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Targeting underspecified segments: A formal analysis of feature-changing and feature-filling rules☆

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Abstract

In this paper, we discuss how the difference between feature-changing and feature-filling processes has not been adequately addressed in rule-based, derivational phonology. We explore two different theories of these processes. One theory analyzes feature-changing in two steps—set subtraction and then set unification. Another analyzes feature-changing in one step—a function that alters the polarity of features. We argue that empirical evidence favours the two-step over the one-step process. In particular, the two-step process provides an account for the lack of rules that target specified segments independently of underspecified segments (so-called by-passing rules). It also explains why there are no attested examples of purely phonological rules that switch the polarity of certain features (e.g., changing /t/ and /d/ to [d] and [t] respectively).

Keywords: Formal phonology; Derivational phonology; Feature-filling; Feature-changing; Underspecification; Polarity rule

1. Introduction

One reason for the rise of Optimality Theory (OT) in the 1990s was widespread acceptance of the claim that ''rule-based theory hardly imposes any limits on the notion of 'possible rule' '' (Kager, 1999, p. 1). The rejection of rule-based formalism in favour of the constraint-based OT model was accompanied by a rejection of the derivational model inherited from traditional generative phonology, such as in Chomsky and Halle (1968). Thus, nearly all of the research in OT ''assumes a parallel implementation'' (McCarthy, 2000, p. 1) without multiple levels of representation. More recently, many OT practitioners have turned back to serialism (McCarthy, 2010, 2000; Pruitt, 2010; Tessier, 2012; Bermúdez-Otero, 2009; Kiparsky, 2010) in recognition that the parallel model appears to be insufficiently powerful. In this context of a renewed respect for derivations, it is prudent to also revisit questions about the nature of rules.[1] This paper contributes to

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[1] We agree with a reviewer who points out that there was in fact a history of attempts to constrain rules, such as Chomsky (1967), Jensen (1974) and Wiese (2000)—see below. The reviewer also insists that it is similarly the case that attempts at limiting the nature of constraints in OT are fairly rare, with a few notable exceptions such as Eisner (1997), McCarthy (2003) and Riggle (2004).

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the development of a more formal analysis of derivational, rule-based phonology (Bale and Reiss, forthcoming). We make explicit some of the typically implicit assumptions concerning the structure of segments and the operations that apply to them. Part of this process involves distinguishing feature-filling rules from feature-changing rules. We outline an account of feature-filling rules where underspecified segments are targeted indirectly through an operation called *unification*: a form of set union that can only combine two sets when the result is consistent, otherwise the operation fails.[2] Crucially, the points of failure are a welcome result, yielding the exact empirical effects needed. Unification prevents rules from creating inconsistent sets of features while also allowing for the type of featural changes needed to model phonological systems.

In contrast to feature-filling rules, feature-changing processes—which change feature values from + to − or vice versa—involve two steps: First, the feature targeted for change is deleted (and thus the segment becomes underspecified), and second, the newly underspecified segment is unified with the feature specified in the change.

This account of feature-filling and feature-changing processes makes predictions about phonological rules cross-linguistically. According to the system developed here, it should be impossible to have a rule that targets a fully specified segment for a featural change without also targeting an underspecified segment with respect to a feature-filling rule. This is due to the fact that a critical part of the feature-changing processes, besides deletion, are feature-filling rules that target underspecified segments. As far as we know, this prediction is empirically borne out. Thus, our formalization helps us to discover and explain new empirical generalizations.

The outline of this paper is as follows. Section 2 discusses some of the key characteristics of feature-filling rules in Turkish. Section 3 argues that traditional SPE-style representations of phonological rules are somewhat misleading in that they use the same symbol sets to represent two different theoretical concepts. A new notational convention is proposed that clearly distinguishes between these concepts. With this new convention in place, sections 4 and 5 outline the interpretation of the primary operator symbol traditionally used in rules, namely →. It is in these sections that we discuss the formal differences between feature-filling and feature-changing processes. Section 6 discusses two models for feature-changing and suggests a way of choosing between them. Some of the consequences of our formal system are discussed in section 7, and section 8 concludes the paper.

2. Underspecification in Turkish

In this section, we review an analysis of Turkish consonants that was first introduced by Inkelas (1995) and Inkelas and Orgun (1995). This analysis critically employs underspecification as a way of encoding a three-way distinction among coronal stops. Feature-filling rules are required to account for the surface variation of these segments.

In Turkish, there is evidence for three types of underlying representations for coronal stops at the end of roots. There are those that surface as [t] in all three environments we consider, there are those that surface as [d] in all three environments, and there are those that alternate between surface [t] and [d], with [t] occurring in a syllable coda and [d] in an onset. The nouns for 'art,' 'etude', and 'wing' in (1) illustrate this contrast.

(1) a. Non-alternating voiceless:
sanat 'art', *sanatlar* 'art-plural', *sanatım* 'art-1sg.poss'
b. Non-alternating voiced:
etüd 'etude', *etüdler* 'etude-plural', *etüdüm* 'etude-1sg.poss'
c. Alternating:
kanat 'wing', *kanatlar* 'wing-plural', *kanadım* 'wing-1sg.poss'

Inkelas argues that this three-way distinction can be encoded by representing the non-alternating [t] as voiceless, the non-alternating [d] as voiced, and the alternating coronal (hereon, symbolized as [ᴅ]) as unspecified for voice.

