Three Improvements to the HPSG Model Theory

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Introduction HPSG is unique among linguistic theories in boasting of a well-developed model theory. However, this model theory is not without its problems. The aim of this paper is to propose three orthogonal improvements to the standard HPSG model theory of Richter 2004. The first one solves the long-standing "Höhle's problem" (Pollard 2001, 2014: 113) of massive spurious ambiguities in HPSG models. This improvement is, strictly speaking, a modification of the linguistic theory that removes unwanted models rather than a modification of the model theory, so it does not necessitate changing the underlying logic (i.e., RSRL), but the other two improvements do involve such changes. The second improvement concerns the analysis of unlike category coordination in Yatabe 2004 (recently invoked in Yatabe and Tam 2021), which requires adding second-order quantification to RSRL. The third improvement is more formal (and, to some extent, philosophical) and consists in a simplification of the HPSG model theory that puts it in line with the usual model theories assumed in logic.

Höhle's problem Consider (1) and assume that the two occurrences of *she* have different INDEX values.

(1) She says she loves him.

In the standard HPSG sort hierarchy (Pollard and Sag 1994: §A.1), *ref* values of INDEX introduce three attributes: PERSON, NUMBER, and GENDER. For both occurrences of *she*, the values of these attributes are objects of sort *3*, *sg*, and *f*, respectively. But, in the case of the two NUM values, are these the same *sg* object, or two different *sg* objects? And what about the values of PERS and GEND? A typical linguistic analysis leaves these questions unanswered, so $2 \times 2 \times 2 = 8$ different configurations of the two INDEX values correspond to such an analysis. Similarly, are the two CASE values the same object of sort *nom* or two different objects? How about HEAD values of the two verbs? And how about the many empty list (*elist*) values in a typical HPSG representation of (1)? Hundreds of different models correspond to (1), differing in ways that linguists do not suspect and certainly do not care about.

A partial solution to this problem is proposed in Richter 2007, where the Unique Empty List Condition stipulates that, within any given structure, there is only one *elist* object. However, the problem is much more general and it is a formal – not a linguistic – problem: it would be unrealistic to expect of linguists that they deal with this massive spurious ambiguity problem within their linguistic theories.

We propose a solution that is based on the observation that, almost always, when two structures look the same, it is safe to assume that they are token identical. For example, in some of the many models of (1), HEAD values of the two verbs are the same *verb* object (with VFORM *fin*, AUX $-$, and INV $-$), so it is safe to constrain models to these in which the two values of HEAD *must* be the same *verb* object. There are very few exceptions to this extensionality assumption, the most prominent one being the standard HPSG binding theory, according to which two structurally isomorphic values of INDEX may be required to be different objects. Similarly, while the INDEX values for the two occurrences of *she* in (1) are structurally the same, two readings of this sentence differ in whether these values are the same *ref* object or two different objects. (A different example of the requirement that two structurally same values be different objects may be found in the architecture for HPSG phonology proposed in Höhle 1999.) Given the rarity of such analyses, we propose that two structurally isomorphic values be the same object unless a particular linguistic analysis explicitly states that such an assumption should not be made.

Technically,[1] we assume the General Identity Principle (GIP) in (2), proposed in Sailer 2003: 116. The relation `are-copies` is defined recursively in a straightforward way: two structures are in this relation if they are of the same species (i.e., maximal sort) and if the corresponding values of their attributes are in this relation.[2]

(2) $\forall\boxed{1}\forall\boxed{2}\,(\texttt{are-copies}(\boxed{1},\boxed{2}) \Rightarrow \boxed{1} \approx \boxed{2})$

In Sailer 2003, the scope of this principle is the part of *sign* that encodes this *sign*'s logical representation, but we will assume that it applies universally. This implies that all run-of-the-mill structures are extensional; for example, if nothing more is said, this would require the two 3rd person singular feminine INDEX values in the representation of (1) to be token-identical. However, the linguist may specify a given sort as intensional, by adding one more attribute, call it INT(ensional), whose value is universally constrained to be – cyclically – the structure of this sort itself; see (3).

(3) $\forall\boxed{1}\forall\boxed{2}\,(\boxed{1}\big[\textsc{int}\ \boxed{2}\big] \Rightarrow \boxed{1} \approx \boxed{2})$

[1] Many thanks to ⟨*withheld for anonymity*⟩ for discussion (including the suggestion of the name INTENSIONAL for the attribute introduced below), as well as for the verification of this solution in MoMo (Richter and Ovchinnikova 2003).

