B1 Formal modeling of frames and functional concepts

1 General Information

1.1 Applicants

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1.2 Topic

Formal modeling of frames and functional concepts

1.3 Scientific discipline and field of work

Mathematical Linguistics, Computational Linguistics

1.4 Scheduled total duration

Six years

1.5 Application period

Three years

1.6 Summary

According to Barsalou 1992 frames as recursive attribute-value structures with constraints form the general format of concepts in human cognition. Based on empirical research, Barsalou's focus in developing frame theory was not on providing a formal theory. We intend to both sharpen and generalize his intuitive conceptions by developing an adequate mathematical model for frames. By examining the formal properties of frames and modeling frames of different concept types, our goal is to obtain a better understanding of frames and an adequate explanation of cognitive processes. This is necessary for the adoption of frames in various fields of application, such as frame-based semantics, medical diagnosis, scientific classification or frame-based knowledge systems.

Frames describe the objects they represent by using attributes with assigned values. The values can be either atomic, or structured frames themselves. They can be specific, underspecified or unspecified. Our assumption is that attributes assign unique values to objects and thus describe functional relations. Hence, the attributes can be seen as the primes of concept formation. As discussed in Petersen 2007, frames can be represented by directed graphs with labeled nodes and arcs. Each node is labeled with a type and each arc is labeled with an attribute.

A model-theoretic interpretation of the graphs will be developed by assigning to each node a type in an appropriate type signature and to each arc an appropriate partial function. To

achieve the goal of building an adequate mathematical model for frames, we have chosen to approach the frame structure from two perspectives: (a) we will investigate how the node-types can be ordered in a type signature such that the set of admissible frames becomes restricted and (b) we will determine and examine the space of attributes. By advancing a proper model-theoretic semantics of frames, the foundations will be established for deploying frames in the various fields of application in a formally rigorous approach.

2 State of the art, preliminary work

2.1 State of the art

According to Barsalou 1992, frames, understood as recursive attribute-value structures, represent a general format to account for the content and structure of mental concepts. The attributes in a concept frame are the properties or dimensions according to which the respective object is described (e.g., COLOR, SPOKESPERSON, HABITAT …). Their values are concrete or underspecified specifications (e.g., [COLOR: **red**], [SPOKESPERSON: **Ellen Smith**], [HABITAT: **jungle**] …). For example, a ball can be partially characterized by the specifications [SHAPE: **round**] and [COLOR: **color**] as being round in shape and unspecified in color. The values of attributes are objects themselves and can therefore also be complex frames with their own set of attributes, and so on, recursively. For example, the value **jungle** of the attribute HABITAT can further be specified by attributes like AVERAGE TEMPERATURE or RAINY SEASON. It is the recursivity of frames that renders them flexible enough to represent information of any degree of detail. Barsalou's frames are typically enriched by various types of constraints. Constraints restrict the set of possible values of the attributes ('not all colors are possible natural hair colors'), establish correlations between the values of different attributes ('the bigger the apple, the heavier it will be'), or interrelate concrete values ('in order to go downhill skiing the destination needs to be mountainous').

Barsalou & Hale 1993 argue that the frame theory is independent of various theories of categorization, such as checklist theory (cf. Katz 1972; Lyons 1977), exemplar theory (cf. Rosch & Mervis 1975; Brooks 1978), prototype theory (cf. Rosch 1973, 1975; Smith & Medin 1981) or connectionist networks (cf. McClelland & Rumelhart 1981; Shanks 1991). Rather, frames are a model for the representation of concepts and present an alternative to pure feature-list representations. The advantage of frames over predicates of First Order Logic is that they do not force one to stipulate a fixed arity and that substructures can be addressed via labeled symbols instead of ordered argument positions.

Frame structures reminiscent of Barsalou's first appeared in several disciplines during the 1970s. In the area of cognitive science their introduction led to a paradigm change (cf. Fahlmann 1977; Minsky 1975): Instead of being taken as atomic units, concepts came to be understood as classes of highly structured entities describable in terms of recursive attribute-value structures. Feature lists and binary features represented a preliminary stage in this process (cf. Chomsky & Halle 1968). The frame perspective also became prominent in artificial intelligence (AI) and linguistics. One of the best-known frame-based knowledge representation languages in AI is KL-ONE (Brachman & Schmolze 1985), which is the predecessor of a whole family of knowledge representation languages, so-called description logics (cf. Donini et. al. 1996; Baader et. al. 2004). Further knowledge representation structures related to frames are Semantic Networks (cf. Quilian 1968; Helbig 2006) and Conceptual Graphs (cf. Sowa 1984, 2000).

In Linguistics, frames were first introduced in Fillmore's case grammar in order to represent verbs and the relational roles of their arguments (Fillmore 1968). This early work laid the foundations for the development of frame semantics (Fillmore 1982, Ziem 2005). Kay 1979 introduced the idea of describing linguistic signs with complex frame structures and he proposed frame unification for their manipulation. These frame structures are now known in computational linguistics (CL) as feature structures and are heavily used in unification-based grammars (cf. Shieber et. al. 1983; Shieber 1986). Inspired by the work of Aït-Kaci on ψ-terms (Aït-Kaci 1984), type hierarchies with appropriateness conditions were introduced in CL in order to restrict the set of admissible typed feature structures (Carpenter 1992).

In grammar theories, feature structures are the data structures which contain the information about the language constituents. The task of a grammatical theory is to constrain which feature structures are admissible. In order to state a grammar, a logical description language (often called feature logic) has to be fixed in which constraints about the admissible feature structures can be stated (for a an overview see Keller 1993 or Rounds 1997). A variety of feature logics has been defined (e.g. Kasper & Rounds 1986, Johnson 1988, Smolka 1989) which are model-theoretically interpreted in a universe of feature structures. Hence, the semantics of those logics do not fix the interpretation of feature structures, rather the feature structures are models themselves or elements of models of logical theories. Furthermore, feature logics operate on feature structures, i.e., on structures that can be represented as directed *rooted* graphs, and not on frames. In order to transfer them to frames, their soundness and completeness and all results on decidability or complexity have to be proven again.