(2) Three underlying segments distinguished with one binary feature
a. /t/ = { − Voice, +Coronal, −Continuant . . .}
b. /d/ = { + Voice, +Coronal, −Continuant . . .}
c. /ᴅ/ = { + Coronal, −Continuant . . .} (no Voice feature)

Thus, each root ends in a coronal stop, and each coronal stop shares the features +Coronal and −Continuant (among others), but such stops critically differ in that /t/ contains −Voice; /d/ contains +Voice; and /ᴅ/ contains no voicing features.[3]

[2] Earlier discussions of unification in phonology include Coleman, 1990; Bird et al., 1992; Scobbie et al., 1996. Interestingly, the earlier work that invokes unification attempts to explain away apparent feature-changing processes, whereas this paper exploits the failure of unification under some conditions exactly for the purpose of capturing the feature-filling *vs.* feature-changing distinction.

[3] As evident from the paragraph above, we follow the common practice of representing segments as sets of ordered pairs. Each ordered pair consists of a value (+ or −) and an attribute, or feature, F_i, drawn from a universal feature set $\mathcal{F}$ that include familiar features described in articulatory terms, such as Nasal, Round, etc. We will use the term *feature* ambiguously to refer to the attributes themselves and to valued features like +Nasal. Context should make the appropriate reading clear.

Although /ᴅ/ does not contain any voicing specifications underlyingly, it is clear that it still surfaces as either a voiced or voiceless segment (i.e., either [t] or [d] as in (1c)). Inkelas hypothesizes that phonological rules *fill-in* the voicing specification by assigning a [−Voice] value when /ᴅ/ appears as part of a coda and a [+Voice] value when it appears as part of an onset.

However, there is a problem with using traditional rule representations, such as $\alpha \rightarrow \beta$ / __γ, to represent the addition of a voicing feature to an underspecified segment. An underspecified segment contains a set of features that are a proper subset of the features contained in the corresponding specified segments. However, any set that is used to identify /ᴅ/ would also identify /t/ and /d/.[4] Thus, two questions arise. How can a rule add a [+Voice] feature to /ᴅ/ in onsets without affecting /t/? And how can a rule add a [−Voice] feature to /ᴅ/ without affecting /d/? In other words: *How can we have feature-filling rules?*

One solution to this problem has been to stipulate that some rules only apply when they fill in feature values without changing already specified values (McCarthy, 1994; Inkelas and Orgun, 1995; Inkelas, 1995). In other words, the rules must be diacritically marked, as we have done in (3) with the symbol FF, to indicate this property of a rule.

(3) Stipulated feature-filling (FF) rules
  a. FF: [+Coronal, −Continuant] → [−Voice] / in Coda
    That is, /ᴅ/ → [−Voice] / in Coda
  b. FF: [+Coronal, −Continuant] → [+Voice] / in Onset
    That is, /ᴅ/ → [+Voice] / in Onset

Thus, by stipulation, (3a) will not devoice an underlying /d/ in a coda, and (3b) will not voice an underlying /t/ in an onset, even though the structural description of the two rules describes a natural class that includes both /t/ and /d/.

The use of a diacritic to mark feature-filling rules implies that there are also feature-changing rules—i.e., rules that change feature-values in a segment from positive (+F) to negative (−F) and vice versa. We can tentatively mark such rules with the diacritic FC for feature-changing. In (4a) we repeat the FF rule (3a), and in (4b) we give the corresponding feature-changing rule.

(4) A feature-filling and a feature-changing rule with the same structural description
  a. FF: [+Coronal, −Continuant] → [−Voice] / in Coda
    that is, /ᴅ/ → [−Voice] / in Coda
  b. FC: [+Coronal, −Continuant] → [−Voice] / in Coda
    that is, /t, d, ᴅ/ → [−Voice] / in Coda

The use of such diacritics obscures what should be a central concern of phonological theory—namely the nature of the functions represented by phonological rules. As is apparent in the examples above, the → used in an FF-rule means something different from the → used in an FC-rule. This study aims to understand what computations are involved in phonological rules such that this difference falls out naturally without diacritic marking. In order to pursue this aim, we need to be careful about our notation. In the next section, we suggest a change in the notation that better represents the actual interpretation of phonological rules.

3. A new notational convention

Assume a language with five vowels, /a, o, e, u, i/. Consider an informal representation of a process that changes [o] and [e] into their high vowel counterparts, presented in (5):

(5) **A Simple Rule:**

o,e	→	u,i	/	__	n, m, ŋ
Target (SD)		Change			Environment

This process turns the mid vowels into the high vowels when they occur before a nasal segment. The vowels *o,e* are the set of target segments. The set of nasal consonants *n, m, ŋ* define the environment.

[4] In the terminology of *SPE* (Chomsky and Halle, 1968), the /ᴅ/ is not *distinct* from /t/ and /d/, since it doesn't conflict with them with respect to the value on any feature. Halle (1959, 32) already makes use of this sense of 'distinct', but calls it 'different'.

A standard formalization of the process in (5) might represent the set of targets as [− High, − Low], assuming these are the only mid vowels in the language.[5]

(6) **Traditional Rule**:
[−High, − Low] → [+High] / __ [+Nasal]

Such notation identifies potential targets through a superset relation: A segment is a target of the rule if and only if it is a superset of the set {−High, −Low}.[6] Thus, the target of our rule is actually a set of segments; that is, a set of sets of valued features, as in (7):

(7) Target—natural class of *segments* $X = \{x : x \supseteq \{-\text{High}, -\text{Low}\}\}$

Similarly, the environment of our rule is the set of segments that are a superset of the set of features {+Nasal}, as in (8):

(8) Environment—natural class of *segments* $Y = \{y : y \supseteq \{+\text{Nasal}\}\}$

The square brackets in the target and the environment in traditional rules like (6) are used to symbolize these natural classes.

