Collaborative Research Center 991

The Structure of Representations in Language, Cognition, and Science

Heinrich-Heine-Universität Düsseldorf

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3.1 About Project A01

3.1.1 Title: Mathematical modeling of frames

3.1.2 Research areas:

104-01 Allgemeine und Angewandte Sprachwissenschaften, mathematical linguistics, formal semantics, logic

3.1.3 Principal investigator(s)

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Do the above mentioned persons hold fixed-term positions? Yes.
End date November 2016. Further employment is planned until the end of the second funding period.

3.1.4 Legal issues

This project includes

1.	research on human subjects or human material.	no
2.	clinical studies	no
3.	experiments involving vertebrates	no
4.	experiments involving recombining DNA	no
5.	research involving human embryonic stem cells.	no
6.	research concerning the Convention on Biological Diversity.	no

3.2 Summary

The project develops the mathematical foundations for a theory of frames. It therefore provides the formal basis for the other projects within the CRC. It ensures consistency and adapts and expands the formal model in exchange with the other projects. Our frame account is inspired by the work of Barsalou, who argues that frames are the adequate model for representing the content and structure of mental concepts. Barsalou introduces frames as recursive attribute-value structures with the attributes being the properties or dimensions by which a concept is defined. The values of attributes can either be fully specified or be left undetermined. Recursiveness of frames is to be understood in the sense that the value of an attribute can itself be a frame, i.e. a set of attribute-value pairs. The focus of our project lies on formal aspects of frames.

In the second funding period the main focus will be on the following five topics: (i) development of a classification of action/event concepts in terms of temporal and causal relations between subevents; (ii) integration of quantification, e.g. monotone increasing vs. monotone decreasing quantifier, polyadic quantification, phase quantification; (iii) integrating probabilistic and normalcy relations into our frame model so effects like typicality and priming can be captured; (iv) development of a compositional model of sentence processing based on probabilistic, normalcy and dependence relations which incorporates both adverbial and adjectival modification as well as quantification; (v) investigation of the relation between (abstract) concept frames and (referring) situated frames. In addition, some strands from the first funding period will be continued. These topics include constraints in and between frames and extending frames to also include n-ary attributes.

3.3 Project Progress to Date

3.3.1 Report and state of understanding

Members of the project in the first funding period were Ralf Naumann (postdoc) and Tanja Osswald (doctoral student). Furthermore, Ivo Jazbec (University of Zagreb) joined us as a long-term visitor, with MGK grant. Tanja Osswald decided to leave the project in spring 2014.

The proposal for the first funding period identified three major topics for the project: (1) an integrated mathematical theory of frames; (2) the space of frames with operations on frames; (3) a dynamic frame model for events and actions. Substantial work has been done on all three topics. We explored different logics to express frame structures, in particular modal logic, dependence logic, and dynamic epistemic logic (topic 1). For operations on frames such as refinement or classification we employed the approach of combining systems (topic 2). A layered dynamic frame model has been developed as a combined system (topic 3). Additionally, we tackled the problem of processing quantifiers and their modifiers in a cognitive plausible way by relating our theory to dependence logic and database theory and by applying tools from theories of belief revision.

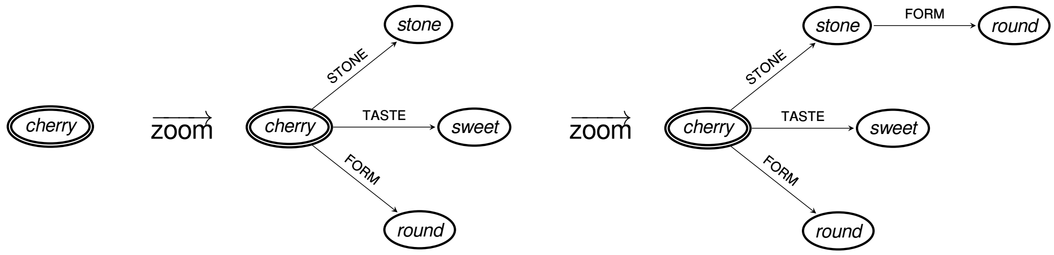
In the following, we roughly distinguish frames at two levels: While *basic frames* correspond to classical attribute-value structures, *higher-order frames* are frames which involve basic frames as substructures and which model, for example, changes in them. The former are the prototype for nominal frames, the latter for event frames. Both frame types must fulfill the main requirement of this project, namely to fit into a frame theory that is cognitively adequate.

(I) Basic frames

In the formal frame theory of Petersen (2007), which was developed within the predecessor project B1 of the research unit RU600, frames as recursive attribute-value structures are defined as a generalized form of typed feature structures based on a type signature that orders the types hierarchically and restricts the appropriate domains and co-domains of attributes. The type signature defines the space of well-typed frames with the subsumption relation and the unification and restriction operation. Frames are represented as directed graphs with labeled vertices and edges. In contrast to ordinary typed feature structures (Carpenter, 1992), the condition that it is always the root node of a frame graph that specifies what kind of objects is represented is dropped. Therefore, the central node and potential argument nodes have to be marked explicitly (Petersen & Osswald, 2014).

Frames as Kripke-structures: In Naumann (2013), the graph-based frame definition was adapted to Kripke-structures and in Naumann & Petersen (2013) the definition was extended to the notion of a team from dependence logic (Väänänen, 2007). Using Kripke-structures has several advantages. Being relational structures at a very abstract level, these structures allow for a variety of applications, making them highly flexible and therefore extremely appropriate for our frame theory. For example, the domains of Kripke-structures can be taken as abstract nodes representing the nodes in a frame for nominal concepts. Different sorts of nodes can be defined in terms of special atomic formulas (or predicates, depending on the logic used) which are true of exactly those nodes that have a particular property. This can be used to characterize the frames for nominal concepts in terms of structural properties which are satisfied by the central node. From a different perspective, nodes need not be atomic but can themselves be complex, e.g. structures that contain information in form of attribute-value pairs. This makes it possible to define the *recursive* character of frames. Furthermore, this flexible perspective allows the application of formal techniques from the theory of combining systems (Blackburn & de Rijke, 1997). In such theories, the focus is on the flow of information between different systems or (types of) objects. This way, different relations can be defined between various kinds of objects. For example, an object like a woman or a dog can either be viewed as an atom (e.g. as an element of an object structure consisting of human beings, dogs, chairs, trees etc.) or as a 'bundle' of properties, i.e. a set of attribute-value pairs. The relation between these two perspectives is modeled by the *refinement* relation in theories of combining systems. In our formal frame theory this relation is used as follows. An attribute can be assigned an atomic value in one context but in another context this object can be viewed as a 'bundle' of properties, i.e. as an entity having an internal structure. Thus, by changing from the external view of the value of an attribute as an atom to the internal view of an object as a set of attribute-value pairs one *zooms into* from one level into another level which provides more detailed information about the object (e.g., Fig. 1).

