
Hammer [ham̄ɐ] *hammer*

b. trockener [tʁɔk̄ən̄əʁ] *dry(comp.)*

c. Dinge [dɪŋ̄ə] *thing(pl.)*, schwanger [ʃvaŋ̄ɐ] *pregnant*

Not only are single medial consonants ambisyllabic after short stressed vowels (7.a), but also after unstressable schwa (7.b). Moreover, the segment /ŋ/ not found in strict onset position can appear in ambisyllabic position.

[4] It has been pointed out by an anonymous reviewer that the adjective-forming derivational suffix – **artig** behaves like a C-initial one w.r.t. syllabification, arguing for the postulation of soft vs. strong morphemic boundaries instead of reference to V/C-initiality. Only soft boundaries would be overrulable by the phonology. However, **-artig** is still transparently recognisable as being composed of **Art** *kind(n.)* and the adjective-forming suffix **-ig**, even retaining an (almost) compositional semantics for **X + -artig** *of kind X (adj.)*. Thus we would rather see **-artig** as a fossilized compound member which therefore falls outside the generalization concerning derivational suffixes. Booij(1985) notes **-echt** as a further example (e.g. **farbecht** *colour-proof*), we have found also **-arm** as in **regenarm** *lit. rain-scarce (adj.), scarce of rain*. As these putative suffixes also occur as free morphemes, but pattern like the **-artig** case in all other respects, they provide additional evidence for a compound analysis. Fortunately, the formal treatment of domain sensitivity is not affected by this discussion.

3 Declarative Syllabification

This section introduces a sonority-driven declarative approach to syllabification. After briefly explaining the approach taken for segmental representations and some discussion of the notion and implementation of sonority, the main model is outlined. The computational framework in which the model is implemented is that of CUF (Dörre&Eisele(1991, Dorna(1992)), a typed feature constraint formalism capable of modelling HPSG grammars. CUF has a formal syntax and semantics and a translation scheme into first order predicate logic exists. Rather than cluttering the paper with pieces of actual code, however, we will be content to describe the type signature of our phonological universe of discourse in the appendix. Occasionally we use first order predicate logic to illustrate the formalisation of phonological representations, following the lead of Bird(1990).[5]

3.1 Prerequisites: Segments and Sonority

Syllabification is taken to be the process of assigning higher prosodic structure, namely subsyllabic functions to a list of *segments*. We decided to base the necessary segmental representations on *articulatory gestures*. In that we adopt proposals advanced by Browman&Goldstein(1989) for an Articulatory Phonology. Articulatory Phonology identifies articulatory gestures which minimally consist of a constriction at a certain place in the human vocal tract as the atoms of phonology. We also adhere to Browman & Goldstein's view of describing gestures as temporally extended entities. Bird&Klein(1990) generalise this view in attributing abstract temporal extension to *all* phonological constituents. In incorporating these ideas we model segments as feature bundles consisting of exactly two feature slots each bearing a gesture. Gestures are further decomposed into a constriction degree feature, a constriction location feature and a constriction shape feature for some gesture types, together with a temporal interval feature. The HEAD gesture slot contains the primary articulation, i.e. the main oral gestures, whereas the COMP gesture slot contains secondary articulation properties such as voicing, nasality, laterality and lip rounding. The advantage of this two-slot scheme apart from formally representing a natural division in kind of articulation is that default properties of certain classes of segments can be captured formally without resorting to nonmonotonic logics. For that purpose we arrange for default properties like 'the default glottis state is voicing' or 'the default velum state is non-nasality' to follow from type conflicts in a disjunctive description when accessing a segment's constriction degree that already bears a different articulatory type in the respective slot. This is illustrated in (8), whereby the inherent voicing of e.g. laterals and nasals can be captured formally in terms of the 'accessor predicate' for glottis constriction degree inspecting the COMP slot of a segment.

(8) $$\forall COMP \forall CD.glottis\_cd(COMP, CD) \leftrightarrow (glottis(COMP) \wedge cd(COMP, CD)) \vee (\neg glottis(COMP) \wedge CD = voiced)$$

Gestures may also be marked inactive as in the case of /h/, which bears no supralaryngal activity, hence has HEAD : *inactive* or underlying schwa, which is inactive in both slots. An

[5] In the formulae, one-place predicates translate to types in the CUF formalism whereas two-place predicates f(AVM, v) usually denote the feature f of an attribute value matrix AVM with value v.

attempt at a full specification of German segments in terms of Browman&Goldstein's model can be found in Walther(1992:30).

Segments are the basis for the computation of *sonority*. This long-used measure of a segments 'overall loudness' can be seen as a partial ordering serving to partition the set of segments into equivalence classes with low vowels usually in the maximal class and voiceless obstruent in the minimal class. Despite its usefulness as an abstraction device for defining syllable contours, the concept of sonority has nevertheless been subject to severe criticism on the basis that no satisfactory definition in terms of identifiable phonetic properties has been established so far. This state of affairs has lead some phoneticians and phonologists to reject sonority altogether (e.g. Butt(1992)). The critics would furthermore point to the apparent circularity in determining the partial ordering: segments are assigned to sonority classes on the basis of their distribution within the syllable, but syllabification itself is usually formulated in terms of sonority.

However, recent advances in machine learning of phonological structure have shown that is indeed possible to solve this chicken-and-egg problem (Ellison(1992)). Starting from a random initial sonority scale Ellison's program finds its way to the optimal language-particular scale. Optimality is assessed with respect to an information measure which, roughly stated, expresses the amount of conciseness inherent in a description of the input corpus syllabified according to the current scale. A corpus of unannotated surface forms is the only language-particular information for this learning strategy to achieve its result and the feasibility of his method has been demonstrated for a range of typologically diverse languages. In order to square the learning approach with the often-assumed universality of a single sonority scale, we might adopt the viewpoint of Keating(1988:294). She relates the impression of a single sonority scale, which in our view would constrain the range of language-particular variations found, to a set of largely but not totally overlapping scales defined on phonetic grounds such as loudness, formant structure etc.

Drawing on the results just cited, we henceforth assume that a learning approach would succeed in inducing a sonority scale for German and therefore feel confident to retain the concept of sonority. Without further discussion we adopt the scale in (9), which has also been assumed by other work on German phonology (Hall(1992, Wiese(to appear)).[6]

(9)

```
                                           high    other
obstruents    | nasals | /l/ |   /ʁ/  | vowels | vowels
------------------------------------------------------------>
                                increasing sonority
```

The very usefulness of the notion of sonority rests on its ability to describe prototypical syllables as instances of a hat-shaped sonority pattern, which has come to be known under the term *sonority sequencing generalization* (Selkirk(1984)). For that purpose it is sufficient to think of sonority as a partial relation *more_sonorous(Segment1, Segment2)*. Another issue

[6] If obstruents were furthermore subdivided to separate stops and fricatives, as suggested by an anonymous reviewer, we would unfortunately predict different syllable structure for e.g. **liebt [li:pt] vs. liebst [li:pst]** *to love(3sg. vs. 2sg)* on the basis of sonority contours alone, recognising a secondary obstruent-only syllable in the latter example.

arises as to whether sonority can be defined entirely in terms of internal articulatory segment properties or whether it must be represented either via additional manner features or by external tabulation of *more_sonorous* facts.[7] Walther(1992) used an internal definition exploiting the constriction degree percolation mechanism based on a simple tube geometry of the vocal tract, as proposed by Browman&Goldstein(1989). At present we would however tend to remain agnostic on how sonority is best represented. This is partly due to difficulties in defining constriction degrees for highly variable segments such as German /ʁ/. /ʁ/ surfaces in obstruent as well as vocalic realizations but nevertheless behaves as if confined to a single position in the sonority scale. It appears then that the Browman&Goldstein(1989) model as it stands might be somewhat too close to physical realism. An investigation of appropriate extensions is however well beyond the scope of this paper.