(9) a. $\{x : x \supseteq \{-\text{High}, -\text{Low}\}\} = [-\text{High}, -\text{Low}]$
b. $\{y : y \supseteq \{+\text{Nasal}\}\} = [+\text{Nasal}]$

However, the square brackets do not always represent natural classes in the traditional rule format. It is standard practice to also write the structural change in square brackets (e.g., the [+ High] symbol in (6) above). Clearly the structural change specification is not meant to define a natural class in the same way as the target and environment specifications. Rather, the structural change provides a list of the features that will be changed or added to the target segments when they appear in the right environment.

Given that the square brackets do not have the same type of meaning for the structural change as they do for the target and environment, we propose replacing the square brackets with another notation. The set-bracket notation, as in (10), marks the difference between natural classes (i.e., sets of sets of features) and mere sets of features.

(10) Structural Change—set of *features*: {+High}

With this new convention in mind, the rule in (6) can be rewritten as in (11).

(11) **Rule with consistent bracketing**:
[−High, − Low] → {+High} / __ [+Nasal]
a. { . . .} denotes sets of features
b. [. . .] denotes sets of sets of features (= sets of segments)

This new notational convention thus consistently differentiates the identification of natural classes from the identification of a set of features.

It is worth noting that in all the examples we discuss, the Structural Change is a unary set. This limitation may be a general property of the phonological system—*i.e.*, all phonological rules only make ‘‘one change at a time’’ Chomsky (1967). This

[5] Or else the target set might be represented as just [− Low], if rules are assumed to apply vacuously.

[6] It is important to note that this interpretation of the target set is not that of *SPE*. In *SPE* (pp. 336–7) a rule applies to anything non-distinct from the rule's target description (i.e., a rule applies to any segment that does not have a featural specification that conflicts with the features in the target description). As pointed out by Reiss (2003a), the *SPE* notion of non-distinctness falls together with this superset interpretation when there is no underspecification, but they are not always equivalent. To illustrate, strict application of the *SPE* interpretive procedure entails that an underspecified vowel that had only the feature [−Round] would satisfy the structural description of a rule like (i), since the representation [−Round] is *not distinct* from the representation [−Nasal].

(i) [−Nasal] → [−Voice]

This is surely an undesirable result, one that we avoid with the superset approach adopted here and implicitly avoided in most of the post-SPE literature. So, once we accept underspecification, the absence of such rules provides an empirical argument to favour the superset interpretation of targets over the non-distinctness interpretation of SPE.

restrictive view is a recurring idea in the phonological literature. For example, it underlies much of the work in Feature Geometry deriving from Sagey (1986) in which groups of features can be inserted, deleted, or spread in a single operation by virtue of constituting a subtree of the full feature tree. The structure allows many apparent feature changes to be treated as a single operation. Reiss (1995) limits rules to a single featural change to account for a putative implicational universal. McCarthy (2000) also points out that in Prince & Smolensky's 1993 implementation of Harmonic Serialism, ''each iteration of Gen is limited to making a single change in the input''. Since we favour the view that the Structural Change involves a single feature, the question arises of why we insist on characterizing the Structural Change as a *set* containing one valued feature, rather than just as a valued feature. Placing the feature in a set allows us to use standard set theoretic operations. Not doing so would just add to the complexity of the interpretation of the operators we use when we deconstruct the traditional '→' symbol.

4. Deconstructing '→' in feature-filling rules

With this new notational convention in place, let's reconsider feature-filling rules and the use of the arrow symbol '→'. In feature-filling rules, the arrow indicates that targets undergo a (potential) change in which features to the right of the arrow symbol are added to the targets. For the sake of clarity, we repeat below one of the examples from Turkish, modified slightly to be consistent with the new notation.

(12) [FF]: [+ CORONAL, − CONTINUANT] → { − VOICE} / in Coda

This rule states that the feature −VOICE is added to underspecified coronal stops. Critically, −VOICE is *not* added to a segment that meets the description of the target, containing +CORONAL and −CONTINUANT, if that segment is *also* specified as +VOICE. In other words, the rule does not affect /d/.

Diacritics are used to distinguish between two different processes associated with the arrow (feature-filling and feature-changing), but they obscure important details about these processes. There are at least two proposals that would remove the diacritic from feature-filling rules. The first proposal involves adding a new value to the feature system. Instead of having just + and − values, features could be specified as being neither + nor −. For the sake of exposition, we will label this value $\emptyset$, i.e., the null value. Under this proposal, so-called underspecification for voice involves the specification of $\emptyset$ VOICE. Thus, the feature-filling rule could be rewritten as in (13).

(13) [$\emptyset$VOICE, + CORONAL, − CONTINUANT] → { − VOICE} / in Coda

However, the availability of a $\emptyset$-value predicts the possibility of rules, such as the one in (14), that can target segments specified $\emptyset$F for a featural change with respect to another feature G, without targeting any of the segments that *are* specified −F or +F.

(14) [$\emptyset$VOICE, + CORONAL, − CONTINUANT] → { + LABIAL} / in Coda

The rule in (14) maps coronals stops that are underspecified for voice, and only those underspecified for voice, to labial stops. We assert that such rules are unattested cross-linguistically, and as far as we can tell, the literature does not propose such rules.

The second proposal for removing the diacritic involves replacing the arrow, or perhaps more accurately described, interpreting the arrow as a type of set union that is sensitive to featural consistency. Regular set union, defined in (15), will combine two sets of features without any restrictions on consistency, as defined in (16).