Although a thorough discussion of the meaning of feature structures and frames is still lacking, important steps toward the formal ontological nature of frames and feature structures can be observed in neighbouring disciplines like formal ontology engineering. Type hierarchies and type signatures are closely connected to formal ontologies in knowledge representation systems. As in the first project period, Guarino's 1992 and Guarino's & Welty's 2000 work on formal ontologies and on the ontological nature of attributes in particular will guide the organization of the type signatures in B1.

2.2 Preliminary work

Sebastian Löbner's scholarship on functional concepts represents the first explorations into this special noun class (Löbner 1979, 1985, 1998a). His investigations into the semantics of intensional constructions of the type *the temperature is rising* (figuring in the famous „Partee puzzle") led to the realization that functional concepts (such as *temperature*) form a special concept type different from sortal nouns (e.g. *airplane*) and other types of nouns (Löbner 1979). Functional nouns refer inherently uniquely and are thus mostly used with a definite article and in the singular. This led to an investigation into definiteness in general (Löbner 1985) and into definite associative anaphora (DAA) of the type *I bought a book; <u>the title</u> was something like ...* in particular (Löbner 1998a). In this paper he argued that the associative anaphoric noun, in this case *title*, is invariantly used to express a functional concept with an extra argument; the argument is the referent of the antecedent NP. More precisely, the DAA names and denotes a plausible attribute in a frame describing the antecedent object (TITLE is a plausible attribute in the frame that would describe a book one would buy). For the first time a connection between Barsalou frames and the grammatical noun type of functional concepts was recognized. An attribute in a Barsalou frame is a functional relation that assigns a value to its argument node; if the attribute can be expressed by a natural language noun, then this noun is a functional concept. This observation linked the architecture of cognitive frames to highly specific linguistic data that distinguish functional concepts from other types of nouns. It also called for a more precise methodology in implementing Barsalou's notion of frame, as the functionality of attributes was not explicitly postulated in his theory. Apart from the intrinsic connention between functional concepts and frames, Löbner provided a first general definition of „attribute" or „dimension" (Löbner 1979: 173-178). Points of relevance are: the possibility of functional composition of attributes (see also the „chaining property" of functioanl concepts in Löbner 1998), the possibility of bundeling attributes of the same objects into one complex „vector" attribute, or, conversely, splitting a complex attribute into a bundle of component attributes. These first investigations provide a starting point for a theory of attribute spaces.

Gerhard Schurz' expertise for heading the project results from his expertise in logic (Schurz 1995) as well as in the philosophy of science and cognitive science. His studies on normic conditionals and non-monotonic reasoning (cf. Schurz 1998, 2001a, 2001b, 2005) are highly relevant for the second project period. On this basis of his findings Schurz 2008 has developed an evolutionist analysis and justification of prototype semantics.

During the first project period, Petersen developed a formal approach to frames which rejects the common claim that the central node of a frame is necessarily its root. With respect to type signatures, the new approach dismisses the artificial distinction between types and attributes in type signatures. A detailed overview of the results is given in the intermediate research report provided by B1.

By modeling frames as connected directed graphs with labeled nodes (types), arcs (attributes) and one distinguished central node, our frame definition follows the definition of typed feature structures as in Carpenter 1992. The main difference is that we do not insist that the central node be a root node, i.e. that all nodes of a frame can be reached via directed arcs from its central node. In accordance with Carpenter 1992 the attributes are supposed to be functional and the types are ordered in a type hierarchy, which induces a subsumption order on frames. Just because of the fact that our frame definition allows the construction of frames in which the central node is not a root we have been able to model functional and relational concepts in frames. A satisfactory solution to the problem of how to model individual concepts by frames is still lacking.

A classification of frame graphs (Petersen 2007)

Petersen 2007 argues that at least in the case of acyclic frames Löbner's concept classes correspond to graph-theoretical aspects of the frames modeling the concepts.

A frame is said to be *acyclic* if the underlying directed graph is acyclic, i.e., if it is not possible to find a path along directed arcs leading from a node back to itself. Our experience with frames constructed in the research group has indicated that frames for concepts are mostly acyclic and that cyclic frames of concepts generally have an embedded acyclic frame which represents the defining properties of the denoted objects. However, there are some rare self-referential concepts like *egoist* or *narcissist* whose frame graphs have to be cyclic.

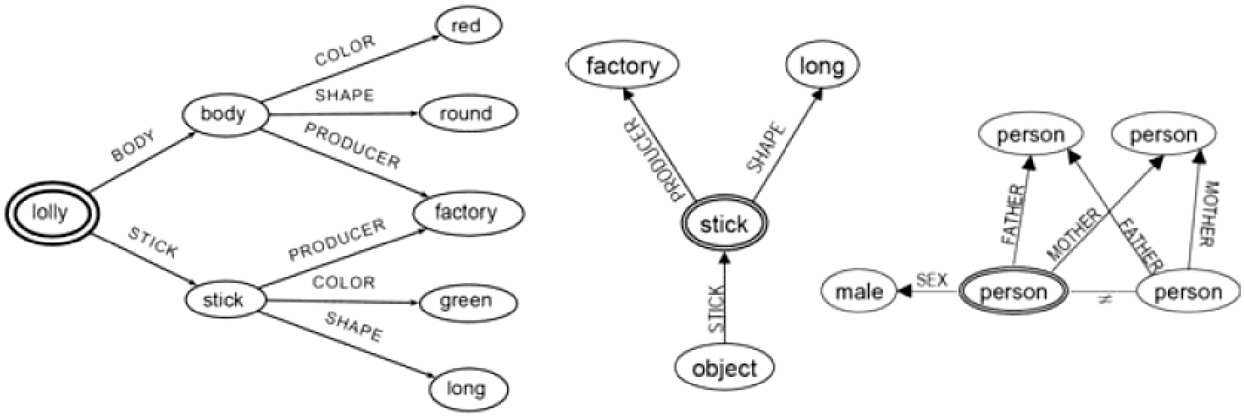

Figure 2: frames for different concepts (left: *lolly*; middle: *stick of*; right: *brother of*)

Figure 2 shows three frames of three different concept classes (the central nodes have double circles; for nouns they represent the referential argument).[1] The leftmost frame represents the sortal concept *lolly*, the frame in the middle corresponds to the functional concept *stick* (in the relational sense of 'stick of something', e.g. a lolly), while the frame to the right matches the proper relational concept *brother.* The *stick*-frame characterizes a stick by *being the* ***stick of*** *an object* (i.e., by a functional relation) and by additional sortal features like *being long* and *being produced in a factory.*[2] Functional concepts differ fundamentally from sortal concepts in that their referential argument is the value of an attribute corresponding to the functional concept; the attribute assigns the referential object to a further (non-central) possessor argument. In essence, the incoming arc (labeled by an attribute corresponding to a functional concept) establishes the functional relation from potential possessors to the referents of the functional concept. The central node in the frame of the sortal concept *lolly* is a source (i.e., a node without incoming arcs.

