A Mathematical Formalism for Linguistic Theories with an Application in Head-Driven Phrase Structure Grammar

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resentation is isomorphic to each possible token in an equivalence class of indistinguishable possible tokens of the language, and for each equivalence class of indistinguishable possible tokens, the strong generative capacity of the grammar contains a representation of the tokens in the class. One of the three definitions of the strong generative capacity of a grammar of Pollard 1999 will establish a direct connection to the exhaustive models of a grammar, thus completing the picture of how the three explanations of the meaning of a grammar are related.

2.2.2.1 SRL

My presentation of SRL follows the definitions of King 1999,[34] which generalizes some of the original definitions of King 1989. For ease of comparison with corresponding notions in HPSG 87 and with the extended formalism of HPSG 94 of Chapter 3, I adopt the notational conventions that I use there.

The fundamental intuition about formal languages that underlies SRL is that each expression of its formal languages is true or false *of an entity* in an interpretation. Given an interpretation, an expression thus denotes a set of entities. It is because of this property that logics like SRL are sometimes referred to as logics of descriptions. The idea is that the languages are used to describe entities. As formal languages of HPSG, they are used to describe the entities that constitute a natural language. SRL provides a class of formal languages, each of which consists of a signature and a class of interpretations of the signature. Each signature provides the non-logical symbols from which the formal language is constructed.

Definition 15 Σ *is an* ***SRL signature*** *iff*

> Σ *is a triple* $\langle \mathcal{S}, \mathcal{A}, \mathcal{F} \rangle$,
>
> $\mathcal{S}$ *is a set,*
>
> $\mathcal{A}$ *is a set, and*
>
> $\mathcal{F}$ *is a total function from the Cartesian product of* $\mathcal{S}$ *and* $\mathcal{A}$ *to the power set of* $\mathcal{S}$.

I call each element of $\mathcal{S}$ a *species*, each element of $\mathcal{A}$ an *attribute*, and $\mathcal{F}$ the *appropriateness function*. The symbols :, $\sim$, $\approx$, $\neg$, [,], $\wedge$, $\vee$, and $\rightarrow$

[34] The definitions of King 1999 are consistent with the ones presented in Pollard 1999.

are reserved symbols, and I will henceforth assume that none of them are a species or an attribute symbol. In contrast to King 1989, infinite sets of species are admitted. The original definition was more restrictive, because King 1989 was interested in logical aspects of SRL that will not play a role below.

It is useful to have a compact terminology to talk about the appropriateness of attributes and species. I say that an attribute α is appropriate to a species σ if $\mathcal{F}\langle\sigma,\alpha\rangle$ is a nonempty set of species. A species σ' is appropriate for an attribute α at some species σ if σ' is an element of $\mathcal{F}\langle\sigma,\alpha\rangle$.

A striking difference between an SRL signature and an 87 signature is that an SRL signature does not include a sort hierarchy. Instead, it simply provides a set of species. This simplification also means that the appropriateness function is much simpler, because it no longer has to enforce the inheritance of appropriate attributes and attribute values in accordance with the ordering of the sorts in the sort hierarchy. In Pollard and Sag 1994 the appropriateness function is given in so-called "feature declarations" that obey the 87 appropriateness conditions that we have seen in 87 signatures: If an attribute α is 87 appropriate to some sort σ, then it is also 87 appropriate to all of its subsorts; and the sort that is the value of the 87 appropriateness function at the subsorts of σ and α is at least as specific as the value of $\mathcal{F}$ at σ and α. At first blush, the lack of an explicit sort hierarchy seems to be a problem for using SRL in formalizing HPSG 94 grammars, because, just as HPSG 87 grammars, they make heavy use of sort hierarchies and of attribute inheritance. However, King 1999, pp. 329–331, shows that the inclusion of a sort hierarchy in the signature of the formal languages for HPSG 94 is mathematically superfluous and that the essential information that is encoded in sort hierarchies can be expressed without them. Before I can explain why this is the case, I need to introduce interpretations of signatures:

Definition 16 *For each SRL signature* $\Sigma = \langle\mathcal{S},\mathcal{A},\mathcal{F}\rangle$*,* I *is a* Σ ***interpretation*** *iff*

> I *is a triple* $\langle\mathsf{U},\mathsf{S},\mathsf{A}\rangle$*,*
>
> U *is a set,*
>
> S *is a total function from* U *to* $\mathcal{S}$*,*
>
> A *is a total function from* $\mathcal{A}$ *to the set of partial functions from* U *to* U*,*

for each $\alpha \in \mathcal{A}$ *and each* $u \in \mathsf{U}$,

$$\mathsf{A}(\alpha)(u) \text{ is defined iff } \mathcal{F}\langle \mathsf{S}(u), \alpha\rangle \neq \emptyset, \text{ and}$$
$$\text{if } \mathsf{A}(\alpha)(u) \text{ is defined then } \mathsf{S}(\mathsf{A}(\alpha)(u)) \in \mathcal{F}\langle \mathsf{S}(u), \alpha\rangle.$$

U is the *set of entities in the universe*, S is the *species assignment function*, and A is the *attribute interpretation function*.