[2] See Sailer 2003: 116, (130), for the formal definition.

(4) $\boxed{1}\begin{bmatrix} \textit{ref} \\ \text{PERS } \boxed{3}\,3 \\ \text{NUM } \boxed{4}\,\textit{sg} \\ \text{GEND } \boxed{5}\,\textit{f} \\ \text{INT } \boxed{1} \end{bmatrix}$ $\boxed{2}\begin{bmatrix} \textit{ref} \\ \text{PERS } \boxed{3}\,3 \\ \text{NUM } \boxed{4}\,\textit{sg} \\ \text{GEND } \boxed{5}\,\textit{f} \\ \text{INT } \boxed{2} \end{bmatrix}$

Assuming that *ref* is specified for INT, and given (2)–(3), the two INDEX values are as in (4). Note that the corresponding values of PERS, NUM, and GEND are token identical: they are of the same sorts and they have no attributes, so they stand in the `are-copies` relation; hence, they must be the same objects according to GIP in (2). How about the whole *ref* objects $\boxed{1}$ and $\boxed{2}$ – do they stand in the `are-copies` relation? According to the definition of `are-copies` in Sailer 2003: 116, (130), $\boxed{1}$ and $\boxed{2}$ stand in this relation iff 1) they are of the same sort (yes), and 2) the values of PERS are in this relation (yes), and 3) the values of NUM are (yes), and 4) GEND (yes), and, finally and crucially, 5) the values of INT, i.e., $\boxed{1}$ and $\boxed{2}$, are in this relation. So, $\boxed{1}$ and $\boxed{2}$ (*qua* the whole objects depicted in (4)) stand in this relation iff they (*qua* the values of INT) stand in this relation. That is, the definition of `are-copies` does not determine whether $\boxed{1}$ and $\boxed{2}$ stand in this relation. This means that same-looking objects with the INT attribute are exempt from GIP – they are truly intensional. Hence, assuming that *ref* is specified for INT, the standard binding theory works despite GIP. Moreover, if no other types are specified for INT, the sentence in (1) has exactly two (instead of hundreds) models, differing only in whether INDEX values of the two feminine pronouns are token-identical or not, i.e., only in a way that is linguistically relevant.

Unlike Category Coordination In order to handle examples such as (5) (from Bayer 1996: 585, fn. 7, (ii.c–d)), Yatabe (2004: 343) assumes a lexical entry for *emphasized* schematically represented in (6), with the category of the object specified disjunctively as an NP (nominal phrase; see *noun*) or a CP (complementiser phrase; *comp*).

(5) a. We emphasized [[Mr. Colson's many qualifications]$_{\text{NP}}$ and [that he had worked at the White House]$_{\text{CP}}$].

b. We emphasized [[that Mr. Colson had worked at the White House]$_{\text{CP}}$ and [his many other qualifications]$_{\text{NP}}$].

$$(6)\quad \begin{bmatrix} \text{PHON } \langle \text{emphasized} \rangle \\ \ldots\text{VALENCE} \begin{bmatrix} \text{SUBJ } \left\langle \left[\ldots\text{HEAD } c\left(\begin{bmatrix} \textit{noun} \\ \text{CASE } \textit{nom} \end{bmatrix} \right) \right] \right\rangle \\ \text{COMPS } \langle [\ldots\text{HEAD } c(\textit{noun} \vee \textit{comp})] \rangle \end{bmatrix} \end{bmatrix}$$

The key idea is the use of the distributive functor, *c*, defined in (7) (Yatabe 2004: 343, (12)):

$$(7)\quad \boxed{1} : c(\alpha) \;\equiv\; \boxed{1} : \alpha \;\vee\; (\boxed{1} : [\text{ARGS } \langle \boxed{a_1}, \ldots, \boxed{a_n} \rangle] \;\wedge\; \boxed{a_1} : \alpha \wedge \ldots \wedge \boxed{a_n} : \alpha)$$

Here α is a description, such as $\begin{bmatrix} \textit{noun} \\ \text{CASE } \textit{nom} \end{bmatrix}$ and *noun* $\vee$ *comp* in (6), and an object $\boxed{1}$ satisfies $c(\alpha)$ – written as $\boxed{1} : c(\alpha)$ – iff it either satisfies the description α directly (see the first disjunct in (7)), or if it is the HEAD value of a coordinate structure with conjuncts having HEAD values $\boxed{a_1}, \ldots, \boxed{a_n}$ (see the second disjunct); in the latter case, each of $\boxed{a_1}, \ldots, \boxed{a_n}$ must satisfy α independently.