The frame for the proper relational concept *brother* describes a brother as a male person for whom a second person exists with whom it shares mother and father. The $\neq$ -link between the two **person**-nodes indicates the inequality relation and ensures that the two nodes can never be unified. The peculiarity of this frame is that the two nodes labeled **person** cannot be reached along directed paths from each other and that there is no third node from which both nodes can be reached. The potential referents of the central **person**-node are characterized by the sortal feature *male* and especially by the existence of referents for the non-central source of type **person**, which represents the possessor argument of the proper relational concept *brother*. The connection between the central node and the node for the possessor argument is established indirectly via the shared values of the FATHER- and MOTHER-attributes. It is char-

[1] The study discussed (Petersen 2007) aimed at an investigation of the acyclic graphs underlying most frames and of the question as to whether the structure of those frames indicates to which class the represented concept belongs. Therefore, the open arguments of the relational concept *brother of* and the functional concept *stick of* are not marked in the frame representations.

[2] The term *stick* is ambiguous. The sortal concept *stick* ('being a long piece of wood') is not considered here.

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acteristic for a *proper relational frame*, i.e. a frame for a proper relational concept, that it has a node which is a source but from which the central node is not reachable along directed arcs.

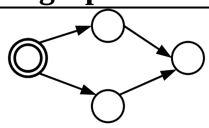
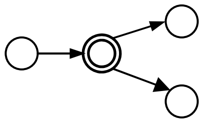
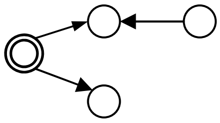
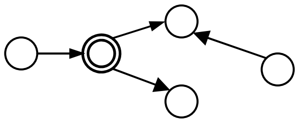
CR	***CS***	***ER***	***ES***	**typical graph**	***frame class***
+	+	+	+		sortal
–	–	+	+		functional
–	+	–	+		proper relational
–	–	–	+		???

Figure 3: classification of acyclic frame graphs

Petersen 2007 demonstrates that the type of concept represented by an acyclic frame is determined by the properties of the central node and the question as to whether or not the frame has a root or a source. A complete classification of acyclic frame graphs with respect to the four binary features is given in Figure 3: „± has source" (±ES), „± has root" (±ER), „± central node is a source" (±CS), and „± central node is a root" (±CR).

While the first three frame classes correspond nicely with concept classes, the fourth class is special. We assume that frames belonging to this class do not represent lexicalized concepts (for further details see Petersen 2007). From the analysis of the graphs underlying concept frames we have derived the following hypotheses:

- The concept classification is reflected by the properties of the corresponding frame graphs.
- Relationality: the arguments of relational concepts are modelled in frames as sources that are not identical to the central node.
- Functionality: The functionality of functional concepts is modeled by an incoming arc at the central node.

Attributes in frames (Petersen & Werning 2007, Petersen 2007)

Our basic assumption about the structure of frames is that attributes in frames are functional and thus correspond to functional concepts. However, this correspondence does not become clear if one applies the standard theory of typed feature structures. As Guarino 1992 points out, frame-based knowledge engineering systems as well as feature-structure-based linguistic formalisms normally force a radical choice between attributes and types. Therefore, frames like those in Figure 2 are common, where the unspecific value ***stick*** is assigned to the attribute STICK. The parallel naming of the attribute STICK and the type ***stick*** suggests a systematic relationship between the attribute and the type that is not captured by the formalism. The distinction between the *denotational* and the *relational* interpretation of a functional concept (as proposed in Guarino, 1992) can be used to explain how a functional concept can act as an expansion both for an attribute and the object that constitutes its value: Let there be a universe $\mathcal{U}$ and a set of functional concepts $\mathcal{F}$. A functional concept (like any concept) denotes a set of entities:

$$\Delta : \mathcal{F} \to 2^{\mathcal{U}}$$

(e.g., Δ(mother) = $\{m \mid m$ is the mother of someone$\}$).

A functional concept also has a relational interpretation:

$$\rho : \mathcal{F} \to 2^{\mathcal{U}\times\mathcal{U}}$$

such that $\forall f \in \mathcal{F} : \rho(f) : \mathcal{U} \to \mathcal{U}$ is a partial function

(e.g., ρ(mother) = $\{(k,m) \mid m$ is the mother of $k\}$).

Additionally, we demand that the denotational and the relational interpretation of a functional concept respect the *consistency postulate* (Guarino 1992), i.e. any value of a relationally interpreted functional concept is also an instance of the denotation of that concept: if $(k,m) \in \rho(\text{mother})$, then $m \in \Delta(\text{mother})$, where m is the value in (k,m). These considerations allow us to clarify the ontological status of attributes in frames:

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- Attributes are not frames themselves and are therefore unstructured.
- Attributes in frames are relationally interpreted functional concepts.
- Hence, frames decompose concepts into relationally interpreted functional concepts.
- Moreover, it is reasonable to claim that functional nouns are lexicalized components of cognitive concept formation.

That the differentiation between the denotational and the relational interpretation of functional concepts is consistent with Barsalou's view on attributes is discussed in depth in Petersen 2007 and confirmed by Barsalou (personal communication).

Like Carpenter 1992 we enrich type hierarchies by appropriateness specifications in order to constrain the set of appropriate attributes for frames of a special type and to restrict the attribute values. However, in contrast to Carpenter 1992 we consequently dismiss the artificial distinction between attributes and types in our definition of type signatures. The attribute set is merely a subset of the type set. Hence, attribute terms occur in two different roles, both as names of binary functional relations between types and as types themselves. Our definition (Petersen & Werning 2007, Petersen 2007) guarantees that Guarino's consistency postulate holds and that Barsalou's view on frames, attributes, and values is modelled appropriately: „Attributes are concepts that represent aspects of a category's members, and values are subordinate concepts of attributes" (Barsalou 1992: 43). The first reference to *attributes* in Barsalou's quote corresponds to the relational sense of the term, the second one to the denotational sense. We consider a frame *well-typed* with respect to a type signature, if all the attributes of the frame are licensed by the type signature and if the attribute values are consistent with the appropriateness specification. Each type signature specifies a class of well-typed frames.