S partitions the universe of entities by assigning each entity exactly one species. I sometimes simply say that an entity has a species. Informally, I also say that a species denotes a set of entities, which is the set of entities that have that species. The attribute interpretation function provides a denotation for the attribute symbols. Each attribute denotes a partial function from entities to entities. The attribute interpretation function must obey appropriateness. That means that an attribute is defined on an entity exactly if the attribute is appropriate to the species of the entity; and if an attribute is defined on an entity, u, then the species of the entity u' which is the result of interpreting α on u, is appropriate for the species of u and α.[35]

With the definition of Σ interpretations in hand, I can now return to the question of how SRL can express HPSG 94 sort hierarchies without representing them in its signatures. The reason that an SRL signature suffices to express the sort hierarchies of HPSG 94 grammars as characterized in Pollard and Sag 1994, pp. 395–396, is the intended interpretation of sort hierarchies. Algebraically, the sort hierarchies of HPSG 94 are finite partial orders.[36] The terminology that Pollard and Sag 1994 uses to describe the direction of the ordering relation is not entirely consistent. Pollard and Sag assume a sort, *object*, which subsumes all other sorts and denotes all entities, and they call all sorts subsorts of *object*. Sorts that do not have a proper subsort are called maximal or maximally specific. This terminology agrees with the sort hierarchy of 87 signatures (Definition 1, page 30). On the other hand, Pollard and Sag 1994, pp. 17–18, assumes a reversed ordering that agrees with the

[35]The reader might notice that the behavior of attribute interpretation with respect to appropriateness corresponds to the total well-typedness of concrete feature structures.

[36]Pollard and Sag 1994, p. 395, also postulates that, for each sort σ_1, for each sort σ_2, for each sort σ_3, if σ_1 is a subsort of σ_2 and of σ_3, then either σ_2 is a subsort of σ_3 or *vice versa*. In other words, no sort is an immediate proper subsort of two distinct sorts. While that condition holds for the grammar of Pollard and Sag 1994, it is not met by grammars with so-called multiple inheritance hierarchies (see Kathol 1995; Sag 1997; Przepiórkowski 1999a, among many others). Since I am interested in a formalism that captures as much of the literature of HPSG 94 as possible, I will ignore Pollard and Sag's additional restriction.

one in Carpenter 1992, where the more inclusive sorts are lower in the ordering. For example, according to that convention *sign* is immediately below the sorts *word* and *phrase*. Since the direction of the ordering is merely a matter of convention, and no mathematical properties depend on which one we choose, I choose to retain the direction of ordering of 87 signatures to keep my terminology coherent across the different formalisms, and because that ordering is consistent with the intuitive understanding of the terms subsort, supersort, and maximally specific sort.

With respect to the denotation of sorts, Pollard and Sag assume that if σ' is a subsort of σ, then σ' denotes a subset of σ. The root sort, *object*, denotes all entities in the interpretation. Each entity is in the denotation of exactly one maximally specific sort. Given the assumptions about the sort hierarchy, the denotation of each of its sorts is thus fully determined by the denotation of the maximally specific sorts that it subsumes. Given the assumptions about attribute inheritance of Pollard and Sag 1994, the domain and range of the function in the denotation of each attribute is also fully determined by the appropriateness of the attribute to maximally specific sorts. For each signature with a sort hierarchy of the kind described above and with the respective attribute inheritance, we can thus give a function that maps it to an SRL signature such that each interpretation of the original signature is also an interpretation of the derived SRL signature. In addition, as King 1999, p. 330, shows, the use of nonmaximal sorts in descriptions of the formal language can easily be understood as metasyntactic notation for bigger, disjunctive descriptions that only use maximal sorts. It follows immediately that the formal languages of SRL are capable of expressing all aspects of HPSG 94 that are related to sort hierarchies.