Fig. 1:



Frames as teams: One of the distinguishing features of our frame theory is the fact that there is no fixed argument structure. Attributes can be added or removed, depending on the context (Löbner, 2014). A challenge for such an interpretation of concepts is quantification, in particular the 'upward unboundedness' of indefinites like 'a man' or 'some dog'. For example, (1) can have three different readings (narrow/intermediate/wide scope).

(1) Every student read every paper that a professor recommended.

In Naumann & Petersen (2013), a first attempt is made to analyze this data. Scopal ambiguities of indefinites are not encoded in (linear) syntactic configurations but rather in terms of dependency relations in the sense of (dynamic) dependence logic (DL) (Väänänen, 2007) and database theory (Abiteboul et al., 1995). The principal idea is that frames can be taken as partial descriptions of objects in which they are characterized as 'bundles' of recursive attribute-value pairs. Formally, regarding objects as 'bundles' of properties makes it possible to represent them as sets of assignments (with the variables corresponding to attributes). Such a view is closely related to the notion of a team in dependence logic or a table in a database. For example, a set of three cherries one can be represented in the team in Table 1.

Table 1

	stone	taste	form	color
c_1	s_1	sweet	round	red
c_2	s_2	sweet	round	black
c_3	s_3	sweet	round	yellow

Using sets of assignments makes it possible to distinguish between global constraints, which are defined relative to all elements of the team, and local (or distributive) constraints, which apply at the level of single elements of the team. In our frame theory, indefinites are interpreted dynamically as relations between teams (or sets of assignments). Indefinites not only add a new element to the context as in Dynamic Predicate Logic but they also impose a (global) dependency relation on the output context. Scopal ambiguities are analyzed as a form of non-determinism: processing a formula in an input context X can lead to different output contexts Y. Each output corresponds to a possible reading of the formula. There are at least two ways of relating frames and teams. On the first perspective, each row (or assignment) in a team is a frame so that a team is a set of frames (a so-called *object frame*). By contrast, if a frame is taken as a concept, a so-called *concept-frame*, a frame corresponds to a whole team. The exact relation between frames and teams will be a topic of the second period.

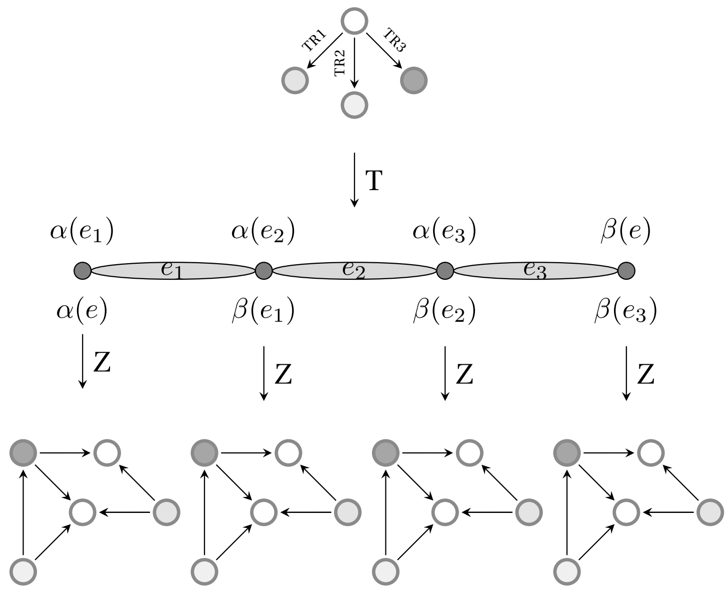
Noun frames: Löbner (to appear in 2015) identifies two layers as the innermost layers in his metaphor of a *nominal onion*. Following Löbner, the innermost *nominal nucleus* consists of lexical noun readings and can be conceptually distinguished by the independent dimensions $[\pm U]$ (inherent uniqueness) and $[\pm R]$ (relationality) (cf. Löbner, 2011). These dimensions have led to the fourfold classification of frame graphs developed in Petersen (2007) for sortal, individual, functional and proper relational frames, which is based on reachability properties of the graph nodes. Petersen & Osswald (2012) analyzes lexical shifts which can change the $[\pm U]$ and $[\pm R]$ values at the nuclei level. As lexical shifts often involve a shift of the centrality feature from one node to another, the graph frame model had to be extended by explicitly marking argument nodes. The second non-referential layer in the nominal onion is the *relation* layer which operates on the $[\pm R]$ feature of a nominal nucleus. Petersen & Osswald (2014) discusses how the possessor argument of a $[+R]$ nucleus frame can be filled by an absolute possessor in a genitive phrase resulting in a $[-R]$ frame, how possessor chains, i.e. chains of $[+R]$ nouns as possessor arguments, are composed in frames and how relationalization operations from $[-R]$ to $[+R]$ are reflected in frame graphs. By comparing the two principal analyzes of genitive constructions, i.e. the argument-only and the modifier-only analysis, it turned out that in a frame approach relational and weakly relational nouns (the latter provide attributes for a $[-R]$ to $[+R]$

shift) are best analyzed in an argument construction while pure sortal nouns are amenable to a modifier construction. Thus, frames favor a split approach.

(II) Higher-order frames

The refinement operation has been used in Naumann (2013) in developing a theory of dynamic frames corresponding to action concepts expressed by verbs. On the one hand, events are atomic entities similar to objects instantiated by nominal concepts like ‘dog’ or ‘tree’. On the other hand, events occur in time and have a (temporal) evolution. This evolution is directly related to the fact that events bring about changes with respect to properties of objects. Thus, similar to ‘ordinary’ objects like dogs, actions or events can be taken as either atomic values of attributes in a frame or as a frame itself that can be related to other frames. The latter possibility is used in our frame theory to model the relation between events (or actions) and objects. This relation involves both the internal perspective on an event (it occurs in time and changes some properties of some objects) and an object taken as a ‘bundle’ of properties (since the values of particular properties are changed).