Implementation of a frame-based knowledge processing system

In order to handle frames, we have extended the grammar engineering system *QType* developed by the computational linguistics group in Düsseldorf. QType is a unification-based system for representing and processing typed feature structures. It enables the definition of type signatures, type constraints and relational constraints. A special feature of QType is that it allows for the definition of type signatures with non-monotonic inheritance (Kilbury et. al. 2006). Thus one can take advantage of default inheritance without facing the drawbacks of default unification. Since Petersen's system *FCALing* uses the QType format for type signatures and typed feature structures, the module *FCAType* of FCALing can be used for automatic induction of type signatures from sets of untyped sortal frames (Petersen 2006, 2008) and for semi-automatic identification of adequate default information (Petersen 2004). By grounding FCALing on methods of Formal Concept Analysis (Ganter & Wille 1999) it is possible to switch back and forth between inheritance-based type signatures and equivalent sets of constraints (Osswald & Petersen 2002, 2003; Petersen 2004; Petersen & Kilbury 2005).

So far, our extension of QType includes the possibility of defining type signatures that eliminate the artificial distinction between attributes and types as discussed under (b). This provides an elegant solution to problems in grammar engineering occurring when frames are employed as semantic representations. For example, in order to model how adjectives modify the meaning of a noun it is necessary to explain that in a phrase like *red body* the value **red** is assigned to the attribute COLOR of the referent of *body*, while *round body* modifies the value of the attribute SHAPE. An unsatisfactory solution would be to introduce one new rule for each adjective dimension, i.e. for each attribute. Our solution is to introduce the notion of a *minimal upper attribute (MUA)* of a type. This is an attribute which is a supertype of the type with respect to the type hierarchy. Hence, a minimal upper attribute of a type is a minimal element of the set of upper attributes of the type. Since the minimal upper attribute of **red** is COLOR and the one for **round** is SHAPE we can formulate a single rule for adjective-noun phrases which states that the type corresponding to the adjective is assigned as a value to the minimal upper attribute of the adjective type. Simplified, the rule can be visualized as follows:

$$\begin{bmatrix}\text{AGR: } \boxed{1}\\ \text{CONT: } \boxed{2}\end{bmatrix}_{\text{np}'} \rightarrow \begin{bmatrix}\text{AGR: } \boxed{1}\\ \text{CONT: } \boxed{3}\end{bmatrix}_{\text{adj}} \begin{bmatrix}\text{AGR: } \boxed{1} & \\ \text{CONT: } \boxed{2} & \begin{bmatrix}\text{MUA}(\boxed{3}) : \boxed{3}\end{bmatrix}\end{bmatrix}_{\text{np}'}$$

By way of multiple inheritances this rule can even be employed in order to capture some cases of ambiguity. Consider the polysemous adjective *hot*, which means either *being very warm* or *being very spicy*. In a type hierarchy the type **hot** could be positioned such that it is a subtype of the attribute type **temperature** as well as of the attribute type **taste**. Then **hot** has two minimal upper attributes and the rule applied to the phrase *hot pepper* would result in two frames: one representing a very spicy pepper [TASTE: **hot**] and one representing a very warm pepper [TEMPERATURE: **hot**], which could be a dish.

In the process of combining the results of B1 and B2 it appeared reasonable to distinguish between reference-shifting attributes (MOTHER) and non-reference-shifting attributes (COLOR). One could assert that the hue of the color of a cherry is still a property of the cherry, while the sex of the mother of Charly is not a direct property of Charly. In order to determine the former, one has to inspect the referents of the central node; however, in order to determine the latter an examination of the referent of the central node, Charly, is not promising. In our extension of QType we have successfully introduced this distinction. In order to analyze a phrase like *bright house* with the single adjective-noun rule explained above, the attribute COLOR has to be marked as non-reference-shifting. We have implemented a general constraint that copies every attribute ATTR of the value of a non-reference-shifting attribute NRS and that attaches the attribute ATTR to the node the arc labeled NRS starts from. Thus, the constraint declares the values of the two attributes as co-referential and the content *bright hous*e would be become:

$$\begin{bmatrix} \text{BRIGHTNESS} : & \boxed{1} \\ \text{COLOR} : & \begin{bmatrix} \text{BRIGHTNESS} : \boxed{1}\ \textbf{bright} \end{bmatrix}_{\textbf{color}} \end{bmatrix}_{\textbf{house}}$$

Up to now, all extensions to QType solely involve an additional pre-processing step which transforms grammars stated in our new Frame-QType format into the standard internal format of QType. All established procedures of QType, such as the parsers, can be maintained without adaptions. Not yet introduced into QType is our new frame format, which abandons the claim that central nodes are roots. Accordingly, frames for functional and relational concepts cannot be handled in QType yet.

Cognitive adequacy of our frame model

Petersen & Werning 2007 discusses the cognitive adequacy of our frame model for the decomposition of concepts. It has been shown that the model can straightforwardly be extended to account for typicality effects as discussed in B2. Furthermore, by applying B2's paradigm of object-related neural synchronization a biologically motivated model for the cortical implementation of frames can be developed. Our confidence in the frame approach has also been confirmed by the fact that the results of Werning's research can be directly translated into our model. For a thorough discussion see the intermediate report B2 filed.

