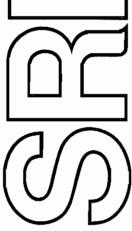FORMAL CONSTRAINTS ON METARULES

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Abstract

Metagrammatical formalisms that combine context-free phrase structure rules and metarules (MPS grammars) allow concise statement of generalizations about the syntax of natural languages. Unconstrained MPS grammars, unfortunately, are not computationally "safe." We evaluate several proposals for constraining them, basing our assessment on computational tractability and explanatory adequacy. We show that none of them satisfies both criteria, and suggest new directions for research on alternative metagrammatical formalisms.

1. Introduction

The computational-linguistics community has recently shown interest in a variety of metagrammatical formalisms for encoding grammars of natural language. A common technique found in these formalisms involves the notion of a *metarule*, which, in its most common conception, is a device used to generate grammar rules from other given grammar rules.[1] A metarule is essentially a statement declaring that, if a grammar contains rules that match one specified pattern, it also contains rules that match some other specified pattern. For example, the following metarule

$$(1) \quad VP \rightarrow V\ VP \Rightarrow VP \rightarrow V\ ADVP\ VP$$
$$[+fin]$$
$$[+aux]$$

states that, if there is a rule that expands a finite VP into a finite auxiliary and a nonfinite VP, there will also be a rule that expands the VP as before except for an additional adverb between the auxiliary and the nonfinite VP.[2] The patterns may contain variables, in which case they characterize "families" of related rules rather than individual pairs.

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[1] Metarules were first utilized for natural-language research and are most extensively developed within the theory of Generalized Phrase Structure Grammar (GPSG) [Gazdar and Pullum, 1982; Gawron *et al.*, 1982; Thompson, 1982].

[2] A metarule similar to our example was proposed by Gazdar, Pullum, and Sag [1982, p. 607].

The metarule notion is a seductive one, intuitively allowing generalizations about the grammar of a language to be stated concisely. However, unconstrained metarule formalisms may possess more expressive power than is apparently needed, and, moreover, they are not always computationally "safe." For example, they may generate infinite sets of rules and describe arbitrary languages. In this paper we examine both the formal and linguistic implications of various constraints on metagrammatical formalisms consisting of a combination of context-free phrase structure rules and metarules, which we will call *metarule phrase-structure (MPS) grammars.*

The term "MPS grammar" is used in two ways in this paper. An MPS grammar can be viewed as a grammar in its own right that characterizes a language directly. Alternatively, it can be viewed as a *metagrammar*, that is, as a generator of a phrase structure *object grammar*, the characterized language being defined as the language of the object grammar.

Uszkoreit and Peters [1982] have developed a formal definition of MPS grammars and have shown that an unconstrained MPS grammar can encode any recursively enumerable language. As long as the framework for grammatical description is not seen as part of a theory of natural language, this fact may not affect the usefulness of MPS grammars as tools for purely descriptive linguistics research; however, it has direct and obvious impact on those doing research in a computational or theoretical linguistic paradigm. Clearly, some way of constraining the power of MPS grammars is necessary to enable their use for encoding grammars in a computationally feasible way. In the sections that follow, we consider several formal proposals for constraining their power and discuss some of their computational and linguistic ramifications.

In our discussion of the computational ramifications of the proposed constraints, we will use the notion of weak-generative capacity as a barometer of the expressive power of a formalism. Other notions of expressivity are possible, although some of the traditional ones may not be applicable to MPS grammars. Strong-generative capacity, for instance, though well-defined, seems to be an inadequate notion for comparison of MPS grammars, since it would

have to be extended to include information about rule derivations as well as tree derivations. Similarly, we do not mean to imply by our arguments that the class of natural languages corresponds to some class that ranks low in the Chomsky hierarchy merely because the higher classes are less constrained in weak-generative power. The appropriate characterization of possible natural languages may not coincide at all with the divisions in the Chomsky hierarchy. Nevertheless weak-generative capacity—the weakest useful metric of capacity—will be the primary concern of this paper as a well-defined and relevant standard for measuring constraints.