The intention of (7) is clear, but it is far from clear how to formally encode it. That is, for each particular description α it is easy to define a unary relation corresponding to $c(\alpha)$ in (7). What is far from clear is how to define *c* in its generality (i.e., in a way simulating (7)), as a binary relation between objects and arbitrary descriptions α. The problem is that, in RSRL, arguments of relations are objects, not descriptions.

We argue that this kind of analysis of unlike category coordination (UCC) is on the right track – to the extent that justifies making RSRL a second-order language, in which not only objects but also their properties may be quantified over.[3] While linearisation-based approaches to UCC were popular in HPSG in 2000s (e.g., Crysmann 2003, Beavers and Sag 2004, Chaves 2006, 2008), it is clear now that at least some cases of UCC must be analysed as direct coordination of small constituents, rather than as coordination of larger verbal constituents and subsequent ellipsis (see, e.g., Levine 2011). Conceding this point, Chaves 2013 proposes to save the law of the coordination of likes (as it is sometimes called after Williams 1981) by reanalysing categories as constellations of some morphosyntactic features and moving troublesome distributive restrictions, such as those encoded in (6), to semantics. Unfortunately, this approach is untenable, given that CASE is one of the remaining categorial features in Chaves 2013 and that instances of unlike case coordination are well known (and have also been discussed within HPSG; see Przepiórkowski 1999: §5.3.1 and Levy 2001: §4). Hence, Yatabe's (2004) is the most convincing approach to UCC currently on the HPSG market and, given that the distributive functor *c* is also explicitly invoked in recent work (Yatabe and Tam 2021: 74), there is an increasing need to make it formalisable.[4]

[3] Second-order systems usually have higher computational complexity than their first-order equivalents, but given that already first-order RSRL is undecidable (Kepser 2004), second-order RSRL is in the same class as standard RSRL.

[4] This analysis also encodes the standard LFG approach to coordination, on which certain properties are distributive so that, when

This calls for extending the syntax and semantics of RSRL to handle second-order quantification. The modifications of the standard RSRL definitions are relatively straightforward:[5]

- signatures do not only specify arities of relation symbols, but also types of their arguments (each either e or et);
- interpretations of relation symbols are trivially modified so that they satisfy such signatures (i.e., they are sets of tuples whose each element is an object or a set of objects, depending on the type specified in the signature);
- the set of variables, $\mathcal{VAR}$, is the disjoint sum of $\mathcal{VAR}_e$ (first-order variables) and $\mathcal{VAR}_{et}$ (second-order variables);
- variable assignments assign objects to elements of $\mathcal{VAR}_e$ and sets of objects to elements of $\mathcal{VAR}_{et}$; the interpretation of quantifiers is extended to second-order variables correspondingly;
- apart from the usual first-order terms $\mathcal{T}^{\Sigma}_{e}$ (for the signature Σ), there are also second-order terms, $\mathcal{T}^{\Sigma}_{et}$, specified recursively simultaneously with the set of formulae, $\mathcal{D}^{\Sigma}$, as the disjoint sum of second-order variables ($\mathcal{VAR}_{et}$) and all formulae ($\mathcal{D}^{\Sigma}$);
- two clauses of the definition of formulae (Richter 2004: 165) are further modified so that:
  - the variables which are arguments of relation symbols are of the right type e or et,
  - $\tau_1 \approx \tau_2$ is a formula if both terms are of the same type (i.e., both are e or both are et);
- importantly, a new kind of formula is added: $\tau_1(\tau_2)$, where $\tau_1 \in \mathcal{T}^{\Sigma}_{et}$ and $\tau_2 \in \mathcal{T}^{\Sigma}_{e}$;
- the interpretation of $\tau_1(\tau_2)$ is the set of all these objects of the universe U on which the interpretation of τ_2 belongs to the interpretation of τ_1; more formally: $D^{ass}_{\mathsf{I}}(\tau_1(\tau_2)) = \{u \in \mathsf{U} : T^{ass}_{\mathsf{I}}(\tau_2)(u) \in D^{ass}_{\mathsf{I}}(\tau_1)\}$.