In Petersen et. al. 2007 we applied our frame model to the explanation of new findings pertaining to the accessibility of synaesthetic metaphors. The results documented in Beseoglu & Fleischhauer 2007 indicate that synaesthetic metaphors expressed by adjective-noun phrases are more accessible, if a dimension concept is used in the source domain (*vivid sound*) than a quality concept (*red sound*). This distinction can be explained by differences inherent to the MUAs of quality and dimension concepts. While the MUA of quality concepts like *red*, *green* or *blue* is COLOR, the MUA of dimension concepts like *vivid* or *loud* is INTENSITY. Compared to COLOR (the MUA of *red*), INTENSITY (the MUA of *vivid*) is a more general attribute, which means that it can be applied to a variety of sense modalities. The adjective *vivid* usually means *high value of visual input* and modifies the attribute INTENSITY in a color frame. Its domain can change when used metaphorically, e.g. when associated with a sound concept as in *vivid sound*, but *vivid* will still modify the attribute INTENSITY. Hence, in order to understand *vivid sound* the inappropriate value **vivid** of the attribute INTENSITY has to be *re*interpreted, while the expression *red sound* demands an interpretation of the inappropriate attribute COLOR in a sound frame. We may conclude the following: (1) the same strategies are generally applied to processing metaphorical and non-metaphorical expressions; (2) an expression is inaccessible, if the frame of the compound expression contains inadequate attributes; and (3) synaesthetic metaphors with dimension adjectives are more likely to be accessed than those with quality adjectives, since the former result in compound frames with adequate attributes but inappropriate values that can easily be adopted by a reinterpretation step.

3 Goals and work schedule

3.1 Goals

According to Barsalou 1992, frames as recursive attribute-value structures with constraints form the general format of cognitive concepts. The product of empirical research, Barsalou's focus in developing the frame theory was not on establishing a formal theory. We want to both sharpen and generalize his intuitive conceptions by developing an adequate mathematical model for frames. In order to model frames mathematically the project has to target two main questions:

- How can frames be formally captured in a mathematical model?
- What are the formal properties of frames (of various types)? What is their semantics?

Why do we need a formal representation of frames? When formalizing frames we are compelled to clarify Barsalou's theory, thus developing a better understanding of the concepts and related phenomena, such as decomposition and composition. Further questions arise in connection with the problem of the status of qualities, instances, classes, types and attributes. What is the ontological status of those objects in Barsalou's frames and in our model? For example, can instances be represented using frames? And if so, are the values of maximal paths in fully specified frames of instances always instances, or can they be qualities as well? Are instance frames finitely limited? Can paths of infinite length occur in frames? Some of these questions correspond to open philosophical questions, which we will not be able to resolve once and for all. However, we might be able to present them from a new perspective. Furthermore, in investigating the answers to those questions which are implied by our model we can acquire a more comprehensive view of the basic assumptions underlying the philosophical debate.

Our goal is to attain a better understanding of frames (not only in the specialized cases they have been applied in so far, but more generally) and an adequate explanation of cognitive processes. This is a necessary condition for the adoption of frames in various fields of application such as frame-based semantics, medical diagnosis, classification or frame-based knowledge systems. By concentrating on frames for concepts that are usually expressed linguistically by nouns, our project can close a gap within well-established graph-based knowledge representation formalisms, which tend to concentrate on *situations* (Frame Semantic: Fillmore 1982) and *propositions* (MultiNet: Helbig 2006, Conceptual Graphs: Sowa 2000).

During the first project period we began to adapt the theory of typed feature structures (Carpenter 1992), in order to capture frames. Continuing this approach we intend to pay particular attention to the space of attributes the frames are built on. One reason why frames or typed feature structures are not well-established in semantics could be that the attribute set is handled as an unstructured set of primitive elements in standard approaches. Furthermore, the relationship between feature structures, feature-based grammatical theories and natural language is not thoroughly clarified (cf. King 1999, Pollard 1999). Our aim is to provide a sound denotational semantics for the type signature, the attribute space and the frames determined by both. This is a prerequisite for the development of a formal frame-based semantics. Since our intention involves perceiving frames as a cognitive representation, a formal frame semantics would address a long-standing desideratum (e.g., in HPSG) by developing a compositional cognitive semantics that is as formally rigorous as equivalent approaches in the area of logic are.

3.2 Methods and work schedule

As discussed in Petersen 2007 frames can be approached by adapting the theory of typed feature structures (Carpenter 1992) and be represented by directed graphs with labeled nodes and arcs. Each node is labeled with a type and each arc is labeled with an attribute. We assume that attributes assign unique values to objects and describe functional relations. The values of attributes can be structured frames themselves. To attain the goal of building an adequate mathematical model for frames we have decided to approach the frame structure from two directions: (a) we will investigate how we can order types in a type signature such that the set of admissible frames is restricted and (b) we will examine the space of attributes on which frames are built. Hence, we reflect the structure of frames by concentrating on the one hand on attributes that correspond to arcs and on the other hand on types that correspond to nodes.

Hence, we will continue applying the typed frame model from the first project period, but by supplementing our research agenda with an investigation into attribute space we gain an extra perspective on frames. Thus, we should be able to scrutinize specific issues, such as modeling constraints, from the point of view that best suits the problem. This is a common approach in mathematics; if we have a theorem that shows structural similarities between one branch of mathematics and another, e.g. Stone's Representation Theorem linking set theory to Boolean algebra, both mathematical fields profit because results can be interchanged. The same results might have been possible directly in the other theory, but at the cost of being very unyielding and full of technicalities.

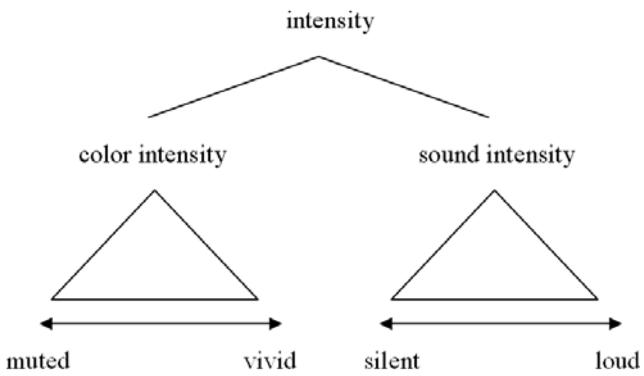
a) Classifying and typing frames

Our approach to adapting the theory of typed feature structures to model frames will be continued. Hence, frames will be regarded as being typed and the types will be hierarchically ordered in a type signature, which is enriched by appropriateness conditions. As discussed in section 2.2 the artificial distinction that has been drawn between attributes and types in type signatures will be dismissed by assuming that the attribute set forms a subset of the type set. In our type signatures attributes occur in two different roles, both as names of binary functional relations between types and as types themselves. We can benefit from the type signature in two ways: first, it specifies whether a frame is admissible (i.e. whether it respects the appropriateness conditions stated in the type signature) and second, it implies a subsumption hierarchy on frames. The investigations initiated during the first project period will be continued (cf. section 2.2).