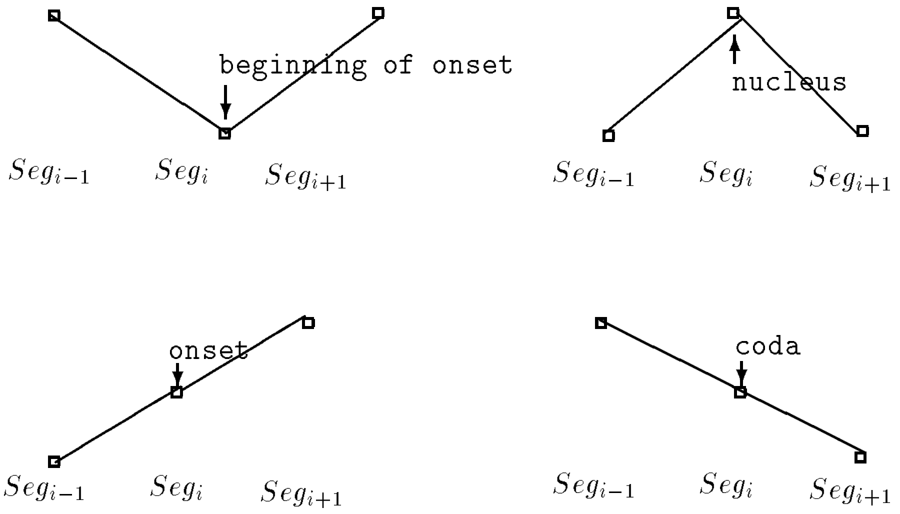
3.2 Sonority-driven declarative syllabification

Although Wiese(1988) and Giegerich(1992), amongst others, have proposed syllabification algorithms for German in a CV–phonology and metrical phonology framework respectively, their proposals suffer from a basically procedural orientation and lack of formalisation. Both use sonority maxima to define syllable nuclei, Giegerich in addition makes use of minima to define the beginning of onsets. However, their proposals lack explicit statements of how to define and handle these sonority extrema in cases of sonority *plateaus*, i.e. stretches of equal sonority. They are not explicit about how to formally capture the domain-bounded nature of syllabification as discussed above. Moreover, Wiese's model is directional in nature and Giegerich makes use of an apparently unrestricted adjunction rule collecting previously unsyllabified material.

Despite these disadvantages, Giegerich's idea of exploiting both sonority maxima *and* minima in defining syllable structure proves valuable for the model presented below. As a first step we identify four basic sonority patterns which serve to identify constituents of the syllable:

[7] Such a tabulation could be made more compact by defining positions in the scale as disjoint types, making segments subtypes of these types and then expressing *more_sonorous* facts over types rather than individual segments.

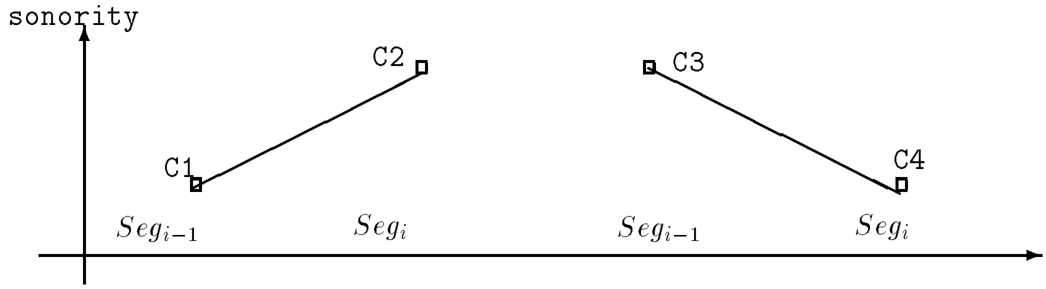
(10)



These sonority patterns can be decomposed into concatenations of of two more basic patterns – either a sonority uprise or a downfall between two immediately adjacent segments – as depicted in (11).

Our global aim is to treat syllabification as the assignment of one of four subsyllabic functions to each segment in a string. Thus at present the status of the syllable itself is epiphenomenal in our theory (cf. also Kaye et al.(1989)), though we could easily recover it from the subsyllabic functions. The subsyllabic function symbols that we adopt are **N**ucleus, **O**nset, **C**oda and **CO** for the ambisyllabic case, i.e. being in coda and onset at the same time. We will justify this particular inventory in section 4. The question now is whether we can establish constraints C1 to C4 in figure (11), so that the correct subsyllabic functions result from strictly local constraint interactions between adjacent segmental positions.

(11)



The left half of (11) says that if *more_sonorous*(Seg_i,Seg_{i-1}) holds for two arbitrary adjacents segments Seg_{i-1},Seg_i at any given position i in a segmental string, constraints C1(Seg_{i-1}) and C2(Seg_i) must hold as well and vice versa for the right half of the picture.

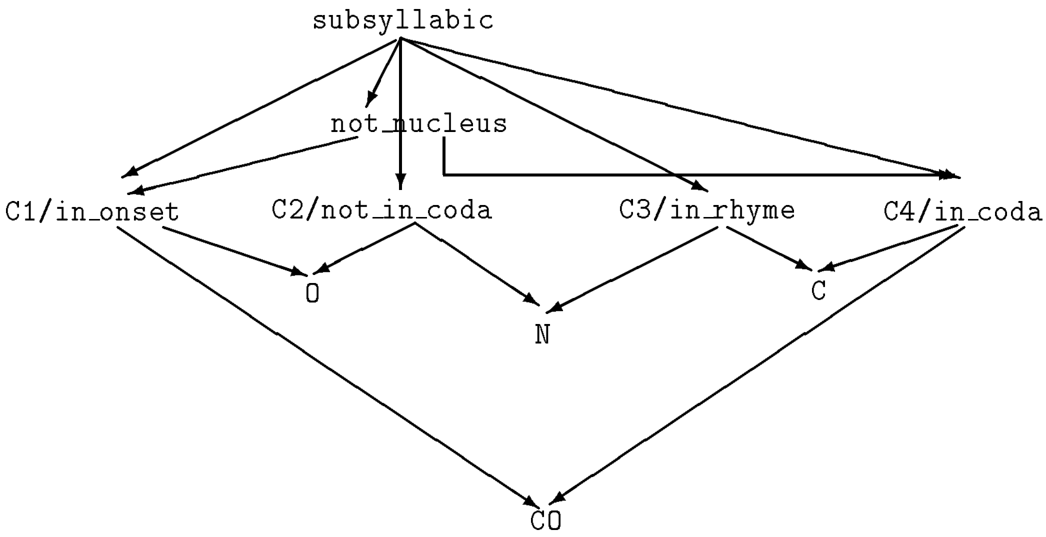
It turns out that the equations in (12) which reflect the concatenations depicted in (10) have a unique solution for the constraints C_i. Formally speaking we model the C_i as types and interpret the constraint interaction $X = Y \wedge Z$ as $X = meet(Y, Z)$ in the lattice-theoretic sense. Then the result can be displayed as the type lattice of figure (13).[8]

[8] As usual, arrows point from a more general to a more specific type that is subsumed by the former.