(15) UNION: For any two sets A and B, their union, $A \cup B$, is the set C such that $x \in C$ iff $x \in A$ or $x \in B$

(16) CONSISTENCY: A set of features ρ is consistent if and only if there is no feature $F_i \in \mathcal{F}$ (the universal set of features) such that $+F_i \in \rho$ and $-F_i \in \rho$.

Under union, { + VOICE, − CONTINUANT} ∪ { − VOICE, + CORONAL} would yield the set in (17).

(17) { + VOICE, − CONTINUANT, − VOICE, + CORONAL}

This set contains both a −VOICE and +VOICE feature and hence is not consistent.

Unification, in contrast to union, is only defined when the resulting set is consistent.

(18) Unification: For any two sets, A and B, the unification of A and B, $A \sqcup B$, is defined iff $A \cup B$ is consistent. When defined, $A \sqcup B = A \cup B$.

Thus, although the unification of { + Voice, − Continuant} and { + Coronal} yields a set, namely { + Voice, − Continuant, + Coronal}, the unification of { + Voice, − Continuant} and { − Voice, + Coronal} is not defined. Because unification sometimes does not yield an output, it is called a *partial operation*.

Exploiting this operation, the feature-filling rule in (12) can be rewritten as in (19).[7]

(19) [+Coronal, −Continuant] $\sqcup$ {−Voice} / in Coda

Recall that the target of the rule (written ''[+Coronal, −Continuant]'') identifies the natural class of coronal stops, i.e., the set {x : $x \supseteq$ { + Coronal, − Continuant}}. Thus the targets are the segments /d/, /t/, and /D/. In contrast to (12), the arrow symbol has been replaced by the symbol for unification. This is meant to indicate that each of the targets which satisfy the structural description (i.e., those in a coda) are unified with the feature set { − Voice}. If unification fails, then the target is unaltered.

The interpretation of the rule in (19) can be broken down as follows:

(20) Feature-filling rule via unification (where $\mapsto$ represents the mapping of one segment to another)

If . . .	Comment:
a. $x \supseteq$ { + Coronal, – Continuant } and	If x is /t/ or /d/ or /D/ . . .
b. x is in Coda and	. . .
c. $x \sqcup$ {−Voice} is defined	If x and {– Voice} are consistent . . .
THEN $x \mapsto x \sqcup$ {−Voice}	Then **replace** x with $x \sqcup$ {−Voice} . . .
Else $x \mapsto x$	If any conditions fail, leave x alone.

Without using a diacritic, the rule correctly applies to all segments subsumed by the target, occurring in the relevant environment:

(21) i. For underspecified segment /D/, unification 'inserts' the feature −Voice, yielding [t]
ii. For specified segment /t/, containing −Voice, unification vacuously 'inserts' the feature −Voice, yielding [t]
iii. For specified segment /d/, containing +Voice, unification is not defined since condition (c) is not met, and underlying /d/ is unaffected

Note that unification is defined for both underlying /t/ and /D/, so there is vacuous unification in the former case. We don't actually target the underspecified /D/ by referring to it, but rather by having unification fail with /d/ and vacuously 'insert' the feature −Voice with /t/.

This proposal accounts for feature-filling rules by appealing to unification as a partial operation. The operation fails in the desired environments and thus we do not need diacritics. We have made the claim that unification is a possible operation in a phonological rule, and thus we contribute to a theory of ''limits on the notion of a 'possible rule' ''. We are not looking for constraints on possible rules, but rather building up a minimal set of operations that rules can use (see Hale and Reiss, 2008, ch. 8 for discussion).

5. Deconstructing '→' in feature-changing rules

If feature-filling rules can be reduced to unification, then perhaps feature-changing rules can also be analyzed in a similar way. Recall that feature-changing rules are different from feature-filling rules in that the features which define the target are often inconsistent with the features that specify the structural change. Consider the example in (22).[8]

[7] We use the unification symbol in phonological rules to represent the function that maps segments that fit the structural description to the same segment unified with the structural change, as described in (20). This is a slight abuse of notation, but allows us to remind the reader about the nature of the mapping. To be clear, we are not using it to represent the unification of the structural description with the structural change.

[8] In a form generalized to other places and manners of articulation, such a rule would correspond to well-known cases of coda devoicing such as German, Polish, or Russian, assuming that the underlying obstruents in these languages are fully specified for voicing.

(22) a. /d/ → [t] / in CODA
b. FC: [+CORON, −CONT, +VOICE] → {−VOICE} / in CODA

Unlike the feature-filling rules, these rules cannot be analyzed as straightforward application of unification, as represented in (23).

(23) [+CORON, −CONT, +VOICE] $\sqcup$ {−VOICE} / in CODA

This rule ends up having no effect on underlying forms. For any segment *x* that is +CORON, −CONT, and +VOICE (i.e., for any segment that is a superset of {+CORON, −CONT, +VOICE}), the result of unioning *x* with the set expressing the change, i.e., {−VOICE}, is not consistent. Hence unification is never defined and, as a result, the rule would map every segment *x* to itself. Clearly, feature-changing rules involve something more than unification.

There are two possibilities of what this ''more'' is. One possibility is that the arrow symbol in feature-changing rules represents a completely different function from the arrow symbol in feature-filling rules. Thus, perhaps it is more accurate to symbolize the rule as in (22b) as opposed to (23). The arrow in (22b) could be interpreted as a function that maps members of the target with their −VOICE feature to segments that are featurally identical except they have a +VOICE feature and no −VOICE feature. In other words, the change happens in one fell swoop as represented in (24).