Frames for different concept types: One issue which is not been satisfactorily solved is the question of how to integrate instances into typed frames. This seems to be a necessary prerequisite to model frames of individual concepts like proper names. We have not yet been able to ascertain as to whether it is desirable to extend the type set to include instance types or whether it would be sufficient to include types for individual concepts. In order to tackle that problem we will first attempt to provide a logical interpretation of type signatures. With respect to functional and proper relational frames (Petersen 2007), we still have to fix our definitions of frame subsumption and frame unification, and we are also compelled to investigate which propositions hold for them. Furthermore, a proper integration and interpretation of argument nodes into our frame model is overdue. Argument nodes represent the open arguments of relational concepts; they are not included in the standard theory of typed feature structures.

Classification of frame graphs: The results derived from our investigation of the graphs underlying the frames of different concept types still pose unanswered questions: „Does the fourth class of frame graphs really represent nowhere-lexicalized concepts?" and if so, „Why are those concepts not lexicalized?". We expect further investigations into frame graphs (also of those analyzed in the new project A6) to shed light on the problem of lexicalization.

Integrating scales into type signatures: On the basis of the standard type-signature approach it is possible to order types with respect to specificity. But what may be required to deal with monotonicity constraints (e.g., „the older the more expensive") or with the necessary reinterpretation of frames for synaesthetic metaphors (cf. section 2.2) is an additional order dimension, which is orthogonal to the specificity order. The following indicates how a type signature for the resolution of a synaesthetic metaphor like *vivid sound* could be envisioned:



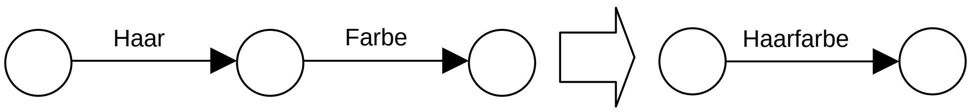
In order to interpret a *vivid sound* as a loud noise we must know that **sound intensity** is an appropriate value for the attribute INTENSITY in a sound frame and that **vivid** corresponds to the right region of the color-intensity scale, while **loud** corresponds to the same region in the sound-intensity scale. Hence, we need to enrich type signatures by specifying additional order relations on types and assigning scales to types.

Default values, non-monotonic type signatures and attribute hierarchies: According to Barsalou frames assign default values to attributes (e.g., *birds have beaks*, *the color of a raven is black*). In more specific frames these default values can be overridden by either more specific values (*ducks have large beaks*) or by inconsistent values (*albino ravens are white*). The former is already implemented in the standard definition of type signatures: subtypes inherit all the appropriateness conditions (i.e., appropriate attribute-value pairs) from their supertypes, but the value types of the appropriate attributes can be restricted to more specific types. The latter case of overwriting default values can be handled by using non-monotonic type signatures as implemented in QType (cf. Kilbury et al 2006). We will expand on our adapted type-signature definition for frames in order to capture non-monotonic inheritance. Since attributes occur as types in our definition, the type hierarchy also induces a hierarchy on attributes. It should be possible to take advantage of the attribute hierarchy by allowing subtypes not only to restrict the values of inherited appropriateness conditions, but also to restrict the attributes to more specific ones. For example, if the appropriateness condition COLOR:**color** is assigned to the type **physical object**, then the subtype **hair** could restrict this condition to HAIR_COLOR:**hair_color**. Up to now, it is only feasible to limit it to COLOR:**hair_color**.[3]

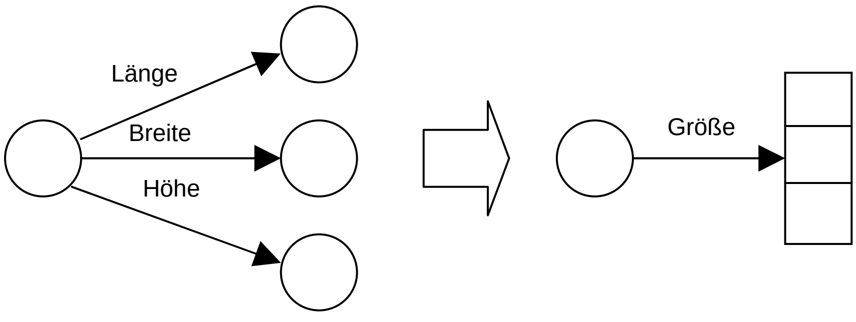
b) Exploring the space of attributes

While our first project period we centered on type hierarchies, we will now turn our attention to the attributes. Concretely, we expect to explore the mathematical structure attributes constitute. We generally treat the space of attributes mathematically as a space of functions, closed under compositon, product and, in part, under decomposition and factorization. It turns out that these operations work similarly to the analogous phenomena on concepts. For example, we can compose the attribute „Haar” and the attribute „Farbe” to yield the new attribute „Haarfarbe”, which models a common cognitive shortcut. Mathematically, we have the condition that the range of the first attribute has to be a subset of the domain of the second attribute.

B1



In addition to composition we often group categories together to describe more holistic phenomena, e.g. we combine „Länge”, „Breite” and „Höhe” for the „Größe“ of an object. This is called a „product” in the attribute space. Under the condition that their domains intersect, we can obtain the product of several attributes. The range of the resulting attribute is a set of vectors, in which each component corresponds to one of the ranges of the former attributes.