Fig. 2:



In the top layer, events are related to objects that are involved in them (see Fig. 2). These relations are defined using thematic roles like ACTOR or THEME, which are attributes in our theory (denoted TR_i in Fig. 2). At this level, both objects and events are taken as atoms, i.e. the internal structure is not taken into account. This relation is static because it does not change during the occurrence of the event. At the second, or intermediate layer, an internal perspective on an event is taken (by the temporalization operation T in Fig. 2): it is related to its proper parts (part-whole relation) and to a temporal interval in which it occurs. In the figure, the e_i are subevents of the same sort as e (say an eating or a running event) and $\alpha(e)$ and $\beta(e)$ are the (temporal) beginning and endpoint of the event, respectively. At the third layer the internal structure of an event at the second layer is related to the internal structure of the objects involved in the event, representing the change the event brings about with respect to particular properties of those objects (by the zooming operation Z in Fig. 2). Traces of the value changes at the bottom layer (e.g., the location specification of an object involved in a motion event) relate to atomic path objects at the top level (see Gamerschlag, Geuder & Petersen, 2014a, for details).

Phase quantification: Besides refinement, a second operation on frames is that of *classification*. If events occurring in time bring about changes with respect to the properties of objects participating in them, frames for action concepts can be classified according to the *types* of changes they bring about with respect to objects. This possibility of classifying one frame in terms of properties of another one has been used in a first attempt at analyzing phase quantification developed in Löbner (1987) and Löbner (1989) in our frame theory (Naumann, 2014b). A sentence like ‘It is already late’ not only requires that it be late at the parameter point (say speech time) but it additionally imposes a condition on a phase (e.g. a temporal interval). For the above example, the constraint requires that there be an interval such that (i) it directly precedes the current one in which ‘late’ is true and (ii) ‘late’ was constantly false on it. As a consequence, ‘late’ must not be true during the whole (contextually given) phase leading up to the current parameter point. Basically, adjectives like 'late' denote properties of time points. However, they can also be viewed as properties of intervals, i.e. convex sets of time points. Thus, such as objects and events, intervals can either be taken as atomic entities or as having an internal structure (using the refinement operation) that can be classified by relations to other frames. In the case of intervals, this classification is done in terms of properties of time points which have been lifted to properties of intervals by modifiers like 'already' or 'still', which impose a constraint that has to hold on the whole interval. For example, for 'late', one gets four different classification structures: (i)/(ii) 'late' either holds or does not hold continuously on the interval and (iii)/(iv) 'late' holds (does not hold) on a first subphase of the interval and continuously does not hold (holds) on the second subphase of the interval.

Lexical verb frames: In intense collaboration with project B02 we applied our frame account to different verb classes and their lexical semantics. The focus was on dimensional verbs like 'taste' and 'warm' which encode a dimension such as TASTE and TEMPERATURE and additionally allow for the specification of a value along this dimension (Gamerschlag & Petersen, 2013); for a description of this work see the report of project B02: (1) *Posture verbs* which allow for an extended locative use like 'sit', 'stand' and 'lie' encode shape and positional information, which are perceived by means of cognitive modules such as gestalt recognition and spatial orientation. These properties render posture verbs an excellent object for the investigation of cognition and language. It has turned out that the recursive frame structure is well-suited for representing the cognitive modules in an adequate way (Gamerschlag, Petersen & Ströbel, 2013). (2) So-called *phenomenon-based perception verbs* such as 'taste (of)', 'sound (of)', and 'look (like)' allow for a use in inferential evidential constructions of the type 'The chocolate egg tastes old'. The puzzle is how admissible inferential uses can be discriminated from awkward uses such as #'The chocolate egg tastes oval'. By representing the object knowledge of the perceived object in a frame with attributes corresponding to the perception dimension (i.e., 'taste') and the dimension of the adjective (i.e., 'age' or 'form') and by defining an inference structure on the type signature, the admissibility of inferential and non-inferential uses can be captured by frame constraints (Gamerschlag & Petersen, 2012; Petersen & Gamerschlag, 2014). (3) Some *movement verbs* like the German verb "steigen" (climb/rise) can be used either as a verb of manner of motion ('Anne climbed a mountain'), as a verb of directed motion ('the balloon climbed') or as an intensional verb of change along a property scale ('the temperature of the liquid rises') (Gamerschlag, Geuder & Petersen, 2014a). Within the scope of an analysis of such verbs we proposed a general frame model for movement verbs that explicitly accounts for the correlations that hold among subevents, manner, positions and the overall path traversed by the theme argument, and yields a representation of the event structure and the argument structure with flexible granularity.

(III) Cognitive adequacy of the frame model

In Naumann (to appear) and Naumann (2011), it is argued that concepts cannot be reduced to past experiences and encounters with objects falling under those concepts that are stored in the mental lexicon. An alternative is developed which combines a modality-independent (or abstract) conceptual component with a modality-specific one. Verbs as concepts are interpreted as ranked sets of nuclei structures in the sense of Moens & Steedman (1988). This information is stored in the Middle Temporal Gyrus (cf. Bedny & Caramazza, 2011). Besides being amodal, this information is underspecified w.r.t. a particular way in which the action is executed (grasp a needle vs. grasp a barbell), i.e. it is not grounded in a particular situation. This underspecification can in general only be resolved if the type of object undergoing the change (needle vs. barbell) is known. Following Willems et al. (2010), this grounding is explained as an implicit simulation in premotor cortex, which is a preenactment of the action that makes it possible to predict the way in which the action evolves and that is distinct from explicit (motor) imagery. By specifying frames for action-related concepts, Vosgerau et al. (to appear) formulates conditions on what it means for a concept to be grounded in cognition. Petersen & Werning (2007) discusses how grounding can be implemented in the frame approach by object-related neural synchronization.

Meaning as context change potential: In Naumann & Petersen (submitted), our frame theory is extended to also capture dynamic aspects (meaning as context change potential) as well as linguistic and cognitive data which show that meaning cannot be reduced to truth conditions. We develop a dynamic frame theory which is based both on dependence logic (Väänänen, 2007) and dynamic epistemic logic (cf. van Benthem, 2011, for an overview). In particular, we borrow from dynamic epistemic logic the insight that the effects of utterances or updates are defined using both the update formula and the current information state and, following dependence logic, formulas are interpreted as sets of sets of assignments. The semantic phenomena to which this framework is applied are numerical expressions like 'two' or 'at least two'. They are interpreted as strategies which change the input information state to which they are applied. Different kinds of such models are distinguished, which correspond to different types of update operations.

3.3.2 Project-related publications of the investigators

Naumann, R. (to appear). Dynamics in the brain and dynamic frame theory for action verbs. In L. Ströbel (Ed.), *Sensory-Motor Concepts - at the Crossroads between Language and Cognition*. Düsseldorf UP.