2. Constraints by Change of Perspective

Peters and Ritchie [1973] have pointed out that context-sensitive grammars have no more than context-free power when their rules are viewed as node-admissibility conditions. This suggests that MPS grammars might be analogously constrained by regarding the metarules as something other than phrase-structure grammar generators. A brief examination of three alternative approaches indicates, however, that none of them clearly yields any useful constraints on weak-generative capacity. Two of the alternatives discussed below consider metarules to be part of the grammar itself, rather than as part of the metagrammar. The third views them as a set of redundant generalizations about the grammar.

Stucky [forthcoming] investigates the possibility of defining metarules as complex node-admissibility conditions, which she calls meta-node-admissibility conditions. Two computationally desirable results could ensue, were this reinterpretation possible. Because the metarules do not generate rules under the meta-node-admissibility interpretation, it follows that there will be neither a combinatorial explosion of rules nor any derivation resulting in an infinite set of rules (both of which are potential problems that could arise under the original generative interpretation).

For this reinterpretation to have a computationally tractable implementation, however, two preconditions must be met. First, an independent mechanism must be provided that assigns

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to any string a finite set of trees, including those admitted by the metarules together with the base rules. Second, a procedure must be defined that checks node admissibilities according to the base rules and metarules of the grammar—and that terminates. It is this latter condition that we suspect will not be possible without constraining the weak-generative capacity of MPS grammars. Thus, this perspective does not seem to change the basic expressivity problems of the formalism by itself.

A second alternative, proposed by Kay [1982], is one in which metarules are viewed as chart-manipulating operators on a chart parser. Here too, the metarules are not part of a metagrammar that generates a context-free grammar; rather, they constitute a second kind of rule in the grammar. Just like the meta-node-admissibility interpretation, Kay's explication seems to retain the basic problem of expressive power, though Kay hints at a gain in efficiency if the metarules are compiled into a finite-state transducer.

Finally, an alternative that does not integrate metarules into the object grammar but, on the other hand, does not assign them a role in generating an object grammar either, is to view them as redundancy statements describing the relationships that hold among rules in the full grammar. This interpretation eliminates the problem of generating infinite rule sets that gave rise to the Uszkoreit and Peters results. However, it is difficult to see how the solution supports a computationally useful notion of metarules, since it requires that all rules of the grammar be stated explicitly. Confining the role of metarules to that of stating redundancies prevents their productive application, so that the metarules serve no clear computational purpose for grammar implementation.[3]

We thus conclude that, in contrast to context-sensitive grammars, in which an alternative interpretation of the phrase structure rules makes a difference in weak-generative capacity, MPS grammars do not seem to benefit from the reinterpretations we have investigated.

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[3]As statements about the object grammar, however, metarules might play a role in language acquisition or in diachronic processes.

3. Formal Constraints

Since it appears unlikely that a reinterpretation of MPS grammars can be found that solves their complexity problem, formal constraints on the MPS formalism itself have to be explored if we want to salvage the basic concept of metarules. In the following examination of currently proposed constraints, the two criteria for evaluation are their effects on *computational tractability* and on the *explanatory adequacy* of the formalism.

As an example of constraints that satisfy the criterion of computational tractability but not that of explanatory adequacy, we examine the issue of *essential variables*. These are variables in the metarule pattern that can match an arbitrary string of items in a phrase structure rule. Uszkoreit and Peters have shown that, contrary to an initial conjecture by Joshi (see [Gazdar, 1982, fn. 28]), allowing even one such variable per metarule extends the power of the formalism to recursive enumerability. Gazdar has recommended [1982, p.160] that the power of metarules be controlled by eliminating essential variables, exchanging them for *abbreviatory variables* that can stand only for strings in a *finite* and *extrinsically determined* range. This constraint yields a computationally tractable system with only context-free power.