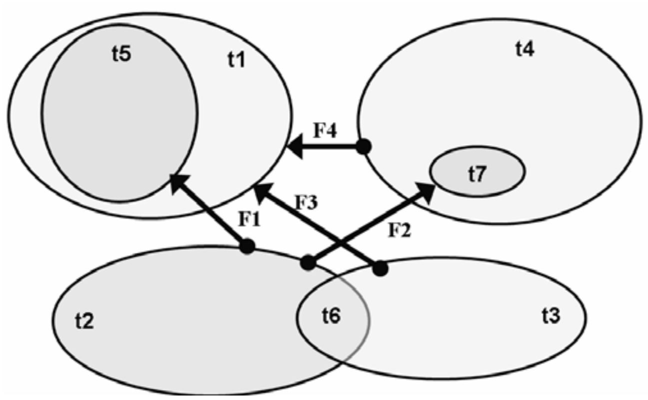


c) Integrating type signatures and attribute spaces

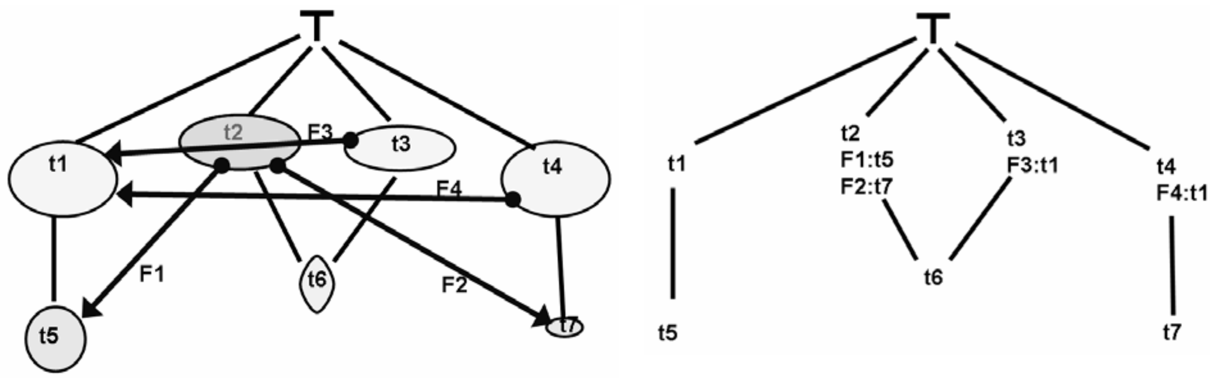
Our aim is to develop an integrated model of frames, such that their structure is determined by a type signature (a) as well as by an attribute space (b). Therefore, we need to ensure that both

[3] This may not be a satisfactory example for the requirement to assume an attribute hierarchy, since it is questionable as to whether hair_color is an adequate attribute in a frame of type hair. Rather, it seems that hair_color is a composed attribute in a frame of type person (see below).

devices are consistent with each other, which can be checked by transforming the attribute space into a type signature and vice versa. Due to the following considerations we are optimistic that we will succeed in unifying the two approaches to frames:



Attributes are defined on spaces of sets, i.e. the domains and ranges of the attribute space. If we denote each set and each intersection by a type and order the sets according to the subset relation, we can use type signatures as a compact and readable way of describing the sets underlying the space of attributes. While the left sketch indicates how the sets can be ordered by subset relation, the sets are replaced by their corresponding types in the right sketch:



The procedure sketched above looks as if the integration process of attribute spaces and type signatures is trivial. However, we expect to encounter obstacles in this process, especially since it is not evident how attribute composition and products of attributes can be transferred into type signatures.

Our mathematical model of frames with underlying attribute space can be used to define an equivalence relation that is considerably weaker than the standard equivalence relation in feature structure theories based on subsumption. In the „Haarfarbe"-example above, we would like to posit equivalence between a frame showing the attribute „Haarfarbe" and a frame showing the attribute „Haar" with a value that is further specified by the attribute „Farbe". According to the standard equivalence relation these two frames are incomparable, because they entail different attributes. By enabling attribute composition, the modeling of many relational concepts can be simplified (e.g. *cousin*, where the relation is defined as „having at least one parent of a parent in common").

d) Enriching frames by constraints

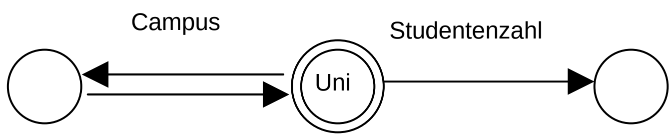
In accordance with Barsalou constraints form a constitutive part of frames. The attributes and values in a frame are not necessarily independent of each other. Some attributes co-occur, the value of one attribute often restricts or determines the value of another attribute, etc. Barsalou expresses those relations using structural invariants and attribute and value constraints.

Our double perspective on frames via type signatures and attribute spaces enables us to state constraints either in the attribute space or in the type signature depending on the nature of the constraint: constraints that restrict the range of an attribute can be relatively easily modeled in type signatures. The same is true for attribute co-occurrence constraints. So far we have omitted monotonicity constrains like „the older the more expensive“ (i.e. for stamps). Declaring an underlying attribute space might provide a plausible approach to handling them; since attributes can be modeled as functions, a continuous space of values is something natural for attributes. By transferring the construction, we may gain insights into what *continuous values* mean on the type side. We expect that by tackling constraints from both directions, we will be able to model a substantially wider range of constraints than we could during the first project period.

e) Semantic phenomena in the light of frames

By clarifying the stucture of the underlying attribute space we expect new methods to explain phenomena from fields like composition, metonymy, metaphors, meronymy, etc. in terms of frames.[4]

Metonymy: Consider the following example of metonymy: an „Uni” (university) has several attributes, among them CAMPUS and STUDENTENZAHL. However, you can use the word *Uni* to denote the campus, but not to denote the „Studentenzahl”. On the basis of our model we could ascertain that one reason for this might be that „Studentenzahl” does not have an inverse function while „Campus” does. This aspect might yield a obligatory condition for defining the existence of metonymies.



Metaphors: B1’s recent results on analysing synaesthetic metaphors in terms of frames will be broadened and applied to metaphors in general.

Conditions for lexicalization: Building on our expertise in analyzing frame graphs we expect to be able to delineate more conditions for the lexicalizability of concepts represented by frames.

Type shifts: For example, type shifts occur, for example, when essential functional concepts are used as sortal ones („Mothers like to dance.”), which has structural implications for the frames modeling the concepts. Together with project A5 we will explore this phenomenon.