(12)

$$
\begin{aligned}
O &= C1 \wedge C2 \\
N &= C2 \wedge C3 \\
C &= C3 \wedge C4 \\
CO &= C1 \wedge C4
\end{aligned}
$$

(13)

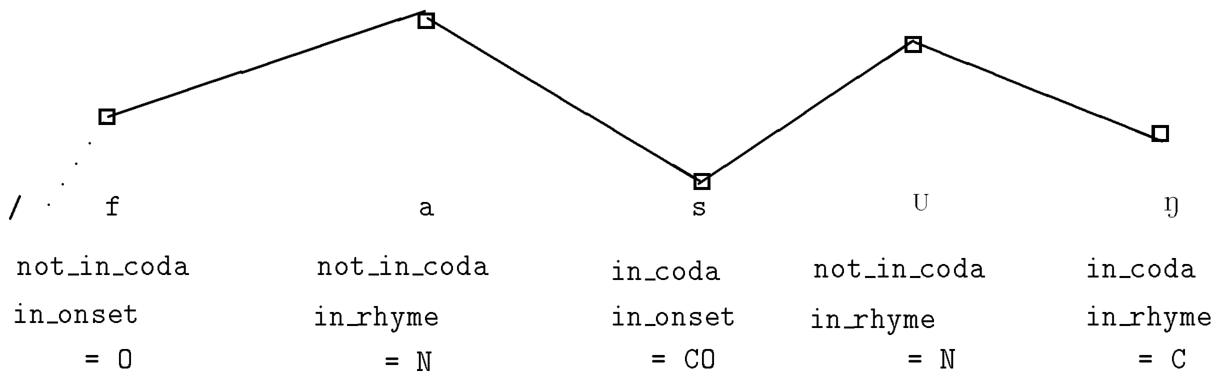


Adding boundary constraints `not_in_coda` and `in_rhyme` for the left- and rightmost elements of a syllabification domain is all we need to complete our basic syllabification machinery.[9] The constraint interactions for **Fassung** [fa̅suŋ] *version* are shown in (14). Note that the resulting subsyllabic functions are derived indepent of any specific temporal order or direction of syllabification. In addition to the general constraint solving process we only require that syllabification be exhaustive. Thus a simple recursive predicate which considers all adjacent pairs in a segmental string, determines whether *more_sonorous*(Seg_i, Seg_{i-1}) or the converse holds and applies constraints C1 and C2 or C3 and C4 to the respective segmental positions, is sufficient. An interesting property of this sonority-driven model is that we do not need a formal equivalent of the *Maximal Onset Principle*, as we exploit sonority minima to detect the start of an onset.

(14)

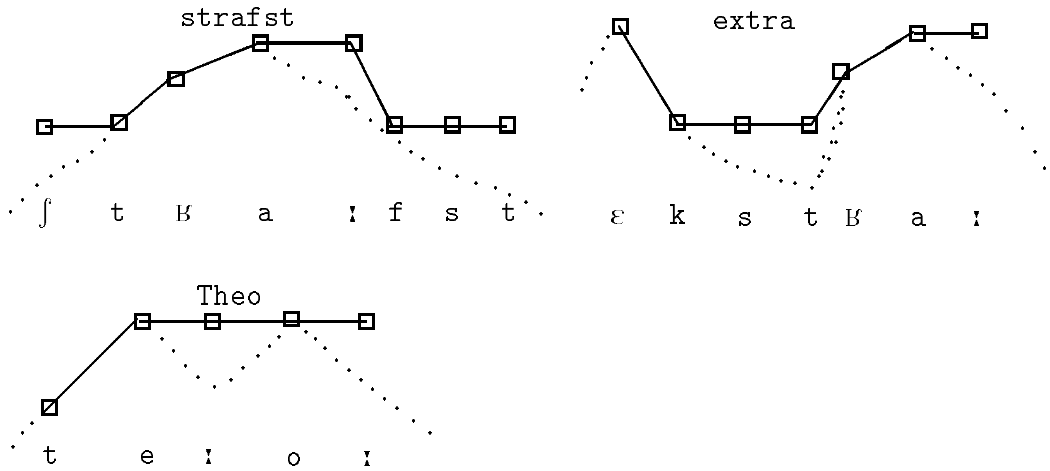
Note that up to a formally insignificant renaming of the C_i and the introduction of two more general types `subsyllabic, not_nucleus` (13) is a faithful representation of the equations and their solution in (12). Specifically, the opposition between types `not_in_coda, in_coda` is not redundantly represented, but crucially necessary in a formal treatment. This is quite parallel to cases like the exclusion of *[+high,+low], which also must be stated explicitly in any formal treatment not embodying a mechanical model of the tongue.

[9] Their choice naturally falls out from assuming uprise from 'zero' sonority at the left edge and downfall to 'zero' sonority at the right edge.



However, we have yet to repair a deficiency of the model as it stands: it cannot handle sonority plateaus as depicted in (15) for the forms **strafst** *punish-pres-2sg*, **extra** *extra*, **Theo** *(proper name)*. Note that the syllable structure for these items would be assigned correctly *if the dotted sonority contours were adopted instead.*

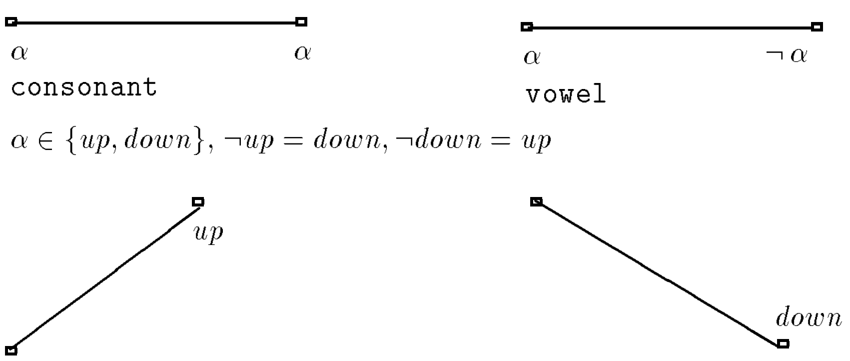
(15)



Formalising our intuition we employ *virtual sonority difference* markers `up` and `down` which are derived from the 'real' sonority differences. While we posit a one-to-one correspondence between real and virtual sonority differences in the non-plateau case (bottom half of (16)), we model the continuing behaviour of consonantal plateaus[10] as well as the alternating behaviour of vocalic plateaus via equality and disequality constraints, respectively, which hold over adjacent marker variables (top of (16)). The theoretical status of virtual sonority differences is that of an auxiliary mechanism which is implemented via 'subcomputations' – such markers do not show up in the phonological representation proper. Specifically, (16) is turned into a small finite state automaton with 2 states (initial state `up`), which is incorporated into basic syllabification. Of course, its subsyllabic constraint assignment must now refer to virtual instead of real sonority differences.