The SRL signature in Figure 2.4 illustrates how a sort hierarchy is expressed in an SRL signature without having it explicitly included. It corresponds directly to the 87 signature with sort hierarchy in Figure 2.2. $\mathcal{S}$ is the set of maximally specific sorts of the 87 signature. The set of attributes, $\mathcal{A}$, does not change. The appropriateness function, $\mathcal{F}$, is now a total function, and it states for every species and every attribute which species are appropriate for them. If no species is appropriate for a given pair then the value of $\mathcal{F}$ at that pair is the empty set. For example, DRIVER is not appropriate to *man*, thus $\mathcal{F}\langle man, \text{DRIVER}\rangle = \emptyset$. For every species, σ, in the 87 signature for which an attribute, α, is 87 appropriate, the value of the corresponding appropriateness function in our SRL signature without sort hierarchy, $\mathcal{F}\langle \sigma, \alpha\rangle$, is the set of the maximally specific sorts subsumed by its sort value in the 87 signature. For example, since *person* is appropriate to the pair '$\langle vw, \textsc{owner}\rangle$' in the 87 signature of Figure 2.2, the value of $\mathcal{F}\langle vw, \textsc{owner}\rangle$ is now the set $\{man, woman\}$.

Figure 2.4: An example of an SRL signature

$\mathcal{S} = \{vw, bmw, man, woman\}$,

$\mathcal{A} = \{\textsc{driver}, \textsc{owner}, \textsc{likes-best}\}$, and

$$\mathcal{F} = \left\{ \begin{array}{l} \langle\langle vw, \textsc{owner}\rangle, \{man, woman\}\rangle, \langle\langle vw, \textsc{driver}\rangle, \{man, woman\}\rangle, \\ \langle\langle vw, \textsc{likes-best}\rangle, \{\}\rangle, \langle\langle bmw, \textsc{owner}\rangle, \{man, woman\}\rangle, \\ \langle\langle bmw, \textsc{driver}\rangle, \{man, woman\}\rangle, \langle\langle bmw, \textsc{likes-best}\rangle, \{\}\rangle, \\ \langle\langle man, \textsc{likes-best}\rangle, \{vw, bmw, man, woman\}\rangle, \\ \langle\langle man, \textsc{driver}\rangle, \{\}\rangle, \langle\langle man, \textsc{owner}\rangle, \{\}\rangle, \\ \langle\langle woman, \textsc{likes-best}\rangle, \{vw, bmw, man, woman\}\rangle, \\ \langle\langle woman, \textsc{driver}\rangle, \{\}\rangle, \langle\langle woman, \textsc{owner}\rangle, \{\}\rangle \end{array} \right\}$$

From a more general perspective, the fact that an explicit sort hierarchy is mathematically superfluous in HPSG 94 but not in HPSG 87 is a consequence of the fact that signatures no longer form the basis of a subsumption ordering of feature structures that is meant to capture their relative degree of informativeness. The lack of a subsumption ordering on the level of entities is directly reflected by the fact that there are no entities of nonmaximal sorts in the interpretations of SRL signatures. The entities are no longer thought of as information bearing objects, but as models of linguistic entities of some kind.

The fact that each 87 signature with a sort hierarchy can be translated into a corresponding SRL signature without a sort hierarchy that has the same interpretations does not mean that sort hierarchies are not linguistically relevant. In principle, it is conceivable that psycholinguistic evidence which supports the representational reality of a sort hierarchy can be found. One research area where this question could be investigated is language acquisition.[37] Green 2000 programmatically explores the idea that first language acquisition proceeds along incremental and largely monotonic extensions of a

[37]To the best of my knowledge, ideas about the psychological reality of sort hierarchies, although alluded to occasionally, are mere speculations that have not been tested in scientific experiments yet. Moreover, the computational results about the description languages of HPSG 94 of Section 3.3 caution against far-reaching assumptions about their psychological reality.

sort hierarchy that is extended as more and more types of linguistic entities are distinguished by the child.[38] From the practical perspective of a grammar writer, sort hierarchies provide the means for a more compact notation of principles and for a useful structuring of the empirical domain in the eyes of the linguist. Even if finite sort hierarchies are superfluous from a mathematical perspective, they can still be an expedient syntactic construct for writing grammars.