(24) **One fell swoop approach to the FC rule in (22b)**:
For each segment *x* that is in a coda and is a superset of { + CORONAL, − CONTINUANT, + VOICE}, *x* maps to the segment *y* such that . . .
i. −VOICE $\in$ *y*
ii. *y* is consistent
iii. (*x* − { + VOICE}) = (*y* − { − VOICE})

The rule in (24) specifies a mapping from a voiced segment *x* to a segment *y* such that *y* is voiceless (clause i. and ii.) and *y* is identical to *x* in all other features besides voicing (clause iii.).

By itself, the function in (24) is not obviously problematic—in fact, it looks exactly like what we want: feature-changing involves switching the +/− value of one (or more) of the features. However, in languages with a three-way contrast between specified and underspecified segments, like Turkish, this type of feature-changing rule makes undesirable predictions. More specifically, allowing a single step featural change would make it possible to have the mappings from underlying to surface segments as represented in (25):

(25) i. /d/ $\mapsto$ t Change!
ii. /t/ $\mapsto$ t No change.
iii. /D/ $\mapsto$ D No change.

A rule could apply to /d/, turning it into [t], and 'bypass' /D/ which does not satisfy the SD of the rule, since /D/ is not a superset of {+VOICE}. Cross-linguistically, this does not appear to be possible.

Adopting a suggestion of Poser (1993, 2004) that is widely accepted (Wiese, 2000; Samuels, 2011; Nevins, 2010; McCarthy, 2007, for example), a second possible account of feature-changing processes analyzes the FC-arrow as representing two separate rules. First, the feature whose value must change is deleted. Second, the opposite value is filled in. In order to delete a feature, we use the operation of set subtraction. Thus, the feature identified to undergo the change is removed from the target segment. With respect to the rule in (22b), this would mean that for all target segments *x*, *x* $\mapsto$ *x* − { + VOICE}. Consider the representation of a deletion rule given in (26) with its intended interpretation in (27).

(26) DELETION:
[+CORON, −CONT] − {+VOICE} / in CODA[9]

(27) For all segments *x*, if *x* is a superset of { + CORON, − CONT} and *x* appears in a coda, then *x* $\mapsto$ *x* − { + VOICE}. Otherwise *x* $\mapsto$ *x*.

[9] As with the unification symbol, we use the set difference symbol in phonological rules to represent the function that maps segments that fit the structural description to the same segment minus the features in the structural change, as described in (27). This is another slight abuse of notation, but it again allows us to remind the reader about the nature of the mapping. To be clear, we are not using it to represent the set formed from subtracting the feature in the structural change from the features in the structural description.

We don't need to list a voicing specification in the target of (26). Nothing will change for the segments /t/ and /D/ since they do not have the +VOICE feature. However, the deletion rule will affect /d/ by deleting its +VOICE feature. Thus the distinction between underlying tokens of /d/ and /D/ will be neutralized: both will become underspecified coronal stops. With the deletion of the +VOICE feature, we are now free to invoke unification to insert −VOICE without violating consistency. The insertion of the feature is no different from the FF-rules discussed in section 4.

(28) Insertion:
[+CORONAL, −CONTINUANT] $\sqcup$ {−VOICE} / in CODA

So under this analysis, the → of a FC *process* is really a sequence of two rules, deletion followed by unification.

6. Choosing between two models

Even if our unification model of feature-filling is accepted, we still need to choose between the two models of how grammar encodes feature-changing processes. The first model, call it the *one-fell-swoop* theory (henceforth, the OFS-theory), has unification-based feature-filling rules and ''one-fell-swoop'' feature-changing rules. The second model, call it the *delete-and-unify* theory (henceforth, the DU-theory), again has unification-based feature-filling rules, but treats feature-changing as a sequence of deletion *via* set subtraction and unification. Both theories involve two types of operations in rules, and thus neither is obviously more elegant.

(29) Inventories of operations for two rule-based theories

	OFS-Theory	DU-Theory
Primitive Operation 1	unification	unification
Primitive Operation 2	'one-fell-swoop'	subtraction

However, if there is independent evidence for subtraction (i.e., evidence not involving feature-changing processes), then an argument can be made that ''one-fell-swoop'' feature-changing rules are not necessary, since they can be reduced to deletion *via* subtraction followed by insertion *via* unification.

It turns out that clear empirical evidence for subtraction is hard to come by. As we have pointed out, there is a tradition since Poser (1993) of treating feature-changing processes as involving deletion followed by insertion. However, since such work tends to posit subsequent rules that insert the opposite valued feature of the one deleted, no *phonetic* evidence is offered for the simple deletion rule.

Wiese's (2000) discussion of coda obstruent devoicing in German is promising, since he explicitly adopts a binary feature system, as we do, and he also adopts the view that final devoicing is deletion ('delinking') of the voice specification on all coda obstruents. Keating (1988) and related work such as Choi (1992) demonstrate that there is phonetic evidence for the existence of surface underspecification—segments can exit the phonology with no specification for some features. In Keating and Choi's cases, the surface underspecification just reflects underlying, lexical underspecification that is not affected by any phonological rules that fill in features. Wiese's case would involve *derived surface underspecification*, deletion of underlying valued features that are not subsequently replaced. Unfortunately, Wiese (p. 204) proposes that the phonetic realization of obstruents unspecified for voicing just happens to be identical to obstruents that are specified −VOICE. He thus implies that there can be no *phonetic* evidence that deletion of +VOICE has occurred without insertion of −VOICE.