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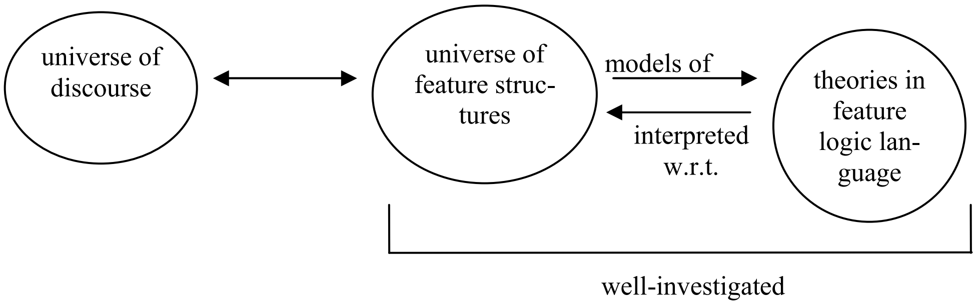
[4] It turned out in the first project period that the study of semantic phenomena in terms of frames is a field that heavily attracts students (e.g. Petersen et. al. 2007). Hence, we may expect Bachelor, Master or PhD theses on these subjects.

Long-term perspective: Preparational studies

f) Frame-based semantics

In the long run our objective is to provide a cognitively adequate frame-based semantics, which handles composition and decomposition according to common principles. One shortcoming of predicate logic is that individual and predicate constants are treated as unstructured entities, while from the cognitive perspective individuals and predicates are rather richly structured. Our idea is to develop a logic in which the non-logical constants are structured frames. It seems to be reasonable to start by adapting Rounds' feature logic which already covers attribute-value pairs. However, it has to be emphasised again that frames in our conception differ fundamentally from feature structures, in that they allow for central nodes that are not roots of the underlying graphs. Furthermore, frames of relational concepts must have special nodes that introduce open argument positions which are not expressible in standard feature structures. The correspondence between feature logics, feature structures and the universe of discourse could be envisioned as follows:



In the standard model-theoretic semantics of feature logic languages, feature structures serve as models of theories stated in those languages. Hence, the objects being reasoned about are feature structures. The relationship between the universe of discourse, which is generally not a class of feature structures or frames, and the models, which are feature structures, are not in the focus of research on feature logics.

Within the next three years, we will pave the way to a frame-based semantics by evolving a model-theory for frames which clarifies the relationship. Therefore, we plan to develop a procedure to transfer frames into logical notation. Our fundamental principal is that frames represent concepts that cannot be expressed in propositional form; thus, we will employ λ-notation to verify our logical rendering of frame contents. The basic assumption will be that each node in a frame is interpreted by an individual of the universe of discourse and each attribute by a partial function on the universe. In the process of working out the details the presence of Rainer Osswald (A6), who worked on those subjects in his PhD thesis (cf. Osswald 2002), will be very valuable.

In order to capture open argument positions in frames of relational concepts, it is planned to adapt the method of node labeling common in Conceptual Graphs (cf. Sowa 1984), where nodes are labeled by pairs of types and 'referents'. The 'referents' can either be individuals, quantifiers, or variables and their interpretation is constrained by the assigned type. By using this labeling technique we hope to capture variables in frames, to gain an adequate handling of individuals and to be able to express more intricate constraints.

g) Implementing a frame-based knowledge representation system

The efforts to extend the grammar-engineering environment QType, in order to account for the processing of frames will be continued. Additional miniature example grammars will be developed that are designed to show how our frames can be applied to account for the processing of lexical semantics (cf. 2.2). Up to the present all of our adaptations have been implemented as preprocessors, so that we were not obliged to interfere with QType internals. Since QType is originally designed to work with typed feature structures in the sense of Carpenter 1992, so far only sortal frames can be handled in our extension of QType. In order to establish an extensive frame-based knowledge representation system, capable of handling functional and relational frames and integrating attribute spaces, it will not be adequate to simply add extra preprocessing steps to QType. Hence, it will be compulsory to implement a new system in the long term. One of the first steps taken in the process of extending QType to handle frames will be the development of an adequate linear representation for frames.

Moreover, the module FCAType of FCALing, which automatically induces type signatures from typed feature structures, has to be adapted to automatically induce type signatures from frames. It has only been possible to use FCAType for the induction of type signatures from sortal frames as of yet. In order to capture functional and relational frames the process of analyzing the input structures has to be extended. Finally, it is necessary to adapt the induced type signatures to account for our new definitions.

Working schedule

The planned working schedule is condensed in the following table. Dark grey fields indicate time periods in which a topic will be brought into focus. Light grey fields indicate time periods in which a topic will be treated less intensively.

	2008/2	2009/1	2009/2	2010/1	2010/2	2011/1
a) type perspective						
b) attribute perspective						
c) integrated perspective						
d) constraints						
e) semantic phenomena						
f) frame-based semantics						
g) implementation						

The table shows that most subjects will be adressed during the whole project period. By the end of the first year we expect to have the basics of our integrated frame model fixed, so that we can reformulate our results from the first project period in terms of the enhanced frame model in the second year. That will also be the point at which we can embark upon the more difficult constraints. We will start by proposing a way to handle attributes with scalar values. Building on this, we hope to be able to model constraints like „the older, the more expensive“ in an integrated fashion. By comparing and translating the constraints in our unilateral approach we expect to attain a deeper understanding of their nature. While we construct our model and collaborate with the other projects, our research will be guided by semantic phenomena from the first year on. In the final year we will combine all this research to describe the structural features of semantic phenomena in our model in a cohesive manner. The primary goal for the last year will be centered on laying the foundations for a frame-based semantics.

Parallel to the modeling tasks sketched above our implementation of a frame-based system will be improved and extended. Until the integration of the two approaches to frames is settled, we will expound on the system QType. As soon as the first unified definitions of the two approaches are fixed we will start to develop a first basic implementation of a frame-based system. It should be emphasized that our implementation work is dedicated to the narrow goal of testing the applicability and consistency of our ideas and definitions and not to elaborating a knowledge processing system for large amounts of real data.

In order to introduce our frame approach to a broader community a monograph that focuses on frames and undertakes an overview of their application in science will be published in close cooperation with project B5 („Conceptual structures in science: frames as a model" to edited by Wiebke Petersen and Heiner Fangerau). Furthermore, a workshop on „formal properties of frames“ is planned for 2010 which will be organized by our project.

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3.3 Experiments involving humans or human materials

☐ **yes** ☒ **no**

3.4 Experiments with animals

☐ **yes** ☒ **no**

3.5 Experiments with recombinant DNA

☐ **yes** ☒ **no**