An Outline of a Dynamic Theory of Frames

Ralf Naumann

Institut für Sprache und Information
Universität Düsseldorf
Germany

Abstract. In this article we present an extension to the theory of frames developed in Petersen (2007). Petersen's theory only applies to concepts for persistent objects like trees or dogs but not to concepts for actions and events that are inherently dynamic because they describe factual changes in the world. Basic frames are defined as Kripke-models. In order to represent the dynamic dimension one needs in addition both combinations of and transformation between such models. Combinations of Kripke-models are used for *temporalization* (representing stages of objects and the temporal development of events) and *refinement* (representing the internal structure of objects). Such combinations are defined using techniques from Finger & Gabbay (1992) and Blackburn & de Rijke (1997). Transformations between Kripke-models are used to represent the factual changes brought about by events. Such transformations are defined using strategies from Dynamic Logic and Dynamic Epistemic Logic, Van Benthem et al. (2005).[1]

Keywords: dynamic frame theory, Kripke models, combining systems, simulations, dative alternation

1 Introduction

Barsalou (1992, 1999), following the work of Fillmore (1982), extended Fillmore's concept of frame, arguing that it is the fundamental representation of knowledge in human cognition which underlies the content and structure of concepts. He defines a frame as a recursive attribute-value structure in which attributes denote properties of objects, like colour or height, whose manifestations are represented by the values, e.g. blond or black for the colour of the hair of a person. Values need not be atomic but can be frames themselves. For example, the attribute *BIRTH* of a person can be a frame consisting of attributes like *DATE* and *PLACE*. A formal theory of frames in the sense of Barsalou was developed in Petersen (2007). Extending the notion of a typed feature structure in Carpenter (1992), she defines a frame as a directed connected graph satisfying the following three conditions: (i) there is a central node (depicted by a double border), (ii) each node is of a particular type indicating the

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sort of the value and (iii) arcs are labeled with functional attributes.[2] In Figure (1) the (simplified) frame for the sortal concept *tree* is given (see Petersen & Osswald 2012 for details). Such frames will be called *Petersen-frames*.

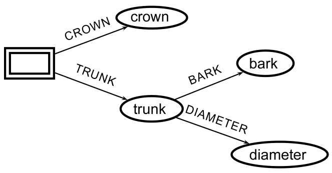

Fig. 1. Frame for the sortal concept *tree*

Both Barsalou's approach and Petersen's formalization of it only apply to static concepts which are related to persistent objects like trees, mothers and dogs and which are usually expressed in natural language by common nouns. What is missing is an account of dynamic concepts that express changes and which are related to non-stative or action verbs like *write*, *go to*, *kick* or *arrive*. Both types of concepts are not independent of each other. Static concepts provide links to dynamic concepts, e.g. in the form of actions that can be performed by or with a given type of objects. Dynamic concepts for action and events, on the other hand, are 'applied' to persistent objects having particular properties the values of which get changed during the execution of the action or the occurrence of the event.

A central question for a frame theory therefore is: is it possible to model dynamic concepts in the same (or at least similar) way as static concepts? Löbner (2011) distinguishes the two options below.

1. There is a uniform format underlying both static and dynamic frames.
2. The format of frames is used only for static concepts. Dynamic concepts are conceived of as procedures operating on static frames. On this view a theory of frames consists of a space of (static) frames and a set of dynamic operations on, or in, that space.

The two options are illustrated by the concept for *x going from A to B*. One attempt at modelling this concept as a frame is depicted in Figure (2).

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[2] Thus, in contrast to Carpenter, Petersen does not require that a feature structure be rooted. A second difference, neglected in the presented context, is that attributes are defined as a special kind of type; see Petersen (2007) for details.

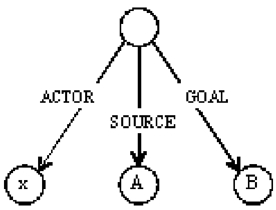

Fig. 2. Fillmore frame

The central node represents the event of going. This event is related by three attributes (modeling thematic relations or roles) to three objects x, A and B, respectively. However, there is no relation between the Source and Goal attributes and the Location attribute of the actor at the beginning and the end of the going-event, respectively. According to option (1), this lack can be overcome in the following way. Frames for events and actions are defined in such a way as containing attributes representing temporal transitions, e.g. a change of the actor's location from value A to value B. This is shown in Figure (3).