On the bright side, there are reported cases of coda obstruents that *are* underspecified for voicing, and are not realized like voiceless stops. Hsu (1998) reports that the distinction among voiced, voiceless aspirated and voiceless unaspirated stops manifested in onsets in Taiwanese does not show up in codas. Instead, coda stops show no voicing (or aspiration) contrast and phonetic evidence of contextually determined variable articulation suggests that they are in fact neither +VOICE nor −VOICE. Hsu (p. 93) suggests that these stops lack a voicing specification entirely: ''Taiwanese word-final stops exit the phonology unspecified for the feature VOICE. (In the absence of a [αVOICE] target, the glottis will remain in the glottal configuration of the preceding segment).''

However, like all of Keating's cases, this surface underspecification in Taiwanese is inherited from lexical underspecification. What we need is a language with the morphology of German, where morpheme-final obstruents can be followed by vowel-initial suffixes that manifest voicing distinctions on the root, but with the neutralized forms that appear in the absence of a suffix showing the surface underspecification that is reported for Taiwanese. Our own survey of the literature, as well as discussion with colleagues (including Pat Keating, p.c.), has not turned up any clear cases of derived underspecification, but this is probably because the issue has not been clearly formulated before. In our view, this is a good example of how clearly formulated phonological questions should guide phonetic investigations.

New phonetic investigations on well-known cases of neutralization may turn out to be amenable to a delinking-without-unification analysis. We may find that even in cases like German or Russian, the derived underspecification analysis provides a better fit for data that is often hard to analyze coherently. Suppose phoneticians do find a systematic difference in the realization of, say, coda-devoiced stops in two languages. One explanation for such a difference would be to posit a new feature to distinguish the two kinds of realization. In other words, we could enrich the set of features ascribed to UG. A second solution is to posit language-specific phonetic realization rules (Kingston and Diehl, 1994). The idea is that the two languages have the same phonological representations for coda stops, say, exiting the phonology, but that the two differ in the interpretation of such representations in the transduction to articulation. The existence of language specific phonetic implementation is widely accepted, but Hale et al. (2007) argue that it raises insurmountable problems for the learner as opposed to assuming an invariant transduction system that maps between features and representations of acoustic or articulatory 'scores'. Our suggestion, that deletion without insertion can occur, provides a third solution for typological variation in the realization of neutralized contrasts. By allowing derived surface underspecification we can explain, for example, the existence of two kinds of coda stops that clearly do not bear the feature +Voice. Some of them will be specified −Voice and others will have no specification for Voice. This consequence of underspecification, the fact that allowing *absence* of a feature value *increases* the typological coverage of a model of phonological UG without increasing the number of primitives ascribed to UG is discussed more fully in Reiss (2012).

Korean is a language that potentially provides evidence in favour of derived underspecification, and thus of feature subtraction or deletion as an independently needed operation. In Korean, coronal obstruents neutralize word-finally to a plain voiceless coronal stop (for a discussion of these facts, see Kim, 1979; Chung, 1980; Kim and Jongman, 1996, among others). For example, in (30) the coronal obstruents /č^h/, /ǰ/, /s/, /t^h/, and /d/ all surface as [t] in the nominative form but not the accusative.

(30) **Korean multiple convergent neutralization**

	nominative	accusative
'face'	[nat̚]	[nač^{h}ɨl]
'day'	[nat̚]	[naǰɨl]
'sickle'	[nat̚]	[nasɨl]
'piece'	[nat̚]	[nat^{h}ɨl]
'grain'	[nat̚]	[nadɨl]

Although many discussions say that the neutralized stop is unreleased [t̚], Kim and Jongman (1996) claim that their phonetic evidence suggests that the stops are in fact often released. Perhaps the variability in Korean is context dependent and reflects surface underspecification, as Hsu (1998) argues for the (lexically surviving) underspecification in Taiwanese.

Though we must await the results of phonetic studies seeking evidence for derived surface underspecification, we can, for the time being, provide a conceptual argument. Abstracting from syllable structure and prosodic phenomena, we can treat the phonology as a complex function mapping segment strings to segment strings. The simplest model assumes that the set of elements constituting the input strings is the same as the set of elements occurring in output strings. If we grant the existence of lexical underspecification *à la* Inkelas (1995) and others, and we grant the existence of surface underspecification *à la* Keating (1988), it seems like an unmotivated stipulation to assume a constraint against mapping strings that contain fully specified members to ones containing some underspecified ones, especially when the latter are allowable output strings (in cases where the underspecification is present lexically).

In light of this conceptual argument, and while we await the phonetic evidence, we will proceed under the assumption that feature deletion, via set subtract or autosegmental delinking, is a valid phonological operation. Under this view, we can favour the DU-Theory over the OFS-Theory.[10]

[10] A reviewer, under the assumption that we hold that a lack of contrast necessarily implies a lack of specification, suggests relating our position to the Contrastivist Hypothesis of Hall (2007) and Dresher (2009). However, as we have tried to clarify here, our argument is not based on the necessity of *all* neutralization being a matter of feature deletion leading to a lack of specification. In fact, we do not rule out neutralization *via* feature-changing processes that neutralize to a specified value in certain contexts, in addition to neutralization by delinking. We predict that both can be attested.

(31)

	OFS-Theory	DU-Theory
Primitive Operation 1	unification	unification
Primitive Operation 2	'one-fell-swoop'	subtraction
Primitive Operation 3	subtraction	

As we see in (31) the OFS-Theory has to be enhanced in order to capture subtraction rules. It now has three fundamental rule types, two of which appear as part of the DU-Theory. The DU-Theory, however, still only requires two rule types: it gets feature-filling processes via unification, derived underspecification-type cases via subtraction, and feature-changing processes via a combination of the two. Occam's Razor favours DU-Theory.