[10] I.e. a real downfall is continued downwards virtually, an uprise is continued upwards.

(16)



We can see an application of the revised syllabification algorithm below:

(17)

N	C	C	CO	O	N	C	O	N	CO	N	C
ɛ	k	s	t	ʁ	a	ː	t	e	ː	o	ː
up	down	down	down	up	up	down	up	up	down	up	down

Some comments are in order here. Note first of all that long vowels and diphthongs receive the labelling `N-C` in final position and `N-CO` in nonfinal position, as depicted in (17). Thus, the recognition of two different subsyllabic functions in these cases deviates from their classical treatment as branching nuclei. At least the final case receives an analysis similar to ours in a number of recent publications: Hall(1992) analyses diphthongs in this way and Noske(1992, Scobbie(1991) extend this to long monophthongs. In view of the trading relation alluded to in section 2 this is rather plausible: In parallel forms like **Film [film], Schaum [ʃaʊm], Scham [ʃaːm]** the uniform labelling `O-N-C-C` formally reflects the uniformity of these cases with respect to final consonant extendability. Moreover, the important distinction between light and heavy syllables is captured in a lucid way by referring to the absence or presence of a `Coda` element. While this distinction suffices for languages like Latin, for Lardil however, where CVV is still light but CVC is heavy[11], a more specific instantiation of this criterion would have to say that in order for a syllable to count as heavy, the coda segment must exist *and* be of type consonantal.

For nonfinal position it is interesting to note that the `CO` label that is assigned to the second element of long vowels by virtue of the syllabification algorithm corresponds to glide formation **Theo [teːjoː]** or glottal stop insertion **Theater [teːʔaːtɐ]**. Such phenomena have been treated as the phonetic trace of an empty onset in the literature (cf. Giegerich(1992)). It is obvious that more constraints are necessary in order to really capture both the exact distribution and relative strength of glide formation and glottal stop insertion, possibly incorporating metrical (foot) structure. Likewise, the non-occurrence of certain hiatus sequences which is discussed extensively in Hall(1992:ch.3) must be treated separately by specific phonotactic

[11] Lardil is an Australian language spoken on Mornington Island. Cf. Hayes (1989:255f.) for further discussion.

statements, which in our view form additional constraints imposed on the possible outcome of basic syllabification. But we would nevertheless argue that (i) the presence of a syllable boundary is correctly predicted by the model via `CO` assignment, importantly without introducing empty categories and (ii) the strength, extent and precise temporal location of the phonetic reflexes of a `CO` labelling are a matter of phonetic interpretation of such prosodically annotated segmental structure, the details of which are beyond the scope of our present investigation.[12]

Unfortunately the model developed so far uniformly assigns ambisyllabic function `CO` to all (virtual) sonority minima. This is incorrect given that after twofold sonority downfall (`down down` virtual sonority pattern) no ambisyllabicity is possible – only {`O, C`} = `not CO` subsyllabic functions are allowed for the minimum segment, as can be inferred from (18.a) (e.g., the relevant portion of **Verfilmung** would be i-up-N,l-down-C,m-down-O). As a consequence the correct rendering of **extra** in (17) would show `O` in place of `CO`. Even in potentially ambisyllabic circumstances (`up down up` pattern) postvocalic consonants only appear ambisyllabic in certain configurations – the allowed functions here are {`C, CO`} = `in_coda` and examples can be found in (18.b). The clue to a proper understanding of these puzzling cases is the insight that the segment occupying a sonority minimum bears the *partial* subsyllabic type `in_onset` ($= O \vee CO$) if and only if it can form a wellformed onset together with its righthand neighbour according to phonotactics.[13] If the phonotactics disallow a particular combination in onset, we have to assign `in_rhyme` to the minimum position. Formally, we employ a disjunction for `in_onset` vs. `in_rhyme` constraint placement. Note that we do not need a default specification here, as the phonotactic preconditions in both disjuncts are mutually exclusive.

(18) a. Verfil.mung, Ord.nung, Sau.na, Verfeu.rung, Sah.ne, At.mung

b. Schmu[ḡ]ler, ho[p̄]la, E[ŋ̄]e, Samm.lung, Wid.mung, Schaff.ner

While we have assumed a specific set of phonotactically illformed onset consonant clusters in (18) (*lm, *dn, *tm, *ml, *dm, *fn), the general treatment does not depend on this particular set. Indeed there is evidence that such filters differ between Standard High German and its colloquial variant, as argued in Giegerich(1992). In case it it is necessary to differentiate between word-initial and medial versions of such filters we would simply specialize the phonotactic statements in question by finer type classification at the word level. Once again we can implement the distinction between potentially ambisyllabic configurations and those which are never ambisyllabic by a small finite state automaton with 4 states, which tracks the virtual sonority differences. The basic syllabification algorithm is altered so that the partial subsyllabic function assigned depends on the state of the automaton at a given position. Additionally we need to underspecify both constraints C1 and C4 to `not_nucleus` to allow for the greater variety of functions that now have to be accomodated.

[12] This is very much in line with the view of Prosodic Analysis/Firthian phonology, where the importance of separating phonetic exponency from phonological description is particularly emphasized. See Richard Ogden, this volume.

[13] More formally, this amounts to a test on phonotactic constraint satisfiability of the minimum segment and its righthand neighbour in a stipulated `in_onset O` frame.

3.3 Length restrictions

Continuing in our modular approach to declarative syllabification we now wish to tackle the problem of how to enforce the *syllable template conditions* outlined in section 2. Note that such a length-restricting device is indeed necessary for German because on grounds of sonority alone nonoccurring forms such as ***Dierlnsts [diːʁlnsts]** would be allowed. The guiding idea here is to devise a set of regular expressions which together delimit the range of word-peripheral as well as medial shapes. This is done in (19).

(19)

$$\begin{aligned} length\_restriction &\Rightarrow (ConsClust\ MinSyll)^{+}\ ConsClust \cap \overline{Schwa\ AnySeg^{*}} \\ ConsClust &\Rightarrow \epsilon\ |Cons|Cons\ Cons|Cons\ Cons\ Cons \\ MinSyll &\Rightarrow FullVowel\ AnySeg|SchwaOrConsNucleus \end{aligned}$$

The regular expressions in (19) may be glossed as follows: One or more occurrences of a consonant cluster plus minimal syllable sequence is followed by another consonant cluster. Any segmental string conforming to these restrictions must not be composed of an initial schwa followed by zero or more additional segments. A consonant cluster itself consists of 0-3 consonants, while a minimal syllable is either composed of a full vowel followed by an obligatory additional segment or consists of a schwa or syllabic consonant. We can easily translate this set of regular expressions into a finite state automaton with 7 states. Conjoining a suitable implementation of this automaton with the basic syllabification algorithm then yields the language-specific instantiation.