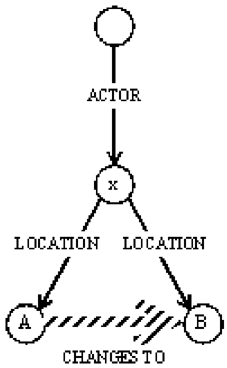

Fig. 3. frame with temporal transition

By contrast, using option (2), events are modeled as procedures that operate on (static) frames. In our example such a procedure would map a frame for the object x with the attribute Location having the value A to a frame for the same object with the attribute having the value B. This is depicted in Figure (4) on the next page.
As noted by Löbner (2011), option (1) calls for an inventive new account of frames with the main problem being the representation of time within frames for verbs. The main difficulty for the second option consists first in deriving frames from a procedural verb representation and second in formally defining the procedures themselves.

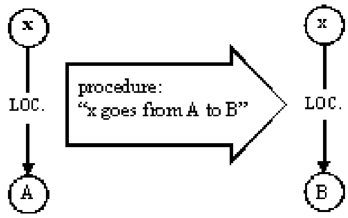

Fig. 4. transition between frames

The rest of the paper is organized as follows. In the next section the theory is presented in an informal way. In the following section a possible formalization both of the structures and of the comnbinations and mappings between them is given.[3] In the last two sections the theory is related to the notion of simulation in Barsalou (1999) and to the frame-based analysis of *send*-verbs in Kallmeyer & Osswald (2012).

2 Static and dynamic frames

A key problem with the frames depicted in Figures 2-4 in the preceding section is that they (i) capture only one aspect (frame in Figure 2), (ii) try to capture different aspects in a single frame (frame in Figure 3) or (iii) that some aspect is not represented as a frame at all (frame in Figure 4). Thus, they either achieve too little or they try to achieve too much within single frames.
By contrast, the approach to a dynamic theory of frames to be developed in the sequel distinguishes different levels of frames: besides basic frames, e.g. Petersen-frames, one also needs combinations of and transformations between frames. One thus arrives at a hierarchical structure in which the different aspects of the dynamic dimension of concepts for actions and events are modelled.
The basic level are frames like those shown in Figures 1 and 2. They are used to model the static dimension, e.g. the relation between an event and its participants. Petersen-frames already represent a second level of frames: refinement. They can be taken to give a detailed or internal (though partial) representation of an object whose type is determined by the central node. On this view, refinement is a relation between a persistent object, taken as an atom, and a representation of it where it is seen as having various properties having certain values. Refinement is a first step to model the dynamic aspect. Action and events change a particular aspect (or particular aspects) of an object, for example its volume or its

[3] Due to lack of space the discussion is restricted to the question of what structures and combinations between them are needed. The equally important issues of how those structures are used to construe the meanings of verbs and of what are appropriate logics (languages) to talk about those structures must be left to another occasion. Preliminary results can be found in Naumann 2012 and section (5) below.

degree of dryness, leaving other aspects unchanged. Different types of events change different aspects of the same object (dry a shirt vs. send a shirt to Mary). It is therefore necessary to represent those properties the values of which get affected during the event.[4] However, refinement alone is not enough for modelling the dynamic dimension because one needs two different representations of the same object: one at the beginning of the event and a second one at its end.[5] Thus, events must be represented in their temporal evolution (occurrence) and Petersen-frames must be related to (appropriate) stages of those evolutions. This level of frames is called *temporalization*. Finally, a fourth level is needed, which represents the dynamics proper, so to speak. At that level the transition (transformation) between one Petersen-frame to the next Petersen-frame in the temporal evolution of an event is interpreted as the result of an update construction between the first Petersen-frame and a particular type of event frame. In the remainder of this section, we will give an informal account of the theory.

Concepts for persistent objects like trees, dogs and mothers, as modelled by Petersen-frames, only have a static dimension in the following sense. These concepts describe what is the case (holds) for an object at a particular moment in time. There is therefore no explicit temporal (or dynamic, change) component. Such concepts (recursively) relate a central node, which determines the type of the object, to a set of attribute-value pairs that represent properties of the object and their values at a particular moment of time, respectively. An example of such a frame is given in Figure (1) above for the (sortal) concept *tree*.