Exchanging essential for abbreviatory variables is not, however, as attractive a prospect as it appears at first blush. Uszkoreit and Peters [1982] show that by restricting MPS grammars to using abbreviatory variables only, some significant generalizations are lost. Consider the following metarule that is proposed and motivated in [Gazdar 1982] for endowing VSO languages with the category VP. The metarule generates flat VSO sentence rules from VP rules.

(2) $VP \rightarrow V\ U \Rightarrow S \rightarrow V\ NP\ U$

Since U is an abbreviatory variable, its range needs to be stated explicitly. Let us imagine that the VSO language in question has the following small set of VP rules:

(3) $VP \rightarrow V$
   $VP \rightarrow V \: NP$
   $VP \rightarrow V \: \overline{S}$
   $VP \rightarrow V \: \overline{VP}$
   $VP \rightarrow V \: NP \: \overline{VP}$

Therefore, the range of U has to be $\{\epsilon, \: NP, \: \overline{S}, \: \overline{VP}, \: NP \: \overline{VP}\}$.

If these VP rules are the only rules that satisfy the left-hand side of (2), then (2) generates exactly the same rules as it would if we declared U to be an essential variable—i.e., let its range be $(V_T \cup V_N)^*$. But now imagine that the language adopts a new subcategorization frame for verbs,[4] e.g., a verb that takes an NP and an $\overline{S}$ as complements. VP rule (4) is added:

(4) $VP \rightarrow V \: NP \: \overline{S}$

Metarule (2) predicts that VPs headed by this verb do not have a corresponding flat VSO sentence rule. We will have to change the metarule by extending the range of U in order to retain the generalization originally intended by the metarule. Obviously, our metarule did not encode the right generalization (a simple intension-extension problem).

This shortcoming can also surface in cases where the input to a metarule is the output of another metarule. It might be that metarule (2) not only applies to basic verb rules but also includes the output of, say, a passive rule. The range of the variable U would have to be extended to cover these cases too, and, moreover, might have to be altered if its feeding metarules change.

Thus, if the restriction to abbreviatory variables is to have no effect on the weak-generative capacity of a grammar, the range assigned to each variable must include the range that would have actually instantiated the variable on an expansion of the MPS grammar in which the variable was treated as essential. The assignment of a range to the variable can only be done *post factum*. This would be a satisfactory result, were it not for the fact that finding

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[4]Note that it does not matter whether the grammar writer discovers an additional subcategorization, or the language develops one diachronically; the same problem obtains.

the necessary range of a variable in this way is an undecidable problem in general. Thus, to exchange essential for abbreviatory variables is to risk affecting the generative capacity of the grammar—with quite unintuitive and unpredictable results. In short, the choice is among three options: to affect the language of the grammar in ways that are linguistically unmotivated and arbitrary, to solve an undecidable problem, or to discard the notion of exchanging essential for abbreviatory variables—in effect, a Hobson's choice.

An example of a constraint that satisfies the second criterion, that of explanatory adequacy, but not the first, computational tractability, is the *lexical-head* constraint of GPSG [Gazdar and Pullum, 1982]. This constraint allows metarules to operate only on rules whose stipulated head is a lexical (preterminal) category. Since the Uszkoreit and Peters results are achieved even under this restriction to the formalism, the constraint does not provide a solution to the problem of expressive power. Of course, this is no criticism of the proposal, since it was never intended as a formal restriction on the class of languages, but rather as a restriction on linguistically motivated grammars. Unfortunately, the motivation behind even this use of the lexical-head constraint may be lacking. One of the few analyses that relies on the lexical-head constraint is a recent GPSG analysis of coordination and extraction in English [Gazdar, 1981]. In this case—indeed, in general—one could achieve the desired effect simply by specifying that the coefficient of the *bar* feature be *lexical*. It remains to be seen whether the constraint must be imposed for enough metarules so as to justify its incorporation as a general principle.