The logical language of SRL is designed to describe (sets of) entities. Given an interpretation, essentially, we can say that entities have a certain sort ("sort assignment"); or that a certain attribute is defined on an entity, whose interpretation then leads to another entity; or that one entity equals another entity. To achieve this, SRL provides a set of terms, which are composed of the reserved symbol, ':', and the attributes of a given SRL signature, Σ, and a set of descriptions, which are built from the terms, the species of Σ, and reserved symbols for expressing sort assignment and equality, '$\sim$' and '$\approx$'. The descriptions are closed under negation, conjunction, disjunction, and implication. Other logical connectives can be obtained by combinations of these. I define Σ terms and Σ descriptions simultaneously:

Definition 17 *For each SRL signature $\Sigma = \langle \mathcal{S}, \mathcal{A}, \mathcal{F} \rangle$, $\mathcal{T}^\Sigma$ and $\mathcal{D}^\Sigma$ are the smallest sets such that*

$: \in \mathcal{T}^\Sigma$,

for each $\alpha \in \mathcal{A}$ *and each* $\tau \in \mathcal{T}^\Sigma$, $\tau\alpha \in \mathcal{T}^\Sigma$,

for each $\sigma \in \mathcal{S}$, *for each* $\tau \in \mathcal{T}^\Sigma$, $\tau \sim \sigma \in \mathcal{D}^\Sigma$,

for each $\tau_1 \in \mathcal{T}^\Sigma$, *for each* $\tau_2 \in \mathcal{T}^\Sigma$, $\tau_1 \approx \tau_2 \in \mathcal{D}^\Sigma$,

for each $\delta \in \mathcal{D}^\Sigma$, $\neg\delta \in \mathcal{D}^\Sigma$,

for each $\delta_1 \in \mathcal{D}^\Sigma$, *for each* $\delta_2 \in \mathcal{D}^\Sigma$, $[\delta_1 \wedge \delta_2] \in \mathcal{D}^\Sigma$,

for each $\delta_1 \in \mathcal{D}^\Sigma$, *for each* $\delta_2 \in \mathcal{D}^\Sigma$, $[\delta_1 \vee \delta_2] \in \mathcal{D}^\Sigma$, *and*

for each $\delta_1 \in \mathcal{D}^\Sigma$, *for each* $\delta_2 \in \mathcal{D}^\Sigma$, $[\delta_1 \rightarrow \delta_2] \in \mathcal{D}^\Sigma$.

[38] The formal foundations underlying Green's account are, however, not entirely clear to me, as her terminology fluctuates between HPSG 87, HPSG 94 and terms that apparently stem from other sources not directly related to HPSG formalisms. It remains to be seen if her research program can be rigorously rendered in a formalism for HPSG.

For each SRL signature Σ, I call each element of the set $\mathcal{T}^\Sigma$ a Σ *term*, and each element of $\mathcal{D}^\Sigma$ a Σ *description*.

A Σ term consists of the reserved symbol, ':', followed by a (possibly empty) finite string of Σ attributes. Just as in Chapter 2, I will use the term "paths" to refer to finite strings of attributes. The symbol ':' can be viewed as the single variable of the languages of SRL. When we define denotations for our expressions, it will denote the entities being described. I call Σ descriptions of the form $\tau \sim \sigma$ *sort assignments*; Σ descriptions of the form $\tau_1 \approx \tau_2$ are *path equations*.

Superficially, the Σ descriptions of SRL do not bear any apparent resemblance to the conventional, loosely specified syntax of AVM diagrams that linguists use. King 1989, pp. 106–135, addresses this issue, and provides a translation from the expressions of formally defined languages of attribute value matrices to SRL's descriptions that, under certain conditions, preserves the intuitively intended meaning of the attribute value matrices. For my discussion of the SRL-based formalisms of HPSG 94, it suffices to know that a translation is possible in principle, and to appeal to an informal understanding of how AVM diagrams and Σ descriptions correspond. Once I have presented my extension of SRL in Section 3.1, I will return to the issue of linguistic notation in Section 3.2 and define an AVM syntax for the extended formalism that is modeled after the notational conventions of the HPSG literature.