Gamerschlag, T., W. Geuder, and W. Petersen (2014). Glück auf, der Steiger kommt– a frame account of extensional and intensional 'steigen'. In D. Gerland, C. Horn, A. Latrouite, and A. Ortmann (Eds.), *Meaning and Grammar of Nouns and Verbs*, Volume 1 of *Studies in Language and Cognition*, Düsseldorf, pp. 115–144. Düsseldorf UP.

Naumann, R. (2014). Phase quantification and frame theory. In D. Gerland, C. Horn, A. Latrouite, and A. Ortmann (Eds.), *Meaning and Grammar of Nouns and Verbs*, Volume 1 of *Studies in Language and Cognition*, Düsseldorf, pp. 237–265. Düsseldorf UP.

Petersen, W. and T. Gamerschlag (2014). Why chocolate eggs can taste old but not oval: A frame-theoretic analysis of inferential evidentials. In Gamerschlag, T., D. Gerland, R. Osswald, and W. Petersen (Eds.), *Frames and Concept Types. Applications in Language and Philosophy. Studies in Linguistics and Philosophy*. Heidelberg, New York, Dordrecht, London, Springer.

Petersen, W. and T. Osswald (2014). Concept composition in frames: Focusing on genitive constructions. In: Gamerschlag, T., D. Gerland, R. Osswald, and W. Petersen (Eds.), *Frames and Concept Types. Applications in Language and Philosophy. Studies in Linguistics and Philosophy*. Heidelberg, New York, Dordrecht, London, Springer.

Gamerschlag, T., W. Petersen, and L. Ströbel (2013). Sitting, standing, and lying in frames: a frame-based approach to posture verbs. In G. Bezhanishvili, S. Löbner, V. Marra, and F. Richter (Eds.), *Proceedings of the 9th International Tbilisi Symposium on Language, Logic and Computation*, Volume 7758 of *Lecture Notes in Computer Science*, Heidelberg, pp. 73–93. Springer.

Naumann, R. (2013). An outline of a dynamic theory of frames. In: G. Bezhanishvili, S. Löbner, V. Marra, and F. Richter (Eds.), *Proceedings of the 9th International Tbilisi Symposium on Language Logic and Computation*. Volume 7758 of *Lecture Notes in Computer Science*, pp. 115–137. Springer Berlin Heidelberg.

Naumann, R. and W. Petersen (2013). An analysis of quantifier scope restrictions in dependence logic. In: M. Aloni, M. Franke, and F. Roelofsen (Eds.), *Proceedings of the 19th Amsterdam Colloquium*. pp. 163–170.

Petersen, W. and T. Osswald (2012). A formal interpretation of concept types and type shifts. In K. Kosecki and J. Badio (Eds.), *Cognitive Processes in Language*, Volume 25 of Łódź Studies in Language, Frankfurt, pp. 183–191. Peter Lang.

Naumann, R. (2011). Relating ERP-effects to theories of belief update and combining systems. In M. Aloni et. al. (Eds.), *Proceedings of the 18th Amsterdam Colloquium*, pp. 160–169. Springer.

3.4 Research Plan

3.4.1 Research questions, aims and hypotheses

In the first funding period we developed a frame model of action/events concepts that is based on a three-level architecture (events as objects, events related to the temporal dimension and events in relation to the dynamic dimension, i.e. as bringing about changes in the world) such that the different layers are related by a refinement and/or a classification relation mirroring different levels of granularity (cf. Fig. 2). This line of research will be extended and deepened in the second funding period by focussing on the following research questions: (i) How can action/event concepts be classified in terms of (a) causal and temporal relations, (b) results/goals brought about by actions and events and (c) the objects involved in those events and the interaction between these objects? We aim at arriving at a hierarchical classification of both action/event types and the corresponding (dynamic) attributes as well as their argument types.

The second leading research question is the development of a dynamic and compositional frame model of propositions, i.e. concepts expressed by sentences. This question is split into the following two topics: (α) How can concepts expressed by nouns and verbs be enriched by concepts expressed by adverbs, adjectives and quantificational expressions like determiners? and (β) How can nominal and verbal concepts be combined in a compositional way to form larger units? The unifying link between (α) and (β) is the assumption that the combination of two concepts is always modelled as a dynamic update operation in the sense of dynamic semantics or dynamic epistemic logic. Concerning quantification, we will use the theory developed in Naumann (2014b) and Naumann & Petersen (2013), which uses Dependence Logic. For update operations, we will build on the theory of updates developed in Naumann & Petersen (submitted) and Naumann (2014a) as well as the update operations defined in de Lavalette (2004) and Benthem & Cepparello (1994). These update operations must be able to capture the dynamic or non-monotonic character of the information flow that is triggered when action/event concepts are combined: (a) the values of attributes have to be changed if an event is described which brings about a change in the world (John went from A to B) and (b) the domain of a frame model has to be changed in case a verb of creation (build, write) or a verb of destruction (kill, destroy, eat) is used. The update operations that we have been using so far do not take into account that updates are in general constrained or ranked by prior probabilities or plausibility (expectancy) orderings, as witnessed by neurophysiological phenomena like the N400 and the P600. It is therefore necessary to integrate probabilities and/or plausibility orderings into our frame theory. Since updating a frame can also change the probabilities and/or the expectancy ordering, update operations must also accomodate such changes in those orderings. In addition, combining concepts to more complex ones has to take into account dependency relations that can arise as an effect of the combination, in particular with respect to the range of values that are admissible for attributes. The integration of such relations into the theory requires to develop an appropriate description language (or logic) in which both probabilistic/expectancy as well as dependence relations can be expressed.

WP 1 Basic frames – their elements and interpretation

In this first work package we will continue our work from the first funding period on frame elements. In particular, we will work on a more fine-grained classification of frame attributes by properties of their domain and co-domain (WP 1.1) and we will investigate dependence relations in frames (WP 1.2).

WP 1.1 Attributes and values

Frames as recursive attribute-value structures are based on the idea that concepts are made up of functional relations between a possessor (i.e. an element of the domain of the function) and a value (i.e. an element of the function's co-domain). However, this perspective does not take into account that the functions involved can be quite different so it is open to the so-called 'Has_a' fallacy (Wilensky, 1987; Artale et al., 1996) by treating all attributes as *arbitrary* functional relations (Guarino, 1992). In our current frame theory, attributes are uniformly interpreted as partial functions. The exact definition of those functions is usually taken for granted or simply left implicit. This has the effect that no distinction is made between different levels of representation which reflect, first, differences in the ontological status of objects represented in the sense of differences in the structural properties of the various ontological domains and, second, the way different ontological domains are related to each other. In this work package, we will investigate what types of attributes are needed in a frame theory and how they are related to each other. Our starting point will be the following threefold distinction: (i) Attributes whose values are primitive in the sense that they do not have any internal structure so that they cannot be further specified in terms of attribute-value pairs (e.g., *scalar* attributes, see Löbner, 2014). (ii) Attributes that relate an object to one of its parts, i.e. a part-whole relation. (iii) Attributes that have values which are structured but which do not stand in the part-whole-relation to the possessor.