3.4 Phonotactics

Though it has been alluded to several times already during our ongoing journey through the depths of syllabification, the vexed question of how to actually implement phonotactics has not been treated so far. This is a difficult area because, as Giegerich(1992:fn.2) correctly points out, " ...filters notoriously resist a comprehensive statement in terms of natural classes." Moreover, such filters are often violated by marginally occuring items (cf. Wiese(1988:93)). Though we do not want to address these important issues here, we do address the question on which these and other authors offer no specific help, namely how to formalise phonotactic restrictions per se. Rather than discussing the many deficiencies and few advantages of the small set of existing proposals on the subject, we present our own treatment below.[14] It is characterized by the use of implicational constraints and the employment of cross-subcategorization between adjacent segments.[15]

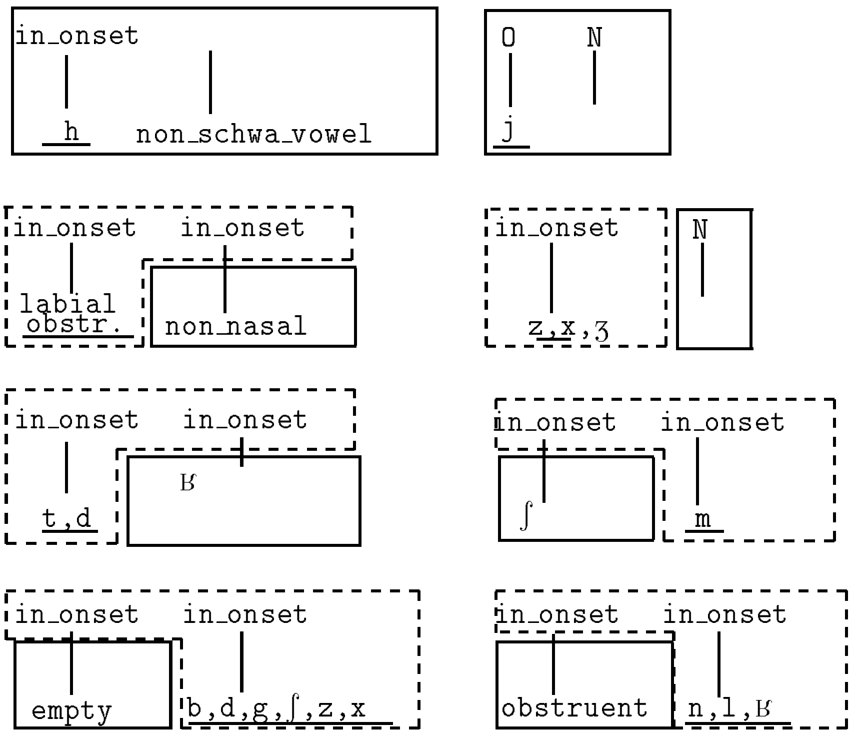
The central idea is that segments subcategorize for their immediate neighbours in a conditional fashion, i.e., dependent on hypothesized subsyllabic functions for themselves and the adjacent segment in question. For an illustration consider the fragment of onset phonotactics for German in (20). Broken lines encompass the antecedent and solid lines encompass

[14] See, however, Walther(1992:47-54) for an overview and discussion of various ways to handle phonotactics that have been proposed in the computational and linguistic literature for German.

[15] The importance of implications for purposes of formal phonology has also been recognised by Scobbie(1991).

the consequent of a material implication. The 'association lines' denote unification. These implications are stored in the segmental lexicon under the entries which are marked by underlining. Note that (20) is neither complete nor maximally concise, also some speaker-dependent exceptions[16] are not accounted for.

(20)



As an example, the segments /n,l,ʁ/ declare: "If I am in an onset and my *left-adjacent* neighbour segment is an onset as well, then it has to be an obstruent." In isolation this constraint would not exclude e.g. */fn,fm,bn,bm,pn,pm/. But it is precisely at this point that cross-subcategorization proves valuable. That is because labial obstruents constrain their *righthand* neighbour to be non-nasal. As a consequence the constraint set for e.g. /fn/ becomes unsatisfiable in onset position, or equivalently, it denotes no possible phonetic realisation. Although these conditional subcategorizations are positive implicational constraints when viewed in isolation, it is their *combination in a particular context* which makes them act as filters. By storing these implications in the *segment descriptions* themselves we favour a kind of object-oriented view of segments as rather active elements which can themselves 'influence' immediate neighbours through constraint interaction. This method requires however that morphological and lexical concatenation must connect the right and left contexts of individual segments so that constraint interaction is possible. Although we have not dealt explicitly with the problem of how to handle lexicalized exceptions to strict phonotactical statements like the ones in (20), we will briefly hint at a possible solution here. Ellison(1992) in his discussion of exceptions to vowel harmony in Turkish shows that if one marks segments in actual words as either regular or exceptional, then by conditionalising the harmony constraints so

[16] E.g. regarding the distribution of /z/: some speakers can readily say **uns're [Un.zʁə]**, **Dussel [dUz̄l]**, while we would pronounce [s].

that they constrain regular-marked segments only, the exceptions can be incorporated as well. Similarly we would type-mark the offending onset segments of items like **Smog, Smoking, Snob** etc. as `lexically_specified`, while normal occurrences of segments would be marked `lexically_unmarked`. We can easily avoid explicit type specification of the regular cases by invoking a compile-time default mechanism. The implicational phonotactics would then be furthermore conditioned to constrain only the `lexically_unmarked` segments.

3.5 Domain-sensitivity

Finally we need to show how to make syllabification domain-sensitive to account for the contrast noted in section 2. Booij(1985),Wiese(to appear) and others have identified these syllabification domains with the prosodic category *phonological word*, mainly because they cut across the morphologically motivated domains as shown already under (6). Both provide independent motivation for the *phonological word* as a valid prosodic constituent of German by showing that reduction in coordinate constructions involving complex words (e.g. **farb– und geruchsloseste** *(most) colour(less) and most odourless*, ***salz– und mehlig** *salt(y) and floury*) is only possible if the elided part[17] is identical to an unelided phonological word in parallel position in the other coordination member. To formally represent this linguistically motivated domain we employ a distinguished feature WORD. In a next step we stick once more to the view that phonological entities are temporally extended events, by declaring the value of WORD to be a subtype of `interval`. Two prosodic words then are identical if and only if their temporal intervals are identical, i.e. coindexed. They are disjoint if and only if there exists a precedence relationship between their intervals. As a third step we allow the description of *morphemes* to refer to lexically nonexisting neighbour segments. This is a natural move given that we already saw the same necessity for the formal treatment of segmental phonotactics. To formalise the intuition that all segments of a morpheme share the same prosodic word *token*, we coindex the WORD values of these segments lexically. In addition morphemes like **–lich** which have been shown to open up a new syllabification domain of their own lexically impose a precedence constraint between their own phonological word and the left-adjacent one. Thus we can formally express the fact that these two words are different tokens of the same type.[18] – Morphemes like **–ig** on the other hand specify that the value of their phonological WORD is coindexed with the word to their left, i.e. the phonological word temporally extends over both the base and the suffix.[19] The syllabification algorithm is modified accordingly so that upon encountering a precedence relationship between the phonological words of two adjacent segments, a right boundary constraint for its subsyllabic

[17] It is still marked in the orthography by '–'.

[18] This actually could be taken to suggest an alternative treatment, namely to take the type-token distinction alluded to here as being fundamental in the formal sense. This idea is pursued further in Walther(1993), where the token concept is treated as an abstract data type. The abstract data type hides its conceptual treatment as an infinite (but for practical applications stepwise enumerable) set of pairwise disjoint subtypes of a terminal type. Note that the integration of tokens into the type systems has the advantage that (super-)type containment tests can still be applied to tokens without failure, only the tokens themselves fail to combine. In our application a phonological description would refer to a *token of type phonological_word*, which is thereby declared unique and thus disjoint from any neighbouring prosodic word. The formal treatment of token and types also could find applications in syntax for the modelling of LFG's 'semantic uniqueness' condition and in morphology to prevent overapplication of identical affixes.