Before discussing a few examples of descriptions, I want to define the denotation of descriptions in interpretations. To understand the denotation of terms, it might initially be helpful to compare the term interpretation function, T_{I}, of a given Σ interpretation $\mathsf{I} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$, to the iterated transition function, Δ^*, of a given concrete feature structure under Σ with transition function Δ. The denotation of the term consisting of the colon corresponds to the transition from one node to another by interpreting the empty path, and the denotation of a term of the form $:\pi$, where π is a nonempty path, corresponds to the transition from one node to another by interpreting π. The elements of U correspond to the nodes of the concrete feature structure.[39] That means that by interpreting a term at an element, u, of U, we transit

[39]There is, of course, no connectivity condition on interpretations that stipulates that each element of U be reachable from some root element in U. The Σ interpretations of SRL are more general structures than (totally well-typed and sort resolved) concrete feature structures. I will discuss the relationship between concrete feature structures and interpretations of SRL signatures in more detail in Sections 2.2.2.3 and 2.2.2.4.

from u to another element of U. In the special cases of a cyclic transition or a term consisting only of the colon, the element that we reach is identical to u. Since descriptions are built from terms, their interpretation depends directly on the interpretation of terms, and I define the two interpretation functions simultaneously:

Definition 18 *For each SRL signature $\Sigma = \langle \mathcal{S}, \mathcal{A}, \mathcal{F} \rangle$, for each Σ interpretation $\mathsf{I} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$, T_I is the total function from $\mathcal{T}^\Sigma$ to the set of partial functions from U to U, and D_I is the total function from $\mathcal{D}^\Sigma$ to the power set of U such that for each $u \in \mathsf{U}$,*

$T_\mathsf{I}(:)(u)$ is defined and $T_\mathsf{I}(:)(u) = u$,

for each $\tau \in \mathcal{T}^\Sigma$, for each $\alpha \in \mathcal{A}$,

$T_\mathsf{I}(\tau\alpha)(u)$ is defined
iff $T_\mathsf{I}(\tau)(u)$ is defined and $\mathsf{A}(\alpha)(T_\mathsf{I}(\tau)(u))$ is defined, and

if $T_\mathsf{I}(\tau\alpha)(u)$ is defined

then $T_\mathsf{I}(\tau\alpha)(u) = \mathsf{A}(\alpha)(T_\mathsf{I}(\tau)(u))$,

for each $\tau \in \mathcal{T}^\Sigma$, for each $\sigma \in \mathcal{S}$,

$$D_\mathsf{I}(\tau \sim \sigma) = \left\{ u \in \mathsf{U} \,\middle|\, \begin{array}{l} T_\mathsf{I}(\tau)(u) \textit{ is defined, and} \\ \mathsf{S}(T_\mathsf{I}(\tau)(u)) = \sigma \end{array} \right\},$$

for each $\tau_1 \in \mathcal{T}^\Sigma$, for each $\tau_2 \in \mathcal{T}^\Sigma$,

$$D_\mathsf{I}(\tau_1 \approx \tau_2) = \left\{ u \in \mathsf{U} \,\middle|\, \begin{array}{l} T_\mathsf{I}(\tau_1)(u) \textit{ is defined,} \\ T_\mathsf{I}(\tau_2)(u) \textit{ is defined, and} \\ T_\mathsf{I}(\tau_1)(u) = T_\mathsf{I}(\tau_2)(u) \end{array} \right\},$$

for each $\delta \in \mathcal{D}^\Sigma$, $D_\mathsf{I}(\neg\delta) = \mathsf{U} \backslash D_\mathsf{I}(\delta)$,

for each $\delta_1 \in \mathcal{D}^\Sigma$, for each $\delta_2 \in \mathcal{D}^\Sigma$, $D_\mathsf{I}([\delta_1 \wedge \delta_2]) = D_\mathsf{I}(\delta_1) \cap D_\mathsf{I}(\delta_2)$,

for each $\delta_1 \in \mathcal{D}^\Sigma$, for each $\delta_2 \in \mathcal{D}^\Sigma$, $D_\mathsf{I}([\delta_1 \vee \delta_2]) = D_\mathsf{I}(\delta_1) \cup D_\mathsf{I}(\delta_2)$, and

for each $\delta_1 \in \mathcal{D}^\Sigma$, for each $\delta_2 \in \mathcal{D}^\Sigma$, $D_\mathsf{I}([\delta_1 \rightarrow \delta_2]) = (\mathsf{U} \backslash D_\mathsf{I}(\delta)) \cup D_\mathsf{I}(\delta_2)$.

For each SRL signature Σ, I call T_{I} the Σ *term interpretation function with respect to* I, and D_{I} the Σ *description interpretation function with respect to* I. As discussed already, a Σ term interpretation function with respect to $\langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$ is a partial function from U to U. More specifically, the colon denotes the identity function, and we obtain the denotation of each term in which a nonempty string of attributes succeeds the colon by functional composition of the denotation of the colon and the attribute interpretation of each of the attribute symbols in the term, with the interpretation of the last attribute coming first.