Additionally, we will focus on the integration of atypical attributes into our theory that (a) do not simply specify a property of an object but represent an operation or a process, or (b) that seem to violate the central frame hypothesis that attributes are functions. Besides the obvious collaboration with **A06** on the ontological status of attributes and their values, we will collaborate with **D05** on procedural, i.e. atemporal dynamic attributes.

Main research questions:

- Which attribute-types have to be formally distinguished? How are they defined and which language / logic is best suited to speak about them? How fine-grained should the attribute classification be? In particular, how many subtypes of the part-whole relation must be distinguished? A part-whole relation need not always involve an independent object. For example, are edges structured objects that can be specified in terms of sets of attribute-value pairs?
- Which value-types have to be distinguished? What kind of orders are needed for the values? How can these orders be integrated into the type signature?
- Do we need tuple- (e.g., LEGS) and set-valued (e.g., MEMBERS) attributes? If yes, can they be integrated into the theory without giving up the central frame hypothesis of functional attributes?
- Do we need n-ary attributes for $n > 1$? Examples are attributes like DIFFERENCE or DISTANCE.

WP 1.2 Constraints in and between frames

The values of attributes in a frame need not be independent of each other but are often constrained by various dependency relations. Our aim is to investigate what types of dependency relations exist and how they can be incorporated into our frame theory. Consider the following examples:

(2) a. Apples are round. / Apples are not triangular. [The value of the attribute FORM is restricted for objects of type 'apple'.]
b. Every dog has a tail. / Dogs have no wings. [Objects of type 'dog' have an attribute TAIL.] / [Objects of type 'dog' do not have an attribute WING.]
c. This melon sounds ripe. [The value of the attribute RIPENESS can be inferred from the value of SOUND.]
d. The older a stamp, the more expensive it is. [In a 'stamp' frame, the value of the PRICE-attribute depends on the value of its AGE-attribute.]

So far we have defined constraints directly on the type hierarchy by appropriateness conditions (ex. (2-a), (2-b)) and inference structures (ex. (2-c), cf. Petersen & Gamerschlag, 2014); that way we could only account for universal constraints which are valid for all frames in the space of frames defined by the type signature. Following this traditional analysis, one is forced to assume non-natural types like 'non-round' for a negative value constraint like 'to be not round'. In addition, negative attribute constraints ('has no wings') can only be expressed in the space of totally well-typed frames, an assumption which is usually too restrictive for our purposes. In this work package our starting point will be dependency relations used in database theory and dependence logic (DL) like functional or multi-valued dependencies. By combining DL and frames we will be able to model a greater variety of constraints and to express constraints which hold within individual frames. Dynamic constraints such as (2-d) are an especially interesting case as they do not only express a dependence relation within one frame, but a dependence relation between a set of frames of the same type (a single stamp cannot be a witness of this constraint). We expect to get many examples for constraints that need to be modeled from all projects working on frames for concrete domains.

The examples in (2) show that the dependency need not hold unconditionally but only in 'normal' or 'typical' cases. For example, a melon that sounds muffled is only normally ripe, i.e. there are exceptions to this rule. In close cooperation with **D01** and the **Mercator** fellow Henk Zeevat, we will add probabilities to our frames to model *diagnosticity* of attributes and *typicality* of attribute values in order to account for vagueness in concept and object frames.

Main research questions:

- How can we model constraints in dependence frames?
- What kind of constraints are important?
- How can we express negative or dynamic constraints?

WP 2 Dynamic higher order frames

In Naumann (2013), a dynamic frame theory for action concepts corresponding to (non-stative) verbs was developed. There are three important questions that were left open in the first period and that will be taken up in the next period: (a) How can the manner component be modeled? (b) What is the exact relation between nominal and action concepts in our frame theory? (c) Is it possible to classify changes expressed by action concepts in terms of properties of those concepts to obtain a finite hierarchy of action concepts that are stored in the mental lexicon? In this work package we will tackle these questions.

WP 2.1 Extending the analysis of dynamic concepts expressed by verbs

What is missing so far in the theory of dynamic concepts developed in the first period is a *classification* (or a hierarchy) of dynamic concepts, comparable to the Löbner classification of nominal concepts (Löbner, 2011). A first step in arriving at such a classification is undertaken in Naumann (2014a) which introduces the notion of a *Degree Transition Model* (DTM). Basically, a DTM models the types of changes an event can bring about with respect to particular properties of objects involved in it in terms of functions which map a state to sets of sets of states (i.e. they correspond to effectivity functions in game logic). In the second period, we will extend this approach with the aim of developing a classification of dynamic concepts. Our main hypothesis is the following: *Verb stems can be classified according to the DTM's they are semantically assigned.* For arriving at such a classification, DTM's will be extended both by the various kinds of changes introduced in de Lavalette (2004) as well as the dynamic modes from Naumann & Osswald (2002).

The theoretical development of DTM's will be investigated in close collaboration with project **B01**. In the first funding period, **B01** developed a decompositional classification in terms of attributes like progression, cause and effect, whereas in our project dynamic concepts were classified in terms of properties of sequences of subevents which are type-identical to the whole event. The two approaches are therefore complementary to each other. Whereas **B01** focusses on a decomposition which relates non-type identical events using both temporal and causal relations, our project stresses the different ways results can be brought about or remain invariant during the occurrence of an event. The goal is to combine these two complementary aspects.

One area of application of the resulting event hierarchy will be the domain of mental disorders investigated in project **B06**. This domain requires a complex hierarchy of different types of events that are both causally and temporally related. This task will be carried out in close collaboration with **B06**.

Decomposing events and actions into different components which are not only temporally and mereologically but also causally related raises the question of whether such a fine-grained analysis is psychologically or mentally real. In order to test our hypotheses about event decomposition we will closely collaborate with project **B03**. In the first period **B03** already investigated the relation between various semantic parameters of verbs and the effect those parameters have during semantic processing on particular brain activities. The major goal of this collaboration is to investigate both theoretically and empirically the relation between the various components of events in a DTM and particular brain activities. Our hypothesis is: *the decomposition into various components is reflected at the level of semantic processing in terms of particular brain activities corresponding to those components.*

In addition there will be external cooperations with Christopher Piñón from the University of Lille and Yoshiki Mori from the University of Tokyo concerning verb decomposition and aspectual classification.