7. Discussion and implications

One advantage of our two-step analysis of feature-changing rules is that it predicts that a phonological system does not allow feature-changing rules to ''by-pass'' underspecified segments. Furthermore, it predicts that no grammar could encode ''polarity rules'': individual rules where two contrasting segments are mapped to their opposite values. We discuss each of these advantages in this section.[11]

7.1. No by-passing

Feature-changing rules that by-pass underspecified segments would be possible under the first analysis in section 5, where change happened in ''one fell swoop.'' For example, consider the feature-changing rule in (32i) along with the feature-filling rule in (32ii).

(32) i. FC: [+CORON, −CONT, +VOICE] → {−VOICE} / in CODA
ii. [+CORON, −CONT] ⊔ {+VOICE} / in CODA

Given the ordering specified in (32) and the first analysis of featural change, these rules would map /d/ to [t] in codas while mapping /D/ to [d]. The rule in (32i) essentially by-passes the underspecified segment when mapping the voiced coronal stop to its voiceless counterpart. This type of ''by-passing'' pattern is not empirically attested cross-linguistically.

Our two-step analysis of featural change cannot replicate this pattern as a single process. The equivalent of (32) would be the set of rules in (33).

(33) i. [+CORON, −CONT] − {+VOICE} / in CODA
ii. [+CORON, −CONT] ⊔ {−VOICE} / in CODA
iii. [+CORON, −CONT] ⊔ {+VOICE} / in CODA

The rule in (33i) would remove voicing features from any /d/ that appears in a coda position, thus mapping it to [D]. The rule in (33ii) would map the underspecified coronals in codas to [t]. This mapping would not only apply to underspecified segments derived from /d/, but also to those that were underlyingly underspecified. After the application of (33ii), all coronal stops in coda positions would be specified for voice. Thus, the application of (33iii) would have no effect, and the by-passing pattern would not occur.

The reasoning behind the ''no by-passing'' property can be summarized informally with the graph in (34).

(34) No bypassing: /d/ must 'pass though' [D] to become [t]

d	→	D	→	t
	deletion (set subtraction)		insertion (unification)	

[11] Another appealing aspect of the second proposal is that it is consistent with certain simplicity constraints outlined in Chomsky (1967). According to the second proposal, what is called FF is modelled by unification and what is called FC is modelled by deletion and then unification. This approach is consistent with Chomsky's (1967) suggestion that rules make ''one change at a time''. If unification is a basic operation we need, then it is appealing to analyze certain processes and combinations of this basic operation with one or more other operations.

Essentially, in our system, feature-changing processes involve a reduction of specified segments to underspecified segments. At the point they become underspecified, they are identical to underlyingly underspecified segments. It would be impossible to target the derived underspecified segments without also targeting the underlying underspecified ones.

It is important to emphasize that our model only prohibits by-passing of an underspecified segment by *a single* two-part feature-changing process. It is logically possible, for example, with an inventory containing /t,d,ᴅ/ to ''get /ᴅ/ out of the way'' in some environment, by shifting /ᴅ/ to, say, [ʙ] (a labial stop without voicing specification); then changing /t/ to [d] by feature-changing in two steps as we have laid out; then changing [ʙ] back to [ᴅ]; then filling in −VOICE so that original /ᴅ/ surfaces as [t]. Our formal system does not rule out such a convoluted derivation, but it is hard to imagine a scenario that would lead a learner to posit such an analysis.[12]

7.2. No polarity rules

Connected to the lack of ''by-passing'' is the impossibility of formulating so-called ''polarity rules.'' Polarity rules map +F *and* −F to their opposites in a given phonological environment. Like by-passing rules, such rules are possible under the ''one-fell-swoop'' analysis in section 5.[13]

Let's assume, as we do in common arithmetic, that −(+) is equivalent to − and that −(−) is equivalent to +. Given this convention, the formulation in (35) expresses a polarity rule.

(35) FC: [+CORON, −CONT, αVOICE] → {−αVOICE} / in CODA

This rule maps any /d/ in coda position to [t] and any /t/ in coda position to [d]. As with the by-passing patterns, the purely phonological ''polarity reversal'' pattern is not clearly attested cross-linguistically. An example would be something like ''Voiced obstruents become voiceless in codas, and voiceless ones become voiced.''[14] In the absence of such purely phonological cases, it is a benefit that such polarity rules are not possible with the analysis adopted in section 6, at least not as a single phonological rule.

To be clear, note that we might try to express the polarity change in our model using subtraction of both values on a feature, as in (36), and then insert opposite values, as in (37).

(36) [+CORON, −CONT, αVOICE] − {αVOICE} / in CODA

(37) i. [+CORON, −CONT] ⊔ {−VOICE} / in CODA
ii. [+CORON, −CONT] ⊔ {+VOICE} / in CODA

However, this will not give us the effect of a direct feature-changing polarity rule like (35). The rule in (36) deletes voicing features. The rule in (37i) adds −VOICE to underspecified coronal stops while the one in (37ii) adds +VOICE. The problem is that however we order the rules in (37), all of the underspecified segments will get the same value for VOICE, rather than getting the opposite valued feature from what was removed.

The lack of polarity rules follows from our interpretation of feature-changing rules as deletion and feature-filling. The deletion rule applies first and thus the feature-filling rule does not have access to which feature was deleted. Hence, feature-filling can no longer distinguish segments that were underlyingly [t] from those that were underlyingly [d].