The denotation of Σ descriptions follows naturally from the denotation of Σ terms: Each Σ description $\tau \sim \sigma$ denotes the subset of entities in U on whose members the Σ term interpretation function (with respect to $\langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$) of τ is defined and yields an entity of species σ. Each Σ description of the form $\tau_1 \approx \tau_2$ denotes the set of those entities in U on which the Σ term interpretation function (with respect to $\langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$) of both τ_1 and τ_2 is defined and yields the same entity in both cases. Negation, conjunction, disjunction and implication of Σ descriptions are interpreted classically as set complement of the denotation of the description, as the intersection and union of the denotations of the two descriptions of the complex description, and as the union of the set complement of the denotation of the first description in the implication with the denotation of the second description, respectively.

A signature expresses how we conceive of the world that we want to talk about as being structured. Assume the particular SRL signature given in Figure 2.4. For the purposes of the following examples, I will take it as fixed and leave it implicit when talking about terms and descriptions. According to the signature, the entities in our universe are of sort *man*, *woman*, *bmw* and *vw*; and there are no other entities. A *bmw* and a *vw* have a DRIVER and an OWNER, who are either a *woman* or a *man*.[40] But neither a *vw* nor a *bmw* have the property of liking somebody or something best. Each *man* and each *woman*, on the other hand, likes some entity of the universe best, and the entity that they like best can be of any sort. Neither a *woman* nor a *man* has a DRIVER or an OWNER. Let us now construct one of the many possible interpretations of this SRL signature.

Suppose the following scenario involving two cars on the parking lot in front of the Seminar für Sprachwissenschaft in Tübingen: The first car, which

[40]Note that these appropriateness conditions exclude, among other conceivable scenarios, multiple owners of a single car.

belongs to Anke, is a Volkswagen. Anke is in the driver's seat. We know that Anke is married, and she likes her husband best. Her husband, of course, likes her best. The second car is a Volkswagen, too. It is owned by Kordula, but since she is on vacation, Detmar is driving it. Kordula and Detmar like each other best. We can capture some facts of this little scenario in an interpretation of our signature. The two cars, Anke, her husband, Detmar and Kordula are the entities in the interpretation. They are assigned the obvious species given the intuitive meaning of the species symbols. The attributes receive a denotation that obeys appropriateness and gives the attributes their natural denotations with respect to the above scenario. Figure 2.5 shows this interpretation, which I will call $\mathsf{I}_{2.5}$.

Figure 2.5: An interpretation of the SRL signature of Figure 2.4

Let $\mathsf{I}_{2.5} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$, with:

U = {Anke, Anke's husband, Detmar, Kordula, first car, second car}

S(Anke) = *woman*,
S(Kordula) = *woman*,
S(Anke's husband) = *man*,
S(Detmar) = *man*,
S(first car) = *vw*, and
S(second car) = *vw*

A(LIKES-BEST)(Anke) = Anke's husband,
A(LIKES-BEST)(Anke's husband) = Anke,
A(LIKES-BEST)(Detmar) = Kordula,
A(LIKES-BEST)(Kordula) = Detmar,
A(OWNER)(first car) = Kordula,
A(OWNER)(second car) = Anke,
A(DRIVER)(first car) = Detmar,
A(DRIVER)(second car) = Anke,
A(LIKES-BEST) is undefined on the first car and on the second car,
A(OWNER) is undefined on Anke, Anke's husband, Detmar and Kordula, and
A(DRIVER) is likewise undefined on Anke, Anke's husband, Detmar and Kordula

We can now inspect the denotation of descriptions in the interpretation $\mathsf{I}_{2.5}$. In (15a) we see that the set of women in $\mathsf{I}_{2.5}$ consists of Anke and Kordula. There is no BMW in $\mathsf{I}_{2.5}$ (15b). Finally, only the second car is a Volkswagen whose owner is also its driver (15c), because Anke drives her own car, whereas Detmar drives Kordula's car; and there is no other car in $\mathsf{I}_{2.5}$.