[19] This can be seen as the formal basis for Booij(1985)'s distinction between 'cohering' and 'non-cohering' affixes.

function is placed on the left segment and, procedurally speaking, we syllabify anew starting from the right segment.

3.6 Arithmetic constraints and phonetic interpretation

The actual use of precedence constraints in an implementation demands that both their formal status is clarified and that suitable means are provided to check the satisfiablity of such a constraint set. We take precedence to hold between temporal intervals. These are characterised by their endpoints (sp_i, ep_i) with $ep_i \geq sp_i$. Thus, an interval (sp_1, ep_1) precedes an interval $(sp2, ep2)$ if and only if $ep_1 < sp_2$. Both the endpoints and the solutions to the disequations are taken from the domain of positive real numbers. While the mathematics of these theoretical devices are well-understood, we still are in need of means to evaluate such *arithmetic constraints*, i.e. equations and disequations solvable in the domain of reals. In our implementation we used the constraint logic programming language CLP($\mathcal{R}$) (Heinze et al.(1991)) which contains such an arithmetic constraint solver, to augment the CUF feature constraint programming language with arithmetic constraints.[20]

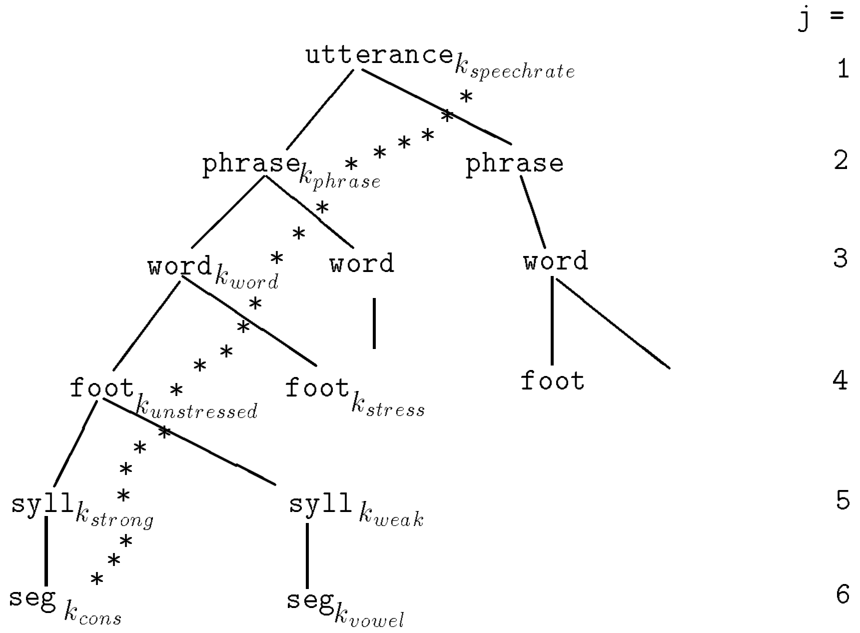
We would argue that this type of constraints may prove beneficial to add to feature unification formalisms in general, especially for applications to phonology. For example, it appears that the 'head-first' interpretation strategy imposed on the evaluation of phonological structure for purposes of phonetic implementation described in Coleman(1992) might be reducible to *conceptual* priority of phonological heads. Apparently the use of arithmetic constraints to encode the phonology-to-phonetics mappings described by Coleman could serve to remove any commitment to a particular processing order. If so, the usefulness of Coleman's approach would be would furthermore enhanced, opening up the possibility of such exciting applications as phonetic implementation within HPSG. In Walther(1992) a similar application is described which implements syllable-conditioned temporal phasing relations between head gestures via an adaption of the scheme proposed in Browman&Goldstein(1988, Browman&Goldstein(1990). This includes the case of intramorphemic predictable schwa (e.g. **At**[ə]**m** *breath*), which is tentatively modelled as a slightly different phasing of onset and syllabic consonant creating a small temporal gap perceived as schwa, in line with the analyses of Browman&Goldstein(1992). Utilising suitable arithmetic constraints, this aspect of phonetic implementation can be carried out concurrently with syllabification proper. Of course, the empirical validity and correct parametrisation must await further research, as there are currently no data available on German articulatory dynamics comparable to the X-ray microbeam data for American English which Browman & Goldstein were able to use. However, we can see no a priori reason why a gesture-based approach to the concurrent and integrated evaluation of phonology *and* phonetics should not carry over to German.

On a more speculative level we might complement the computation of the relative temporal arrangement of individual gestures with an approach to the computation of the phonetic

[20] Further details of this extension are described in Walther(1992). In the future we seek to replace CLP($\mathcal{R}$) by a variant of the more standard SICSTUS-PROLOG augmented with arithmetic constraints that has recently become available (DMCAI clone). Note that such an augmented logic programming framework is really necessary here, as the evaluation of arithmetic expressions in the scope of the `is/2` operator in ordinary PROLOGs is only allowed when all variables in such expressions are instantiated. Generally we cannot rely on this being the case without compromising the desired arbitrary order of constraint solving. Stipulating such an execution order, apart from reintroducing procedurality, would usually make the constraint solving mechanism task- (e.g. analysis only) and grammar-specific, a clearly undesirable consequence.

length of these gestural intervals, which recognizes length-determining coefficients throughout the whole prosodic hierarchy. As is suggested in (21), we might define the overall impact of prosodic structure on gestural length as, say, the product (or some other suitable function) of level-wise length coefficents k_j along a projection line.

(21)



This idea of localising individual coefficents to different hierarchically organised domains which are then related via arithmetic constraints is not an entirely new one: A rather similar architecture has been implemented by Whitelock(1991) for a computational model of the syntax-prosody interface. In his work a PATR interpreter augmented with an arithmetic constraint solver serves to execute a model of Japanese syntax and intonation.

4 Syllable-dependent phonological processes

Many phonological processes have been described as either interacting with syllabification or referring to syllable structure.[21] While the prime case of such an interaction in German is undoubtedly given by schwa epenthesis, its complications are well beyond the scope of this paper.[22] But a simpler yet rather interesting case is given by the probably most well-known phonological rule of German, *Final Devoicing*.

Final Devoicing has long been thought of as one of *the* prime candidates for a feature-changing rule. This is because of its apparent nature as an absolute neutralization of voicing contrast for obstruents in final position. We can see some of the relevant data in (22).[23]

[21] The distinction between interaction with the assumed *process* of syllabification and mere reference to its outcome, static syllable structure, depends on the phonological and processual paradigm assumed: both may amount to one and the same thing.

[22] See e.g. Wiese(1988),Giegerich(1987) for a description and the treatment of intramorphemic schwa in Walther(1992).

[23] Examples are mainly taken from Wiese(1990).