Note that, apart from the extended interpretations of relation symbols, models are not affected by these changes: they are still collections of objects of particular species related via particular attributes.

Given these extensions, the lexical entry in (6) may be represented as in (8), with the definition of c in (7) formalised via relation c in (9).

(8) $$\begin{bmatrix} \text{PHON} & \langle \text{emphasized} \rangle \\ \ldots\text{VALENCE} & \begin{bmatrix} \text{SUBJ} & \langle [\ldots\text{HEAD } \boxed{1}] \rangle \\ \text{COMPS} & \langle [\ldots\text{HEAD } \boxed{2}] \rangle \end{bmatrix} \end{bmatrix} \begin{array}{l} \wedge\ \alpha_1 \approx (: \sim \textit{noun} \wedge :\text{CASE} \sim \textit{nom}) \\ \wedge\ \alpha_2 \approx (: \sim \textit{noun} \vee : \sim \textit{comp}) \\ \wedge\ \mathsf{c}(\boxed{1}, \alpha_1) \wedge \mathsf{c}(\boxed{2}, \alpha_2) \end{array}$$

(9) $$\forall \boxed{1}_e\, \forall \alpha_{et}\ (\ \mathsf{c}(\boxed{1}, \alpha)\ \Leftrightarrow\ \alpha(\boxed{1})\ \vee\ \exists \boxed{a_1} \ldots \exists \boxed{a_n}\ (\boxed{1}[\text{ARGS } \langle \boxed{a_1}, \ldots, \boxed{a_n} \rangle]\ \wedge\ \alpha(\boxed{a_1}) \wedge \ldots \wedge \alpha(\boxed{a_n})\ )\ )$$

Simplifying the HPSG Model Theory Since King 1999, HPSG models are assumed to be exhaustive (see Richter 2004, 2007; cf. Pollard 1999), i.e., contain all possible kinds of structures licensed by the grammar. For example, a single HPSG model of English will contain structures for all possible English utterances and words, as well as many partial structures satisfying the grammar (e.g., various *local* or *synsem* objects). This corresponds to the intuition that grammars describe whole languages. However, there is another valid intuition: that grammars describe possible utterances. This latter intuition leads to much smaller models: each model corresponds to a single utterance and only the collection of all models corresponds to the whole language.

By way of analogy, consider the artificial toy problem of describing all configurations of black and white objects such that each black object is related to at least one white object and vice versa. The following first order formulae are a reasonable theory of such configurations:

(10) $\forall x.\ black(x) \leftrightarrow \neg white(x)$

(11) $\forall x \forall y.\ bw(x,y) \rightarrow black(x) \wedge white(y)$

(12) $\forall x.\ black(x) \rightarrow \exists y.\ white(y) \wedge bw(x,y)$

(13) $\forall x.\ white(x) \rightarrow \exists y.\ black(y) \wedge bw(y,x)$

Together they are saying that everything is either $black$ or $white$ (see (10)) and that there is a relation, bw, which holds between $black$ things and $white$ things (see (11)) such that every $black$ thing is in this relation with some (at least one) $white$ thing (see (12)) and every $white$ thing is related to some (at least one) $black$ thing (see (13)). There are models of this theory of any cardinality apart from 1 (including transfinite cardinalities): the empty model satisfies (10)–(13) and so does, e.g., any model which contains exactly one $white$ thing and arbitrarily many (but at least one) $black$ things appropriately related to it. Now imagine that, as in (R)SRL, models were required to be exhaustive, i.e., each model would have to contain all possible configurations of white and black objects. It is not clear what such models would contribute to our understanding of the described black and white configurations above the simpler non-exhaustive models, but it is clear that they would be dubious from the point

they are applied to a coordinate structure, they independently distribute to all conjuncts (see, e.g., Dalrymple and Kaplan 2000 and Przepiórkowski and Patejuk 2012).