Main research questions:

- Is it possible to classify changes expressed by action concepts in terms of properties of those concepts to obtain a finite hierarchy of action concepts that are stored in the mental lexicon? That is, is it possible to define a hierarchical type structure of DTM's?
- What other types of properties are relevant for classifying DTM's?
- How are the elements in a higher-order frame related to each other?

WP 2.2 Modelling the inner structure of an event and its modifications

In close cooperation with **B09**, we will further refine the model of a dynamic frame developed in Naumann (2013) and depicted in Fig. 2. So far, the manner component of a verb is mainly modeled by assigning an adequate event type to the event argument frames at the top level, similar to the 'run(e)' or 'scuffle(e)' analysis in classical PL approaches. This level of decomposition is insufficient to account for manner modifications as analyzed in **B09**. Building on our first considerations in Gamerschlag, Geuder & Petersen (2014a), we will zoom deeper into event frames, e.g. by decomposing the force constellation responsible for an event or by modelling the intention of an agent and its relation to the event. Operations for the modification of the event structure have to be developed on the basis of such a decomposed event structure. An especially hard problem are the scope taking modifications discussed in **B09**.

Our event model must reflect the fact that the frames at all levels in Fig. 2 are highly interrelated. The differences in admissibility of constructions such as *Der Ballon steigt* 'The balloon climbs' vs. *? Die Ziege steigt* 'The goat climbs' or *Die Ziege steigt auf das Dach* 'The goat climbs onto the roof' vs. *? Die Schnecke steigt auf die Pflanze* 'The snail climbs onto the plant' involve dependencies between the first and third level.

We will distinguish between *inner activities* of an event and *outer changes* brought about by an event. For example, in a movement verb like *scuffle*, the inner activity refers to how the body of the agent moves (i.e., manner of motion) while the outer change refers to the path covered by it. The path semantics of Zwarts (2005) will be applied to model outer changes as suggested in Gamerschlag, Geuder & Petersen (2014a) for directional movement verbs and degree achievements in general. For this WP we will mainly work with **B09** but also with **A02** and **B01** on questions concerning the structure of event frames. In addition there will be an external cooperation with Christopher Piñón from the University of Lille on adverbs and adverbial modification in general.

Main research questions:

- What refinements of our dynamic frame model are needed in order to account for the inner structure of an event?
- How can event modifications be modeled in frames? Which event components can be modified?
- How can event types be distinguished with respect to the manner component? How is this distinction reflected in the frame structure?
- How are inner activities and outer changes related in a dynamic frame model?
- What is the exact relation between nominal and action concepts in our frame theory? (see also WP 2.1)

WP 3 Quantification
In this work package we will continue our work on quantificational expressions and on phase quantification. The results of this work package are directly relevant for the development of an incremental and compositional frame theory of sentence processing (WP 4.2).

WP 3.1 Determiners and the inner structure of frames expressed by complex noun phrases
In Generalized Quantifier Theory, determiners (or, more generally, quantificational expressions) like 'a' and 'every' are interpreted as relations between sets. For example, 'every' is interpreted as the subset relation. So far, such cardinality or quantificational information cannot be expressed in our frame theory because a frames only contain sortal information (e.g. 'it is a cherry') together with information that can be inferred from strict or defeasible constraints (see WP 1.2). The information expressed by quantificational expressions does not add a value to an attribute (say, QUANTITY). Rather, it is interpreted as an operation on frames. This idea will be made formally precise by using the notions of a team and a supplement operation on teams from dependence logic (Väänänen, 2007; Naumann & Petersen, 2013). For example, the concept expressed by 'cherry' can be modeled by the following team consisting of exactly one row (assuming that both strict and defeasible constraint information is added).

	stone	taste	form	color
c_1	s_1	sweet	round	red

The function of a numeral like 'three' consists in supplementing this team in such a way that the cardinality information associated with the numeral is satisfied.

	stone	taste	form	color
c_1	s_1	sweet	round	red
c_2	s_2	sweet	round	red
c_3	s_3	sweet	round	red

Given a particular situation in which 'three cherries' is used, the supplement operation is restricted by a context set (Peters & Westerstahl, 2006). Assuming an 'exactly' interpretation of 'three', the sentence 'Three cherries are sweet' is true in a context represented by the following team consisting of three cherries and a peach since the intersection of the denotation of cherries with the denotation of sweet objects is (exactly) three (see Naumann & Petersen, submitted, for details on the interpretation of bare numerals in our frame theory).

	stone	taste	form	color
c_1	s_1	sweet	round	red
c_2	s_2	sweet	round	black
c_3	s_3	sweet	round	yellow
p_1	s_4	sweet	round	yellow

The difference between the graph representation (see Fig. 1) and the team representations of a frame (see tables above) is that between an abstract (or nonsituated) and a referring (or situated) frame. Thus, in our frame model the cognitive function of quantificational expressions like 'three' is orthogonal to that of modifiers like 'red'. Whereas the latter add a particular value to an attribute, the former are interpreted as a supplement operation which 'multiplies' the number of frames (or rows in the corresponding team representation). This raises the question of how different constituents in an NP are combined with the basic abstract concept frame expressed by the noun. Our starting point for the structure of NPs is the layered analysis of the *nominal onion* proposed in Löbner (to appear in 2015). In this model, different layers like unit forming (plural), quantity (numerals) and quantification are distinguished which are applied to the noun in a linear fashion. We will investigate how far we can go by following this model and make necessary adaptions. By letting the onion metaphor guide our research, we will have to distinguish between different levels of conceptualization and mechanisms, as for example unit forming and actual quantity specification. The unit and quantity layers will be first approached by a team analysis with Link-style sums. On nominal frames we will cooperate with **C10** on the question of how adjectives modify noun frames at different functional layers of an NP and with **C09** on the mass/count distinction at the quantity layer.