(22) a. Lo[p] - Lo[b]es, Ra[t] - Ra[d]es, - Sar[k] - Sar[g]es,
akti[f] - akti[v]es, Gra[s] - Gra[z]es
b. orange (adj.) [oʁaŋʃ] - Orange (n.) [oʁaŋʒə]
c. Ra[t] - Ra[t]es, Bioto[p] - Bioto[p]e, star[k]-star[k]en
d. kin[t]lich {kind}{-lich}, kin[d]isch {kind+ -isch}
e. Ja[kt] *hunt(n.)*- ja[g]en *to hunt(inf.)*- Ja[kd]en *hunt(pl.)*
f. Ebbe [ɛb̄ə] *low tide*, Bagger [bag̅ɐ], Kladde [klad̄ə],
vs. Ebbstrom {[ɛp]}{[ʃtʁoːm]} *stream of low tide*

The examples under (22.a) show obstruent-final stems, where obstruents surface voiced only when nonfinal. Nonfinality here results from the addition of inflections. Final Devoicing also applies to loanwords, even if they contain voiced obstruents which are not part of the native inventory such as /ʒ/, as seen under (22.b). The nonalternating voiceless obstruents in (22.c) obviously form a separate class.

That the correct description of finality must refer to the syllable and not to the morpheme is evident from the contrast noted in (22.d). However, cases like those in (22.e) casts doubt on the simple reference to absolute syllable-final position, as we witness in **Jagd, Magd** etc. instances of multiple final devoicing. In line with proposals made by Vennemann(1982), Rubach (1990) and others we posit the coda as the relevant domain for Final Devoicing.[24] This is clearly more adequate than adopting an analysis such as that of Wiese(1991), who requires late adjunction of initially extrasyllabic material and cyclic devoicing rule application as procedural devices to retain the seemingly simpler structural description of syllable finality.

Several experimental studies, most recently Port&Crawford(1989), have questioned whether final devoicing indeed is absolute and have taken experiments, which showed better-than-chance disambiguation of minimal pairs like **Rad** *bike* vs. **Rat** *council* (69 % correct for Port&Crawford(1989)) as support for their claims to the contrary. Brockhaus (1991), in her review of the neutralisation debate in the experimental literature includes the study cited above[25], but concludes that the differences in obstruent realisation are not salient enough to be of much use in normal communication. She points out that contextual factors at the syntactic and semantic level are more likely to aid disambiguation in practical circumstances. Her own informal survey indicates that such minimal pairs always differ in at least one of these non-phonological dimensions. Thus we feel confident in continuing to view Final Devoicing as an alternation which phonology should indeed be able to describe.

Our challenge now is to model this neutralisation in the DP framework, where feature-changing is impossible due to the usual monotonicity assumption. We note in passing that the analyis of Wiese(1990) is feature-changing and procedural despite Wiese's attempt to describe Final Devoicing in a monotonic unification-based setting. He postulates an initial generalisation step operating on feature structures to get rid of the unwanted [voice:+] specification

[24] Hall(1992) rejects the coda approach to Final Devoicing on theory-internal grounds, namely violation of the Linking Constraint in cases like **Jagd**. No such problems exist in the present framework, however, as the Linking Constraint is not employed. Also see Scobbie(1991) for extensive criticism of the Linking Constraint, to which we would add that apparently any formalisation would involve negation because of the need to explicitly exclude unmentioned association lines. Negation is generally regarded as an undesirable feature by mainstream generative phonologists.

[25] She notes that due to refined experimental design the more recent studies in her survey do not suffer from hypercorrect spelling-based pronounciations, which allegedly biased the older studies.

of underlyingly voiced obstruents, which is supplemented by a *later* default fill-in of [voice:–]. The general idea of our own proposal – which is monotonic and non-procedural in the strict sense – is to exploit the crucial distinction made by DP between description and denotation. Thus we will be arriving at a single description which however has the potential of denoting two different classes of objects. As a first step we posit initial entries for alternating voiced and non-alternating voiceless obstruents as exemplified for the labial stops in (23).[26]

(23) a. $/b/ : \exists S.lip\_closure(S) \wedge (in\_onset(S) \rightarrow voiced(S))$
b. $/p/ : \exists S.lip\_closure(S) \wedge voiceless(S)$

Note that these representations are based on strictly surface-true generalizations, hence should be easily learnable. It has been objected to this kind of analysis that it predicts languages without Final Devoicing, e.g. English, to have different segmental descriptions for obstruents. In our view this is rather an advantage, as these differences give formal content to (i) the fact that prosodic information is very important for language acquisition, hence should be naturally reflected in the representations learnt and (ii) these languages sound very different and it seems not very realistic to explain these differences by sole reference to an all-powerful phonetic implementation module.

Now we are ready to state the Final Devoicing constraint:

(24) $\forall S.obstruent(S) \wedge C(S) \rightarrow voiceless(S)$

We may gloss this as follows: Any segment that is an obstruent and bears the subsyllabic function of (strict) coda C also must have the voiceless property. Again this is a surface-true generalization. Note that in the gesture-based framework we could also implement finer glottis state specifications instead of $voiceless(S)$ which would account for the difference in production of devoiced obstruents noted in the experimental studies. Importantly, we view (24) as a *lexical constraint imposed on the segmental lexicon* – in other words, a special kind of lexical rule – and demand that it be conjunctively added to all segment descriptions, following the quantor's prescription. While this results in unchanged logical descriptions for non-obstruents and voiceless obstruents, because either the antecedent of the implication in (24) is not satisfied or the consequent is already there, it gives us a new representation for alternating voiced obstruents:

(25) $/b/ : \exists S.lip\_closure(S) \wedge (in\_onset(S) \rightarrow voiced(S)) \wedge (C(S) \rightarrow voiceless(S))$

Now (25) describes both surface forms of an underlyingly voiced obstruent in a single formula. However, in a given syllabification context, only one of the antecedents can ever become true resulting in the corresponding voicing specification as an automatic consequence.

Examining the properties of the analysis above we note first of all that a phonological rule which was deemed to scan an arbitrary string of segments has been reduced to a *strictly local* representation, which 'knows' how to act in a given context. This formalization of

[26] The segmental entries have been simplified, omitting temporal and head/complement information, which is irrelevant to the present discussion. Of course we take the examples to stand as the outcome of a general compile-time statement which encompasses the entire class of obstruents. Note also that the voiceless obstruents contain a trivialisation of the implication employed for their voiced counterparts; we could have written the logically equivalent $\top(S) \rightarrow voiceless(S)$, where $\top$ is the 'always true' constraint.

final devoicing can therefore be once again said to be object-oriented in style. Multiple final devoicing follows from our formalization as well without assuming additional mechanisms, because all final obstruents get `C` functions by means of normal syllabification, namely the virtual sonority downfall imposed on the final sonority plateaus in these cases.

A further property to note is that this formalization correctly accounts for the *failure of final devoicing to apply to ambisyllabic voiced obstruents*. The relevant data can be seen in (22.f). This simply follows from the fact that we have restricted final devoicing to apply to strict codas. Strict codas are defined as `C`, not less specific `in_coda` elements of our subsyllabic function type lattice, but `CO` is defined as `in_coda` $\wedge$ `in_onset`, which is incompatible with `C`. Thus, at the small price of a finer classification of subsyllabic functions we have been able to dispense entirely with additional formal devices such as the Linking Constraint or equivalents, which are usually invoked at this point in the generative literature to deal with 'a rule's failure to apply in circumstances of multiple linking'. The correct behaviour of our solution rests on two moves we have made: We have (i) choosen the simplest possible option to represent such ambisyllabic segments, namely that they are occupying one segmental *and* skeletal position and (ii) allowed for phonological 'rules' (turned representations) to refer to the presence of quite specific subsyllabic functions associated with a given position. That our solution turns out to handle this problematic area with such ease is taken here as independent evidence that the particular choice of subsyllabic functions is adequate.