Similar to concepts for persistent objects, concepts for actions and events have a static dimension. This dimension represents the relation between an action/event and the (persistent) objects participating in it. In the present context these relations are defined in terms of thematic roles like *Actor*, *Theme* or *Recipient*. These relations between an event and its participants too are static in the sense that they do not change during the occurrence of the event. This component can be represented by frames of the type in Figure (5), which are a variant of a Fillmore frame. Such frames will be called *static event frames (SEFs)*.

In an SEF both the event and the objects it is related to are taken as atomic, undivisible entities with no internal structure. In order to arrive at the dynamic dimension of the concepts for actions and events both types of entities, persistent objects and actions/events, must be assigned some kind of internal structure, which is then used in representing those entities over (or in) time (temporalization). The key idea to be used is the concept of *refinement*.

The idea of refinement can be illustrated by the following example taken from Blackburn & de Rijke (1997). When working with a graphical user interface on a computer, the desktop usually contains a number of icons. These icons are just 'blobs' as long as the user does not click on them.

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[4] As will be shown in section (4), this aspect is also closely related to the notion of a *simulation*.

[5] For many types of events it is also important to model what happens *during* the occurrence of the event; see below for details.

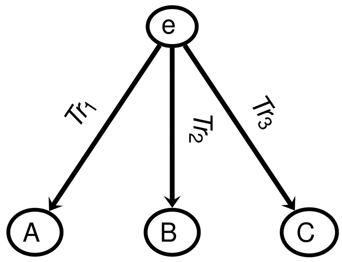

Fig. 5. static event frame

However, when one wants to perform a certain task, one gets a more refined view. One double-clicks on an icon and as an effect one zooms into another level of structure.[6] So in a refinement there are two levels which are linked by a relation. At the higher level an entity is seen as an atom without internal structure, whereas at the lower level one gets a more detailed (or fine-grained) view of the entity. For persistent objects this means that information about (some of) their properties and their corresponding values (at a particular moment in time) is provided. In the case of actions and events the information concerns the temporal (dynamic) development of the event in time. Thus, in a frame theory refinement both for persistent objects and events has to do with a relation between those entities and time.[7]

For persistent objects, a Petersen-frame is already a refinement of the object at the central node. For actions and (non-boundary) events one has to take into consideration that, contrary to persistent objects, they occur in time. They have a beginning (left boundary) and an end (right boundary) point.[8] During any proper part of the time span corresponding to those two points only part of the event exists (or occurs).[9]

There are different ways of how the boundary of an event can be defined. For example, it can be taken to be a time point. An alternative view, investigated in Pinon (1997), consists in taking the beginning and the end of an event to be a special sort of event, called *boundary events*,

[6] An example from linguistics, also discussed in Blackburn & de Rijke (1997), is GPSG. In this grammar formalism feature structures are used to refine the notion of grammatical category. Nodes in a parse tree are not just decorated with atomic information about categories (like np or vp, for example). Rather these atomic categories become refined by being assigned a feature structure that contains information about various subatomic features and values.

[7] For persistent objects one may speak of a temporalized perspective or a stage (for the latter, see Kallmeyer & Osswald 2012 and the references cited in that article).

[8] Thus, we do not consider infinite events.

[9] The difference to persistent objects is the following. Although persistent objects have a beginning (say birth or creation) and an end (say death or destruction) too, they do not occur in time in the sense that for a proper part of their lifespan only a proper part of them exists. Rather, they are completely present at any moment during that time span. For more on this distinction, see for example Wiggins (1980).

which have no temporal extension in the sense that their run-time is a singleton. In the sequel we will adopt this latter alternative since by using it we do not need to explicitly introduce a separate domain of time points (or, alternatively, of time intervals).[10]
One way of modelling this relation between an event and its left and right boundary as a frame is given in Figure (6), where α and β are attributes that are interpreted by two functions assigning to an event its left and right boundary, respectively.

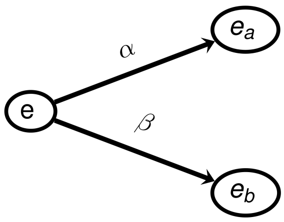

Fig. 6.