Even with such motivation one might raise a question about the advisability of the lexical-head constraint on a meta-theoretical level. The linguistic intuition behind the constraint is that the role of metarules is to "express generalizations about possibilities of subcategorization" exclusively [Gazdar, Klein, Pullum, and Sag, 1982, p.39], e.g., to express the passive-active relation. This result is said to follow from principles of $\overline{X}$ syntax [Jackendoff, 1977], in which just those categories that are subcategorized for are siblings of a lexical head. However, in a language with freer word order than English, categories other than those subcategorized for will

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be siblings of lexical heads; they would, thus, be affected by metarules even under the lexical-head constraint. This result will certainly follow from the liberation rule approach to free word order [Pullum, 1982]. The original linguistic generalization intended by the lexical-head constraint, therefore, will not hold cross-linguistically.

Finally, there is the current proposal of the GPSG community for constraining the formal powers of metarules by allowing each metarule to apply only once in a derivation of a rule. Originally dubbed the *once-through hypothesis*, this constraint is now incorporated into GPSG under the name *finite closure* [Gazdar and Pullum, 1982]. Although linguistic evidence for the constraint has never been provided, the formal motivation is quite strong because, under this constraint, the metarule formalism would have only context-free power.

Several linguistic constructions present problems with respect to the adequacy of the finite-closure hypothesis. For instance, the *liberation rule* technique for handling free-word-order languages [Pullum, 1982] would require a noun-phrase liberation rule to be applied twice in a derivation of a rule with sibling noun phrases that permute their subconstituents freely among one another. As a hypothetical example of this phenomenon, let us suppose that English allowed relative clauses to be extraposed in general from noun phrases, instead of allowing just one extraposition. For instance, in this quasi-English, the sentence

(5) Two children are chasing the dog who are small that is here.

would be a grammatical paraphrase of

(6) Two children who are small are chasing the dog that is here.

Let us suppose further that the analysis of this phenomenon involved liberation of the NP $\overline{S}$ substructure of the noun phrases for incorporation into the main sentence. Then the noun-phrase liberation rule would apply once to liberate the subject noun phrase, once again to liberate the object noun phrase. That these are not idle concerns is demonstrated by the following sentence in the free-word-order Australian aboriginal language Warlpiri.[5]

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[5]This example is taken from [van Riemsdijk, 1981].

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(7) Kurdu-jarra-rlu   ka-pala   maliki   wita-jarra-rlu
    child-DUAL-ERG AUX:DUAL dog-ABS small-DUAL-ERG
    yalumpu   wajilipi-nyi
    that-ABS   chase-NONPAST
    Two small children are chasing that dog.

The Warlpiri example is analogous to the quasi-English example in that both sentences
have two discontinuous *NP*s in the same distribution. Furthermore, the liberation rule ap-
proach *has* been proposed as a method of modeling the free word order of Warlpiri. Thus,
it appears that finite closure is not consistent with the liberation rule approach to free word
order.

Adverb distribution presents another problem for the hypothesis. In German, for ex-
ample, and to a lesser extent in English, an unbounded number of adverbs can be quite freely
interspersed with the complements of a verb. The following German sentence is an extreme
example of this phenomenon [Uszkoreit, 1982]. The sequence of its major constituents is given
under (9).

(8) Gestern   hatte   in der Mittagspause
    yesterday   had   during lunch break
    der Brigadier   in der Werkzeugkammer
    the foreman (NOM) in the tool shop
    dem Lehrling   aus Boshaftigkeit langsam
    the apprentice (DAT) maliciously   slowly
    zehn schmierige Gusseisenscheiben unbemerkt
    ten greasy cast iron disks (ACC)   unnoticed
    in die Hosentasche gesteckt
    in the pocket   put
    Yesterday, during lunch break in the tool shop, the
    foreman, maliciously and unnoticed, put ten greasy cast
    iron disks slowly into the apprentice's pocket.