(15) a. $D_{\mathsf{I}_{2.5}}(:\sim \textit{woman}) = \{\text{Anke, Kordula}\}$

b. $D_{\mathsf{I}_{2.5}}(:\sim \textit{bmw}) = \emptyset$

c. $D_{\mathsf{I}_{2.5}}([:\sim \textit{vw} \wedge :\text{OWNER} \approx :\text{DRIVER}]) = \{\text{second car}\}$

Note that in a different interpretation of the same signature, the descriptions in (15) might denote different sets of entities. As soon as there are BMWs in the interpretation, '$:\sim \textit{bmw}$' denotes that set of cars. Moreover, it is easy to see how the symbols of the sort hierarchy of the 87 signature of Figure 2.2 that are not present in our corresponding SRL signature can be understood as an abbreviation of disjunctive descriptions. For example, '$:\sim \textit{person}$' can be defined as a metasyntactic notation for '$[:\sim \textit{man} \vee :\sim \textit{woman}]$', which denotes the set comprising Anke, Anke's husband, Detmar and Kordula. In other words, a sort assignment with a sort σ that is not a species is interpreted as the disjunction of the sort assignments with the species that σ subsumes in the envisaged sort hierarchy of an 87 signature.

An HPSG 94 grammar is a pair consisting of a signature and a set of expressions of the description language, the principles of grammar. Definition 19 captures this conception of a grammar with the notion of an SRL grammar:

Definition 19 Γ *is an* ***SRL grammar*** *iff*

Γ *is a pair* $\langle \Sigma, \theta \rangle$,

Σ *is an SRL signature, and*

$\theta \subseteq \mathcal{D}^{\Sigma}$.

Since an SRL grammar always includes a fixed signature, Σ, I will simply talk about descriptions of SRL grammars below instead of Σ descriptions of SRL grammars.

The purpose of a grammar is to describe a natural language. In HPSG 94, the most important means to delineate a natural language is clearly the set of principles. It is, therefore, a prerequisite for determining what an SRL grammar means to define what a set of descriptions means. The denotation of a set of descriptions, θ, in a given interpretation, I, is the set of all entities in I of which each description in θ is true:

Definition 20 *For each SRL signature* Σ*, for each* Σ *interpretation* $\mathsf{I} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$*,* Θ_{I} *is the total function from the power set of* $\mathcal{D}^{\Sigma}$ *to the power set of* U *such that for each* $\theta \subseteq \mathcal{D}^{\Sigma}$*,*

$$\Theta_{\mathsf{I}}(\theta) = \left\{ u \in \mathsf{U} \,\middle|\, \begin{array}{l} \textit{for each } \delta \in \theta, \\ u \in D_{\mathsf{I}}(\delta) \end{array} \right\}.$$

I call Θ_{I} the *theory denotation function with respect to* I. For example, the theory $\theta_1 = \{[: \sim bmw \rightarrow \neg : \approx :], \ [: \sim vw \rightarrow : \text{OWNER} \sim woman]\}$ describes every entity in the interpretation $\mathsf{I}_{2.5}$, i.e., $\Theta_{\mathsf{I}_{2.5}}(\theta_1) = \{$Anke, Anke's husband, Detmar, Kordula, first car, second car$\}$. This is so, because each of the descriptions of θ_1 describes every entity in $\mathsf{I}_{2.5}$: The first, '$[: \sim bmw \rightarrow \neg : \approx :]$,' describes all entities that are not BMWs or not identical with themselves. This is true of all entities that are not BMWs and false of all BMWs. Since $\mathsf{I}_{2.5}$ does not contain any entity of sort *bmw*, the description is true of all entities in $\mathsf{I}_{2.5}$. The second description in θ_1 describes entities that are not VWs or whose owner is a woman. That is true of all entities that are not VWs and of all VWs whose owner is a woman. In other words, it is true of all entities in $\mathsf{I}_{2.5}$, because Anke, Anke's husband, Detmar and Kordula are men and women, and the two VWs are owned by Anke and Kordula, respectively.

As the example shows, the theory denotation of a finite set of descriptions equals the description denotation of the conjunction of the descriptions that the set contains. A finite theory can thus be expressed by the conjunction of the descriptions in it, and for the finite case, theories and theory denotation functions are not strictly necessary. However, the inductive definition of the languages of SRL does not permit infinite conjunctions. The theory denotation functions with respect to an interpretation thus add the possibility of interpreting infinite theories.

Denotations of theories in interpretations do not yet determine the meaning of a grammar by themselves. The theory denotation function only tells us of which entities in an interpretation a set of descriptions is true. This property can, however, be exploited in a first approximation of the intended interpretations of a grammar. Clearly, the linguist is only interested in those interpretations of a grammar in which every description is true of every entity: Every description of the grammar describes every entity in the interpretations, or, equivalently, no description is false of any entity in the intended interpretations. Interpretations that have that property with respect to a given grammar are called *models* of the grammar:

Definition 21 *For each SRL grammar* $\Gamma = \langle \Sigma, \theta \rangle$*, for each* Σ *interpretation* $\mathsf{I} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$,

I *is a* Γ ***model*** *iff* $\Theta_{\mathsf{I}}(\theta) = \mathsf{U}$.