Main research questions:

- How are (abstract) concept frames and (referring) situated frames related to each other? Is the *nominal onion* a useful metaphor in frame modelling? What is the exact relationship between frames and teams?
- What compositional mechanisms for frames are needed at the level of noun frames? (see also WP 4.2)

- How can the distinction between collective, distributive and cumulative readings be formally modeled? For example, 'John and Mary met' only has a collective but no distributive interpretation. This sentence cannot be interpreted as the conjunction of the two (ungrammatical) sentences 'John met' and 'Mary met'.
- How can differences between monotone increasing ('a' and 'at least') and monotone decreasing ('at most') quantifier (or scalar modifier) expressions be captured? For example, in contrast to monotone increasing quantifiers, monotone decreasing quantifiers cannot be analyzed as an existential quantifier over witness sets but require in addition a maximality condition.
- How can polyadic quantification be represented in our frame theory? In polyadic quantification, a quantifier expression binds several variables simultaneously. For example, in 'Politicians are usually willing to help constituents' the quantifier expression has one variable ranging over politicians, and another one ranging over constituents (see Peters & Westerstahl, 2006, for details).

WP 3.2 Phase quantification

According to Löbner (1987) and Löbner (1989), quantification not only applies to NPs like 'a dog' or 'every woman', but also to other syntactic categories. In Naumann (2014b), a first step in integrating phase quantification in our frame theory was undertaken by analyzing 'already/still/not yet/no longer late', which involve a change occurring in time. In the next period, this analysis will be extended to other concepts involving phase quantification. The focus will be on concepts expressed by verbs with a modal (epistemic, deontic, alethic) component like the example in (3).

(3) He will $\left\{\begin{array}{c}\text{accept}\\ \text{claim}\\ \text{refuse}\\ \text{renounce}\end{array}\right\}$ compensation.

Our first thesis is: *in order to capture such differences, it is necessary to distinguish between a static meaning that captures truth conditions and a dynamic meaning that captures how these truth conditions may have come about*. Static meanings are modeled by basic frames whereas the dynamic meaning is modeled by shifts from basic frames to higher-order frames. Formally, we plan to model this dynamic meaning component by combining frames with game theory. The basic building blocks are (atomic) extensive games of perfect information. Winning positions in these games correspond to basic frames. The effect of this kind of lift is twofold. First, the winning positions of the resulting game for a player are those of the nonlifted atomic extensive game. Second, the difference from the underlying atomic game is that the resulting game also encodes information about how such winning positions can be attained, following one of the different possible strategies. A phase quantificational expression like 'already' denotes a particular strategy in this complex game. So our second main thesis is: *Phase quantification can be modeled as strategies on the dynamic meaning of the expressions they operate on*. On this topic we will closely collaborate with project **C10**.

Main research questions:

- How can a game-theoretical semantics be integrated into our current frame theory? In answering this question, we will build on the theory of Pacuit & Simon (2011), who define strategies as finite labeled trees.
- How can our approach to (proper) quantificational expressions like 'every' or 'some' be combined with this approach to phase quantification?

WP 4 Towards a theory of language comprehension and composition

The aim of this work package is to develop the basic ideas for a theory of language comprehension and composition that is cognitively adequate as well as mathematically rigid. The work package will consists of two parts. At the begin of the funding period we will collaborate with the designated **Mercator** fellow Henk Zeevat on an integration of frames into his recent theory on language comprehension. Based on the results we will pick up this topic again at the end of the funding period and aim at a fully frame-based theory. The separation of the two sub-packages is necessary for practical reasons: Due to his retirement Zeevat will officially only be available within the first two years, while the mature step towards an integrated compositional frame-based theory can naturally only be taken in the last part of the funding period. We do not expect to finish this work within this funding period and plan to extend it into a potential third funding period.

WP 4.1 Frames as mental representations

In his recent book, our designated **Mercator** fellow Henk Zeevat develops an account of language production and interpretation in which grammar-based production relies on simulated comprehension and comprehension conceived as incremental semantic composition of mental representations is constrained by simulated production (Zeevat, 2014). There is a strong convergence between Zeevat's account of mental representation and the Düsseldorf frame model, in its conception, aims and applications. For example, Zeevat's incremental account of interpretation is very similar to the incremental approach to quantifier understanding in Naumann & Petersen (submitted), the account of semantic composition is similar in both models, but in other respects (discourse phenomena, psychological interpretation, philosophical interpretation, lexical semantics, logical complexity) the models are complementary though in principle compatible. Combining Zeevat's mental representations with the Düsseldorf frame model offers a unique opportunity to develop an integrated framework for both lexical, logical and dynamic semantics with strong logical, philosophical and empirical foundations which might also offer a proper interface to action planning and visual imagination. The main aim of this WP is to construct and further develop an integrated frame-based account of mental representation. Obviously, in order to reach this goal we will work closely together with **D02**.

Main research questions:

- Is it possible to integrate frame-based and representationalist accounts of meaning in a useful way?
- Is it possible to merge Zeevat's approach to incremental interpretation with the Naumann & Petersen (submitted) approach?
- What is the proper notion of external truth and meaning given that representations only have an indirect relation with truth-conditions?

WP 4.2 Building a sentence compositionally

In the first period, the problem of deriving frames for complex syntactic structures like NPs, VPs or sentences has been a topic of investigation in project **A02**, using techniques like unification and constructions. We will investigate a second, quite different strategy that is based on approaches in neuroscience. In particular, we will take up the suggestion made in Baggio & Hagoort (2011), who argue that 'language use builds upon an extensive repertoire of stereotyped, non-novel utterances, and novelty in many cases amounts to local, predictable variations that do not require a generative grammar or a compositional semantics to be accounted for'. The alternative proposed by Baggio and Hagoort is based on the view that what is stored in the mental lexicon are the syntactic frames of Vosse & Kempen (2000) or the scenarios that encode verb phrase meanings in the event-based approach of van Lambalgen & Hamm (2005). The central research question will be: *How can such structures be defined in our theory so that an incremental and compositional analysis is possible?* Our starting point will be the observation that a frame defines a partially ordered set of models where the ordering is defined in terms of the information 'contained' in those models. This partial ordering already defines the possible ways in which information can be added to a frame. As a consequence, these orderings can be used to define possible 'evolutions' of a frame during sentence processing in the brain. Now, the central hypothesis to be investigated is the following: *it is possible to define a finite set of types of evolutions that can function as the unification-ready structures envisaged by Baggio and Hagoort*. The starting point of our analysis will be the theory of partially ordered nuclei structures developed in Naumann (2011). Such structures describe changes in terms of results and the way they are brought about by actions/events. The probability that one of those structures is described by a sentence depends both on the sorts of objects involved in such types of changes and the sort of an action/event that brings about such a change. For example, after having parsed the (subject) NP 'a duck', a structure (evolution) instantiated by a swimming event is more probable than an instantiation by a jumping event. Similarly, whether a particular result is brought about depends on the sort of the event. For example, for a writing event, it is more probable that its incremental theme, say a letter, gets finished than that the attempt fails at some stage. By contrast, for a verb like 'swim', it is more probable that no particular result is brought about since 'swim' is an activity verb. By combining the probabilities for the sort of the event and possible outcomes, a comprehender can defeasibly infer a most plausible nucleus structure when encountering a particular constituent of a sentence like 'a duck'. In order to define such probabilities, the nuclei structures in Naumann (2011) must be extended to allow a more fine-grained classification. This will be done by incorporating both DTM's (WP 2.1) and distinctions like those between inner action and outer change (WP 2.2). In addition, these structures will be combined with the three-tiered architecture of dynamic concepts developed in Naumann (2013).