Now this latter phenomenon sounds very familiar under a quite different heading, namely the discussion of geminate integrity and inalterability found in the literature. Though German has no true geminate consonants and we have been able to predict ambisyllabicity under the general syllabification scheme, in effect it seems that the failure of final devoicing to apply to the ambisyllabic cases under (22.f) amounts to an instance of geminate inalterability. Similary, the process of schwa epenthesis in German never breaks up ambisyllabic segments, so it appears we have 'geminate' integrity as well. Concentrating on inalterability here, the reasonable question arises as to whether there are more instances of 'geminate' inalterability in German, and the answer seems to be yes.

Consider the data on German /ʁ/-vocalisation under (26) below.[27]

(26)
a. sehr [ze:ɐ̯] - Seher [zejɐ]
b. besser [bɛs̄ɐ] - bess'res [bɛs.ʁəs]
c. reich [ʁaɪç], frisch [fʁɪʃ]
d. Sperre [ʃpɛʁ̄ə], Karre [kaʁ̄ə]

Without too much discussion we quickly summarize the regularity underlying these alternations in the following Coleman-style picture:

(27)

`in_onset`	`N`	`C`
|	|	|
[ʁ]	[ɐ]	[ɐ̯]

[27] See Griffen(1982) for more data and a finer classification coupled with a Dynamic Phonology analysis. Griffen is however confined to the non-ambisyllabic case.

The crucial cases for our purpose here are the ambisyllabic items listed in (26.d), which pattern with the strict onset /ʁ/'s of (26.c) in not undergoing vocalisation, while the strict coda cases *do* show vocalisation.

Geminate integrity and inalterability have been discussed at length by Scobbie(1991) in the framework of Attribute-Value Phonology framework (AVP). While in our view Scobbie successfully demonstrated the superiority of a declarative approach to the problem at hand, his proposals nevertheless suffer from representing true geminates as sharing of a melodic segment between two adjacent skeletal positions. This means that additional principles and formal devices of AVP such as the Sharing Constraint and possibly default interpretation are crucially needed in his account to achieve the intended stability effects.[28] It is suggested here that a *strictly local* treatment by means of a 'compound' subsyllabic function `CO` is preferable to capture the phenomena at hand, as no additional devices are needed. In a sense, multiple linking takes place once-and-forever in the type lattice, thus being described by the static background axioms of our phonological theory rather than by more dynamic configurational structure.

The phonological rules which systematically fail to apply to the geminate case are very similarly described in Scobbie's work as implicational constraints referring to the presence of certain specific syllable functions, so his type of analysis of the phonological alternations involved can be carried over to the present framework without complications. To cover the length distinction of geminates as compared to 'normal' segments we however would seek to interpret `CO` structures in phonetic implementation.[29] Possibly this could even be achieved in a compositional fashion by distinguishing k_{in_onset} and k_{in_coda} length coefficients respectively, whose subsyllabic function counterparts are both contained in `CO`. Cases of length contrast neutralizations in e.g. word- or phrase-final positions would then similarly be subsumed under the general treatment of phonetic length as hierarchical interpretation of phonological structure suggested above, with corresponding attenuating k-coefficents of the higher constituents coming into play. To extend this treatment to partial geminates such as [mb] we might prespecify an internal phasing offset between the HEAD and COMP gesture of a single segment[30], which makes much sense in a gestural framework.[31]

Of course, the above remarks are of speculative nature and a precise clarification of this proposal must await further research. This also needs to cover 'geminate' vowels, i.e. long monophthongs, for which a similar treatment might be imagined. The question of how one then could model the type of trading relation between vowel length and number of coda consonants described for German would have to be answered. But the overall enterprise seems very promising.

5 Conclusion

We have presented a declarative modular treatment of syllabification which is based on a sonority-driven assignment of partial subsyllabic functions modelled as types. It is compa-

[28] Scobbie(1991:88):"A true geminate involves sharing and *sharing must remain local*."

[29] See also the arguments for lengthening being phonetic rather than phonological given in Polgárdi(1993).

[30] I.e., to the effect that the controlled velum gesture terminates before the lip gesture

[31] Browman&Goldstein(1990:308) discuss the introduction of dynamical regime types or 'periodic attractors', which are related to this discussion.

tible with a declarative constraint-based conception of grammar such as HPSG. The model proposed formally covers some of the more problematic areas identified above such as sonority plateaus, length restrictions, ambisyllabicity and phonotactic wellformedness as well as domain sensitivity. We highlighted the usefulness of arithmetic constraints for describing the temporally extended nature of phonological structure and sketched some ingredients necessary for concurrent phonetic interpretation of such structure. We also presented a novel declarative analysis of German Final Devoicing. On the more speculative side we pointed out to links between Final Devoicing's failure to apply to ambisyllabic obstruents and the treatment of geminate inalterability in general, exploring some of the implications for the latter and relating them once again to phonetic interpretation.

Further research must seek to complete the phonotactic descriptions and simplify the overall syllabification process as well as proceed in establishing the prospects of our more speculative proposals.

The non-speculative part of the work reported here has been implemented in the CUF unification grammar formalism and is available from the author on request.

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A Type definitions

The type signature of our phonological universe, as depicted below, is composed of expressions of the type language for CUF devised in Dorna(1992). $Type = TypeExpression$ defines Type by means of TypeExpression. Interesting TypeExpressions for our purposes include $Subtype1|\ldots|SubtypeN$, which in combination with the above denotes the disjoint partitioning of a Type into a set of Subtypes and $\sim Type$, which models negation of a Type. $Type :: feat1 : Valuetype1, \ldots, featN : ValuetypeN$ declares features feat1 to featN as appropriate for Type with corresponding restrictions on possible values of these features. Appropriateness declarations are monotonically inherited by subtypes. Finally, $Subtype < TypeExpression$ declares Subtype to be lower in the inheritance hierarchy than each of the types described by TypeExpression.

```
top =  basic | scalars | phonological_constituent.
basic = list | ... .
list = elist | nelist.
nelist:: 'F':prosodic, 'R':list.
scalar = articulatory_constriction | interval.
articulatory_constriction = degree | location | shape.
interval:: ti:temporal_interval.
interval = mid_interval | small_interval.
phonological_constituent = gesture | segment | prosodic.
gesture < small_interval.
gesture = inactive | active.
active:: cd:degree.
vocal_tract < active.
vocal_tract = oral | velum | glottis.
oral:: cl:location.
oral = lips | tongue.
tongue = tip | body.
body:: cs:shape.
segment:: head: gesture, comp:gesture.
prosodic:: word:mid_interval.
subsyllabic < prosodic.
subsyllabic:: seg:segment.
subsyllabic = in_onset | not_in_coda | in_rhyme | in_coda.
'O' < (in_onset | not_in_coda).
'N' < (not_in_coda | in_rhyme).
'C' < (in_rhyme | in_coda).
'CO' < (in_onset | in_coda).
not_nucleus < subsyllabic.
not_nucleus = ~ 'N'.
```