[5] See Richter 2004: §3.1 for the standard definitions and meanings of particular symbols. We simplify throughout by ignoring chains.

of view of the standard (ZFC) set theory: such models would be too large to be sets.[6]

Also in the case of HPSG, exhaustive models lead to some serious problems, identified in Richter 2007.[7] One, dubbed *twin structures*, is that some parts of the model might simultaneously belong to two different utterances, which does not correspond to any empirical facts. Another, called *stranded structures*, is that models may contain structures smaller than utterances (e.g., certain structures rooted in *local* objects), including structures (called *stranded monster structures* in Richter 2007) which may never be parts of any utterances and which are intuitively clearly ill-formed. Richter 2007 deals with these problems by imposing restrictions on HPSG signatures, to the effect that all sorts (including such formerly atomic sorts as *nom* or *sg*) are specified for the attribute EMBEDDED, whose value is the root of the utterance. This leads to very different structures than HPSG linguists are used to, and to massive cyclicity.

Richter 2007: 102 claims that the problem of *stranded monster structures* arises because "[t]he grammars in the HPSG literature are not precise enough for their models to match the intentions of linguists". (This justifies the solution alluded to above, consisting in the modifications of the grammar rather than the model theory.) We do not agree with this diagnosis. On the contrary, we claim that the problem arises because the HPSG model theory does not sufficiently meet the needs of linguists, who only care about utterances and their components, and do not intend their grammars to say anything about, for example, arbitrary objects of sort *local* outside of utterances.

We demonstrate that all the problems identified in Richter 2007 disappear when a leaner approach to modelling is adopted, upon which each model corresponds to a single utterance. Specifically, we propose that HPSG models be *rooted* (*point generated*) in the sense of modal logic:[8] one object of the universe is singled out and it serves as the root of the model. Technically, the definition of interpretation is now a quintuple $\langle \mathsf{U}, \mathsf{r}, \mathsf{S}, \mathsf{A}, \mathsf{R} \rangle$, where U, S, A, and R are defined in the standard way (i.e., as the universe, assignment of species to objects, interpretation of attributes, and interpretation of relation symbols, respectively; Richter 2004: 157), and $\mathsf{r} \in \mathsf{U}$ is the distinguished object. We assume that the root may be accessed directly in formulae, i.e., that the definition of terms (Richter 2004: 162) is extended so that not only ":" and a (first-order) variable may be the prefix of a path, but also the reserved symbol r, whose interpretation is the root object r.

One immediate advantage of this approach is that it makes it easy to state constraints on utterances. For example, the requirement that utterances have empty SLASH may be stated directly as in (14) (assuming that empty sets are modelled via objects of sort *eset*; Richter 2004: 281), without the need for technical boolean attributes such as ROOT (see, e.g., Ginzburg and Sag 2000).

(14) r NONLOCAL SLASH $\sim$ *eset*

In order to make sure that the distinguished object r is really the root of the whole model, we assume the following constraint, where `component` is defined in the standard way (e.g., Sailer 2003: 115–116):

(15) $\forall \boxed{1}\ \texttt{component}(\boxed{1}, r)$

This states that each object in the model is reachable from r via some sequence of attributes.

This simple extension of HPSG models to rooted models solves the problems addressed in Richter 2007. There are no *twin structures*, as each model corresponds to a single utterance, and there are no *stranded structures* (*monster* or not), as each structure is a part of an utterance. Unlike the proposal in Richter 2007, this solution does not require extensions of signatures and does not result in rather different models than what HPSG linguists are used to, ones that have the cyclicity-inducing EMBEDDED attribute defined on every sort. In the full paper we show that this solution is also compatible with the general approach of Pollard 1999.

Conclusion We proposed three independent improvements to the standard model theory of HPSG. They are conservative in the sense that they do not – or only minimally do – impact extant analyses. Only the first, the solution of Höhle's problem – which is, strictly speaking, an improvement of grammars rather than of the model theory – requires a minimal modification of the standard signature: adding INT to *ref*. We feel this is a small price to pay for getting rid of the long-standing embarrassment of massive spurious ambiguity of HPSG theories. The other two improvements do not require any changes in previous linguistic analyses, but they open new possibilities: to quantify over descriptions (which is required to formally encode Yatabe 2004) and to state constraints on utterances in a direct way. The last improvement also provides an alternative – and leaner – solution to the problems identified in Richter 2007.

[6] In brief, they would contain configurations of arbitrarily large cardinality, so they themselves would not have any cardinality (as there is no maximal cardinality).

[7] However, the solutions proposed in Richter 2007 still assume exhaustivity.

[8] See, e.g., Blackburn *et al.* 2010: 56, 107; cf. also *singly generated* models in Pollard 1999.

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