The theory, θ, of an SRL grammar, Γ, denotes the entire universe of entities, U, in each Γ model, $\mathsf{I} = \langle \mathsf{U}, \mathsf{S}, \mathsf{A} \rangle$. Since every entity in the interpretation $\mathsf{I}_{2.5}$ is in the denotation of each element of θ_1, $\mathsf{I}_{2.5}$ is a Γ model of the grammar Γ that consists of the signature of Figure 2.4 and θ_1. Intuitively speaking, no entity in $\mathsf{I}_{2.5}$ violates the conditions of not being a BMW and of being owned by a woman if it is a Volkswagen. Not every theory has a nonempty model. Consider the theory, θ_2, that contains the single description '$: \sim vw$.' A Γ model with the theory θ_2 may only contain entities of sort *vw*, because '$: \sim vw$' is only true of VWs and false of all other entities. But by virtue of the signature, each Volkswagen must have an owner who is either a woman or a man. Therefore, no Γ model with the theory θ_2 can contain a Volkswagen; each Γ model with the theory θ_2 must have an empty universe.

Considering the notion of a model of a grammar from a linguistic perspective, it restricts the candidates for the meaning of a grammar to those interpretations whose entities do not violate any principles. For example, assuming that a grammar contains a correct specification of subject verb agreement in English, the sentence *John love Mary* cannot be in any model of the grammar, because it violates subject verb agreement. The sentence contains at least one entity that is not described by at least one description in the theory of the grammar. The models of SRL grammars will be the starting point for all three explications of the meaning of HPSG 94 grammars in the following three sections.

My introduction to SRL deliberately omitted the logic of SRL and results pertaining to it, because the logic of SRL is of no immediate relevance for the characterization of natural languages in the SRL formalism. For completeness, I mention some of the logical aspects of SRL here.[41] For each SRL signature Σ with a finite set of species, King 1989 provides a Hilbert and Ackermann style calculus, and shows that the inference relation that the calculus determines is sound and complete with respect to entailment, i.e., for each set of Σ descriptions θ and for each Σ description δ, θ infers δ if and only if θ entails δ. Kepser 1994 then proceeds to show that for each SRL signature

[41] See King 1999, pp. 328–329, and the literature cited there for a more comprehensive overview over the logical results about SRL.

with a finite set of species and a recursive set of attributes, the satisfiability problem is decidable: There is an effective algorithm that decides for each SRL signature of the kind indicated, and for each description δ generated by that signature, whether there is an interpretation of the signature in which δ has a nonempty denotation. In Section 3.3, I will return to the question of the significance of these and related results to a theoretical linguist who uses formal languages of the kind that HPSG 94 envisages in order to describe natural languages.

2.2.2.2 Exhaustive Models

In a substantial reformulation of an earlier attempt to characterize the meaning of HPSG 94 grammars in King 1994, King 1999 investigates the question of when an SRL grammar is true of a natural language. King (1999) formulates three necessary conditions for an SRL grammar to be true of a natural language. These conditions are met if a natural language belongs to a certain class of models of a given SRL grammar. King calls that class of models the class of *exhaustive models* of a grammar. The meaning of an SRL grammar is thus determined as delineating the class of its exhaustive models, and the grammar is true of a language, $\mathcal{L}$, if $\mathcal{L}$ is an exhaustive model of the grammar.

In this section, I present the motivation behind King's notion of exhaustive models, and their definition. As the introductory, short description in the preceding paragraph of King's approach reveals, the perspective of King 1999 is realistic in the sense that the task of SRL grammars is to directly characterize natural languages without the intervention of some modeling mathematical structure.[42] The natural languages themselves are the intended models of grammars. The realistic approach to the meaning of scientific theories is the most important feature that distinguishes King's explanation of the meaning of HPSG 94 grammars from the explanations of Pollard and Sag 1994 and of Pollard 1999, which choose a representational approach. Despite their fundamentally different assumptions about the ontological status of the structures that grammars characterize, the three formalisms are very similar and mathematically closely related. Understanding the technical side to the

[42]The term *realistic* is meant in a pre-theoretical sense here; it is not meant to be a technical characterization of King's philosophy of science. In particular, King does not explicitly call himself a realist. I use the term to refer to his view because it emphasizes his predominant interest in describing linguistic behavior directly, and stresses the contrast to the representational view of Pollard and Sag.

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