An alternative way, to be adopted in the sequel, consists in assigning to an event a frame which is a linear (or sequential) transition structure in which the left and right boundary are nodes that are linked by the event itself. Such frames will be called *Temporal Event Frames*.

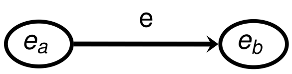

Fig. 7. temporalized event frame

For events, the above way of refinement already amounts to temporalization because the internal structure represents the event as occurring in time. Temporalizing their participants requires another strategy. A first attempt at defining temporalization in the domain of persistent objects could consist in assigning to each such object in an SEF a Petersen-frame. However, this attempt fails for at least two reasons. First, it only captures the relation between the object and its set of property-values pairs at a particular moment in time during the occurrence of the event. Second, since the root of an SEF has, at least in general, an extended temporal

[10] Though we occasionally will refer to time points in the sequel. One way of relating boundary events to a flow of time consisting of time points is to assume that each boundary event is assigned exactly one time point as its run-time.

extension (a proper interval), it would be unclear to what stage of the event the Petersen-frame should be applied. Thus, assigning to each leaf in an SEF a Petersen-frame by a refinement-relation is not what we are looking after.

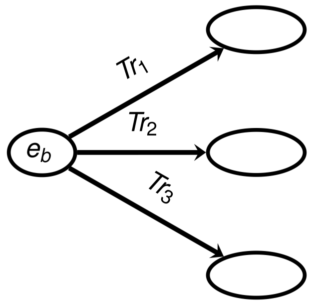

Fig. 8. temporalized static event frame with Petersen-frames as values

The key observation is that a *temporalized SEF (t-SEF)* has to be assigned not to the event itself but to its temporalized representation, that is, to its left and right boundary e_a and e_b, respectively. For example, the t-SEF assigned to e_a represents what holds of the objects participating in the event e (modelled by the SEF assigned to e) at the left boundary of e. Thus, the general idea is that for a boundary event a thematic relation links it to a refined (or temporalized) representation of an object to which the event of which it is a boundary is related by the same thematic relation. This representation models the properties of the object at a particular moment in time, namely at that moment corresponding to the boundary. If such a t-SEF is assigned to each node in a TEF, one gets a description of how the object develops (or changes) during the occurrence of the event. This is shown in Figure (8) where the values are Petersen-frames.

Thus, the general architecture is the following. Non-boundary events are related to persistent objects represented as atomic objects. This relation is captured by SEFs. By contrast, boundary events are related to a more fine-grained (or temporalized) representation of the object. This relation is captured by t-SEFs.

The dynamic dimension of concepts for actions/events can now be defined as an operation on (or transformation between) t-SEFs: the t-SEF assigned to e_a is transformed by the event e into the t-SEF assigned to e_b. If this operation is to be modeled by a frame two questions that have to be answered are: (i) what is represented by such a frame? and (ii) how is the operation between a t-SEF and this type of frame be defined? Beginning with the first question, such a frame has to represent what change is brought about by the event. One way of how this can be done consists in specifying what has to hold for the event to occur (its precondition) and what holds after the event has occurred (its postcondition).[11] For example, the change expressed by *become dry* requires that at the right boundary of the event the object undergoing the change (say some piece of clothing like a shirt) is dry, i.e. it has the maximal value on the dryness scale, say 0, whereas at the left boundary of the event this object had a non-zero degree of dryness. This kind of change is definite in the sense that a unique value for the right boundary of the event is determined. By contrast, the change expressed by *become drier* is indefinite in the sense that the only condition imposed on the right boundary of the event is that the degree of dryness be lower than the degree at the left boundary. The pre- and postcondition are not independent of each other. First, they are both formulated with respect to the same property of an object participating in the event and second the values of this property must be distinct.

An answer to the second question must account for the following constraints. First, the (input) t-SEF at e_a must satisfy the precondition imposed by e because otherwise the event e cannot occur. Second, the transformation consists in assigning to the property that gets changed a new value, namely the value resulting from the change brought about by the event. The frame corresponding to the dynamic dimension of the concept for an action/event can now be defined as having two attributes corresponding to the pre- and postcondition, respectively. Such frames will be called *update frames*.