An important question to be addressed is: How are the frames representing the various constituents combined with each other? In answering this question, we will investigate both unification and type-theoretical accounts, which mainly use functional application and / or functional composition, as well as combinations of the two approaches. This will be done in close cooperation with project **B01**, which uses unification, and project **C09**, which uses a type-theoretical approach. In order to capture default and priming effects as well as non-monotonic aspects, various update operations will be investigated (see Naumann & Petersen, submitted, for an example of an update operation). Concerning questions of probabilistic reasoning, we will collaborate with project **D01** (see WP 1.2). In addition, there will be a collaboration with Tim Fernando from the University of Dublin concerning type theory as well as questions that relate to the dynamic and update architecture.

Main research topics:

- The 'evolution' of frames for nominal concepts depends on the type of change they undergo. The question, therefore, is: is it possible to define the space of changes in terms of a classification of events denoted by frames for action concepts?
- What types of update operations on frame models are needed? For example, if a comprehender chooses a particular evolution on the basis of a part of the sentence, say the predicate, this choice is defeasible, i.e. the choice may need to be revised if further constituents have been processed. It is therefore necessary to incorporate into our frame theory update operations which change or revise a given choice.
- What types of supplement operations from dependence logic are needed for the combination of basic frames with quantity, quantificational and scalar modifying expressions? What is the relationship to other update operations? Is it possible to give a uniform definition of an update operation?
- There are at least three alternatives of how to integrate probabilities: (i) probability measures, (ii) ranking functions and (iii) relative likelihood (Halpern, 2005). A first step in integrating probabilistic reasoning into our frame theory has been taken in Naumann (submitted).
- If probabilities and dependence relations are integrated into our frame theory, an appropriate description language (logic) must be developed.

Timeline

	WP 1.1	WP 1.2	WP 2.1	WP 2.2	WP 3.1	WP 3.2	WP 4.1	WP 4.2
year 1	N,(P)		N		N,P		P, (N)	
year 2	N,(P)	N,(P)	N	N,P,(L)	N,P	N,L	P, (N)	N, (P)
year 3		N,P	N	P,L		N,L		N, (P)
year 4			N	P,L				N, (P)

(L: Löbner, N: Naumann, P:Petersen. Brackets indicate a minor role in a work package)

3.5 Role within the Collaborative Research Centre

The central aim of this project is to construct the formal architecture for a unified theory of frames that covers linguistic, philosophical, cognitive and psychological aspects of frames. Our focus therefore lies not only on providing formal definitions of frames for object and action concepts but also on the relation between those concepts and the ways they are expressed in language. In addition, we investigate mappings between and operations on frames and develop a hierarchical formal structure in which different layers of frames can be analyzed. We use tools from various disciplines like logic (modal logics, dependence logic, description logic and higher-order logics), mathematics (probability theory), AI (theories of actions, defeasible reasoning), philosophy (theories of belief revision) and psychology (theories of grounded cognition). This makes the project a highly interdisciplinary one, despite its theoretical and formal focus. We thereby provide not only formal tools but also solutions for technical problems of more empirically oriented projects. In addition, we extend and generalize the theoretical results of other projects.

In order to achieve its goals, A01 has been in intensive exchange with the other projects. Within the first period this exchange led to documented collaborations with six out of the fifteen other CRC-projects. Together with A02, A01 organized the workshop 'Bridge-14: Bridging formal and cognitive semantics' (proceedings with Düsseldorf University Press and one edited volume with Brill planned) and the colloquium 'Meaning and Cognition'. With A03, A01 published one article on grounded cognition (Vosgerau, Seuchter & Petersen, to appear). With A05, A01 organized the workshop 'Concepts and Categorization' (edited volume in preparation with Mentis). With B01, B02, and C01, A01 edited two volumes on frames and concept types, namely Gamerschlag, Gerland, Osswald & Petersen (2014b) and Gamerschlag, Gerland, Osswald & Petersen (to appear). With B01, A01 worked on intensifiers and verbs of emission and presented their work at a conference (Fleischhauer, Gamerschlag & Petersen, 2014). With B02, A01 worked on different types of verbs and published five articles and presented common research at several conferences (see

A01

paragraph "Lexical verb frames" in Section 3.3.1). Additionally, A01 collaborated with many other projects in the organization of ESSLLI 2013.

In the following we only list the main cooperations for the second funding period which are outlined in the descriptions of the single work packages:

A06: ontological status of attributes and their values (WP 1.1).
B01: event structure and verbal modification (WP 2.2), composition (WP 4.2).
B03: neural realizations of nominal and verbal concepts (WP 2.1).
B09: event structure and modification of verb frames (WP 2.2).
C09: mass/count distinction in noun and verb frames (WP 2.1), composition (WP 4.2).
C10: noun frame structure and modification of noun frames (WP 3.1).
D01: probabilities in frames and typicality effects (WP 1.2), composition (WP 4.2).
Mercator fellow: probabilities in frames (WP 1.2), mental representations (WP 4.1).

Additionally, there will be minor cooperations with other projects. With respect to the **formal properties** of frame theory we will profit from the insights **A05** gains by investigating the subtle distinctions made in the precursors of frame theory in philosophy. **A02** tackles similar problems as A01, but from a different perspective: it aims at a formal model for frames at the syntax-semantics interface and its implementation. **B08** will profit from our approach to type signature induction.

We expect challenging problems for our theory from all projects working on **concrete frames** for specialized tasks. These include **B06** and their need to represent temporal and causal relations, **C08** working on semantic operations in morphology, **D04** requiring a frame model for common ground and information structure, and **D05**, which uses atemporal dynamic attributes to model phonological processes.

Finally, the **cognitive adequateness** of our formal model is challenged by the results of the empirical findings of **A04** about the cognitive status of different kinds of attributes and **D03** about constraints in frames of social interaction, and by the considerations of **D02** on mental representations and the problem of reference from the perspective of Philosophy of Mind and Cognition.

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