[12] It is interesting to note that no-bypassing can also be derived in an OT model *under certain assumptions about the constraint set*, CON. For example, if there are MAX and DEP constraints for valued features, but no general IDENT constraints for features, no-bypassing follows (we leave this to the reader to confirm). Including IDENT constraints undermines this result. Our goal here is to provide an understanding of the mechanism of feature-filling in a rule-based phonology, however, the identification of patterns such as what we call bypassing, makes it clear that the issues raised are relevant to other formal frameworks, and should bear on a theory of what kind of constraints should be included in an OT grammar.

[13] We are assuming that variables are permitted that range over coefficient values (such as the α variable). Such variables are integral to the representation of assimilation and dissimilation rules. McCawley (1973) argues that such rules should only be regarded as shorthand for a series of rules, rather than as single rules capturing a single generalization. However, we take the view that the grammar itself makes use of Greek letter variables, for example to express identity conditions in rules (Reiss, 2003b).

[14] The issue has received some attention, although it is often combined with the question of whether there are morphologically conditioned processes that reverse phonological feature signs. Moreton (1999) demonstrates that exchange rules are not possible in OT under certain assumptions, and this is assumed to be a favourable result. Fitzpatrick et al. (2004) provide discussion of putative cases. Bye (2006) is skeptical of the existence of polarity rules. Paul de Lacy (2012) provides a discussion of the evidence for morpho-phonological polarity as well as a website of references and papers. Many of these sources discuss morphologically conditioned cases such as ''a voiced consonant changes to a corresponding voiceless consonant before the plural suffix...and vice versa'' (Gregersen, 1972). Others confound issues of phonological computation with accounts of phonological change, such as an analysis discussed and adopted by Anderson and Browne (1973) that uses a single set of underlying forms to derive two different Czech dialects, or the SPE use of polarity rules to account for the Great Vowel Shift.

Even if we attempt to remove and add features one at a time, as represented by the series of rules in (38), we would not be able to capture the ''polarity reversal'' pattern.

(38) i. [+CORON, −CONT, −VOICE] − {−VOICE} / in CODA
ii. [+CORON, −CONT] ⊔ {+VOICE} / in CODA
iii. [+CORON, −CONT, +VOICE] − {+VOICE} / in CODA
iv. [+CORON, −CONT] ⊔ {−VOICE} / in CODA

After the application of the rule in (38ii), all coronal stops will be specified for +VOICE. Thus the rules in (38iii) and (38iv) will apply to all coronal stops rather than only to those that are underlyingly voiced.[15]

7.3. No ''non-distinctness'' targeting of underspecified segments

We have just seen that our model does not allow direct reference to underspecified segments. A related issue is whether they can be included in target sets that they do not conflict with. Kiparsky (p.c. 2013) asked whether a rule that specified +CONTINUANT → + VOICED should affect something that is ∅CONTINUANT (unmarked for CONTINUANT). Kiparsky's question makes sense given the interpretation of rules in *SPE* (pp. 336–7) where a rule applies to anything non-distinct from, that is, consistent with, the rule's target description. As pointed out in footnote 6 above, the *SPE* notion of non-distinctness/consistency falls together with subsumption when there is no underspecification.

SPE had no underspecification that was relevant to the computations of rules and, in fact, generative phonology typically interprets rules using subsumption: If the set of the features in a target description is a subset of (that is, gives a more general description than) the features of a potential input, then the rule applies. As pointed out in Reiss (2003a), strict application of the *SPE* interpretive procedure entails that underspecified vowels that had only the feature representation [−ROUND] would satisfy the structural description of a rule like (39), since the representation [−ROUND] is *not distinct* from the representation [−NASAL]—the two are consistent.

(39) [−NASAL] → [−VOICED]

This is surely an undesirable result.

The model we have developed avoids this result, and similarly, answers Kiparsky's question in the negative. This is because there is no way to directly refer to the absence of a feature. The apparent reference to underspecified features falls out of our use of the partial operation of unification.

8. Conclusions

In this paper, we have deconstructed the traditional arrow → of phonological rules into two operations: deletion and unification. We have suggested that all feature-filling rules are best represented by a unification operation and that all feature-changing rules are best represented by deletion, modeled with set subtraction, followed by unification. If correct, the empirical consequences of this model are far reaching—the results bear on the nature of every phonological rule in every language. Our formalization leads to a system that makes several apparently correct predictions: we predict that there are no synchronic, purely phonological polarity rules; we predict there are no by-passing rules; and we predict that there are no rules that rely on underspecification of a feature F in order to define a set of targets for a process affecting another feature G. We have contributed to a model of possible phonological rules by offering a formalism that provides two fundamental operations, unification and subtraction, and offering a framework for discovering others.

[15] As with ''by-passing'', it is possible to get ''polarity reversal'' through a more convoluted set of rules. For example, it would be possible to. . .

i. map [d] to [D] through subtraction;
ii. map [D] to [B] (underspecified labial stop) through subtraction of place of articulation and then unification of the labial feature;
iii. map [t] to [D] through subtraction;
iv. map [D] to [d] through unification;
v. map [B] back to [D] through subtraction of place of articulation and then unification of the coronal feature;
vi. and then finally map [D] to [t] through unification.

However, as with the by-passing, it is hard to imagine how a child would be able to acquire such an abstract phonological process, especially given that there is no evidence in adult grammar that coronals are ever mapped to labials. Furthermore, the choice of mapping to a labial, rather than, say, a velar, would be as arbitrary to a learner as it is to a linguist positing it.

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