(9) $ADVP \ V_{FIN} \ ADVP \ NP_{SUBJ} \ ADVP \ NP_{IOBJ} \ ADVP \ ADVP \ NP_{DOBJ} \ ADVP \ PP$
    V_{INF}

A metarule might therefore be proposed that inserts a single adverb in a verb-phrase
rule. Repeated application of this rule (in contradiction to the finite-closure hypothesis) would

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achieve the desired effect. To maintain the finite-closure hypothesis, we could merely extend the notion of context-free rule to allow regular expressions on the right-hand side of a rule. The verb phrase rule would then be accurately, albeit clumsily, expressed as, say, $VP \rightarrow V\ NP\ ADVP^*$ or $VP \rightarrow V\ NP\ ADVP^*\ PP\ ADVP^*$ for ditransitives.

Similar constructions in free-word-order languages do not permit such naive solutions. As an example, let us consider the Japanese causative. In this construction, the verb suffix "-sase" signals the causativization of the verb, allowing an extra NP argument. The process is putatively unbounded (ignoring performance limitations). Furthermore, Japanese allows the NPs to order freely relative to one another (subject to considerations of ambiguity and focus), so that a flat structure with some kind of extrinsic ordering is presumably preferable.

One means of achieving a flat structure with extrinsic ordering is by using the ID/LP formalism, a subformalism of GPSG that allows *immediate dominance* (ID) information to be specified separately from *linear precedence* (LP) notions. (Cf. context-free phrase structure grammar, which forces a strict one-to-one correlation between the two types of information.) ID information is specified by context-free style rules with unordered right-hand sides, notated, e.g., $A \rightarrow B, C, D$. LP information is specified as a partial order over the nonterminals in the grammar, notated, e.g., $B < C$ (read B precedes C). These two rules can be viewed as schematizing a set of three context-free rules, namely, $A \rightarrow B\ C\ D$, $A \rightarrow B\ D\ C$, and $A \rightarrow D\ B\ C$.

Without a causativization metarule that can operate more than once, we might attempt to use the regular expression notation that solved the adverb problem. For example, we might postulate the ID rule $VP \rightarrow NP^*, V, sase^*$ with the LP relation $NP < V < sase$, but no matching of NPs with $sase$s is achieved. We might attempt to write a liberation rule that pulls NP-$sase$ pairs from a nested structure into a flat one, but this would violate the finite-closure hypothesis (as well as Pullum's requirement precluding liberation through a recursive category). We could attempt to use even more of the power of regular-expression rules with

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ID/LP, i.e., $VP \rightarrow \{NP, sase\}^*, V$ under the same LP relation. The formalism presupposed by this analysis, however, has greater than context-free power,[6] so that this solution may not be desirable. Nevertheless, it should not be ruled out before the parsing properties of such a formalism are understood.[7] Gunji's analysis of Japanese, which attempts to solve such problems with the multiple application of a *slash introduction* metarule [Gunji, 1980], again raises the problem of violating the finite-closure hypothesis (as well as being incompatible with the current version of GPSG which disallows multiple slashes). Finally, we could always move causativization into the lexicon as a lexical rule. Such a move, though it does circumvent the difficulty in the syntax, merely serves to move it elsewhere without resolving the basic problem.

Yet another alternative involves treating the right-hand sides of phrase structure rules as sets, rather than multisets as is implicit in the ID/LP format. Since the nonterminal vocabulary is finite, right-hand sides of ID rules must be subsets of a finite set and therefore finite sets themselves. This hypothesis is quite similar in effect to the finite-closure hypothesis, albeit even more limited, and thus inherits the same problems as were discussed above.

4. The Ultimate Solution

An obvious way to constrain MPS grammars is to eliminate metarules entirely and replace them with other mechanisms. In fact, within the GPSG paradigm, several of the functions of metarules have been replaced by other metagrammatical devices. Other functions have not, as of the writing of this paper, though it is instructive to consider the cases covered by this class. In the discussion to follow we have isolated three of the primary functions of metarules. This is not intended as an exhaustive taxonomy, and certain metarules may manifest more than one of these functions.

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[6]For instance, the grammar $S \rightarrow \{a, b, c\}^*$ with $a < b < c$ generates $a^n b^n c^n$.

[7]Shieber [forthcoming] provides an algorithm for parsing ID/LP grammars directly that includes a method for utilizing the Kleene star device. It could be extended to even more of the regular expression notation, though the effect of such extension on the time complexity of the algorithm is an open question.

First, we consider generalizations over linear order. If metarules are metagrammatical statements about rules encoding linear order, they may relate rules that differ only in the linear order of categories. With the introduction of ID/LP format, however, the hypothesis is that this latter metagrammatical device will suffice to account for the linear order among the categories within rules. For instance, the problematic adverb and causative metarules could be replaced by extended context-free rules with ID/LP, as was suggested in Section 3 above. Shieber [forthcoming] has shown that a pure ID/LP formalism (without metarules, Kleene star, or the like) is no less computationally tractable than context-free grammars themselves. Although we do not yet know what the consequences of incorporating the extended context-free rules would be for computational complexity, ID/LP format can be used to replace certain word-order-variation metarules.

A second function of metarules was to relate sets of rules that differed only in the values of certain specifed features. It has been suggested [Gazdar and Pullum 1982] that such features are distributed according to certain general principles. For instance, the slash-propagation metarule has been replaced by the distribution of slash features in accord with such a principle.

A third function of metarules under the original interpretation has not been relegated to other metagrammatical devices. We have no single device to suggest, though we are exploring alternative ways to account for the phenomena. Formally, this third class can be characterized as comprising those metarules that relate sets of rules in which the number of categories on the right- and left-hand sides of rules differ. It is this sort of metarule that is essential for the extension of GPSGs beyond context-free power in the Uszkoreit and Peters proofs [1982]. Simply requiring that such metarules be disallowed would not resolve the linguistic issues, however, since this constraint would inherit the problems connected with the regular expression and set notations discussed in Section 3 above. This third class further breaks down into two cases: those that have different parent categories on the right- and left-hand sides of the metarule and those that have the same category on both sides. The first case includes those

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liberation rules that figure in analyses of free-word-order phenomena, plus such other rules as the subject-auxiliary-inversion metarule in English. Uszkoreit [forthcoming] is exploring a method for isolating liberation rules in a separate metagrammatical formalism. It also appears that the subject-auxiliary inversion may be analyzed by already existing principles governing the distribution of features. The second case (those in which the categories on the right- and left-hand sides are the same) includes such analyses as the passive in English. This instance, at least, might be replaced by a lexical-redundancy rule. Thus, no uniform solution has yet been found for this third function of metarules.

We conclude that it may be possible to replace MPS-style metagrammatical formalisms entirely without losing generalizations. We are consequently pursuing research in this area.

5. Conclusion

The formal power of metarule formalisms is clearly an important consideration for computational linguists. Uszkoreit and Peters [1982] have shown that the potential exists for defining metarule formalisms that are computationally "unsafe." However, these results do not sound a death knell for metarules. On the contrary, the safety of metarule formalisms is still an open question. We have merely shown that the constraints on metarules necessary to make them formally tractable will have to be based on *empirical linguistic evidence* as well as solid formal research. The solutions to constraining metarules analyzed here seem to be either formally or linguistically inadequate. Further research is needed in the actual uses of metarules and in constructions that are problematic for metarules so as to develop either linguistically motivated and computationally interesting constraints on the formalisms, or alternative formalisms that are linguistically adequate but not heir to the problems of metarules.

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