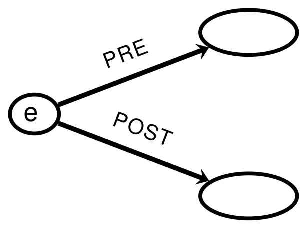

Fig. 9. update frame

Both the pre- and postcondition can be given as formulas of the language that is used to talk about t-SEFs. Applied to the example of *becoming dry*, one gets (1), yielding the frame representation in Figure (10). Here we use modal logic as a language to talk about frames. See section(3) and Blackburn (1993, 1994) for details.

(1) a. precondition : <THEME><DRYNESS>¬ 0
b. postcondition: <THEME><DRYNESS>0

[11] In Dynamic Logic, a program has both a (weakest) precondition specifying under what conditions this program can be executed and a (strongest) postcondition specifying what holds after a (terminating) execution of the program; see e.g. Harel et al. (2000) for details.

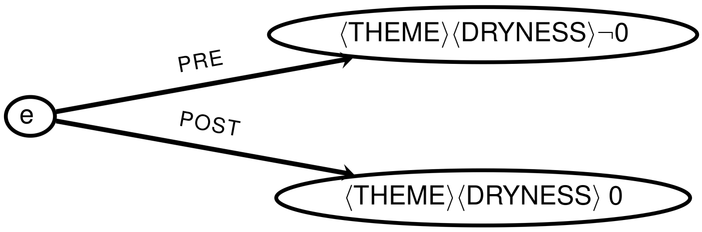

Fig. 10. update frame with values

The operation yields an output t-SEF only if the test whether the input t-SEF satisfies the precondition imposed by the UF succeeds. The resulting t-SEF is constructed from the input t-SEF by a substitution (or assignment) operation: the property affected by the change is assigned a new value (or, the old value (at e_a) is replaced by a new value given by the postcondition). This is shown in Figure (11). Applied to (1), one gets: Tr = THEME and PROP = DRYNESS. The value v can be any value other than 0 on the dryness-scale so that the precondition $v^* \neq 0$ is satisfied. The result of the update construction, i.e. of applying the update frame with root e to the t-SEF on the left, is the t-SEF on the right where the value v is replaced by v'.

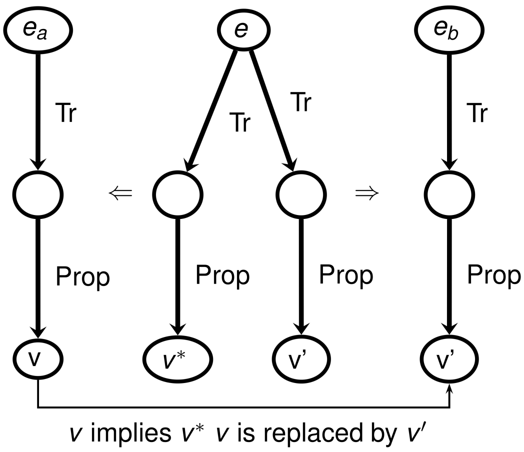

Fig. 11. update construction

Summarizing the informal account of this section, one has: Concepts for actions and events consist of

– a static dimension (modelled by a static event frame SEF)
– a temporal dimension (modelled by a temporal event frame TEF)
– temporalized static event frames (t-SEF), which combine the static and the temporal dimension
– an update dimension (modelled by an update frame UF)
– an update construction which maps t-SEFs and an update model to t-SEFs

3 A possible formalization

In this section we will sketch a possible formalization of the ideas presented in section(2). We will concentrate on defining the different structures and their combinations. Concerning the question of which logics (languages) are appropriate for those structures we only give an example of a simple modal logic. The discussion of more expressive logics (which are certainly needed) must be left to another occasion. We will begin by giving the definition of a feature structure in Blackburn (1993).

Definition 1 (feature structure) *A feature structure of signature* $<L,A>$ *with L a non-empty set of possible labels and A a non-empty set of (atomic) information, is an ordered triple* $< N, \{R_l\}_{l \in L}, \{Q_a\}_{a \in A} >$, *where N is a non-empty set of nodes; for each* $l \in L$, R_l *is a binary relation on N that is a partial function; and for each* $a \in A$, Q_a *is a unary relation on N.*

According to this definition, feature structures are a special kind of Kripke models consisting of a set of nodes together with a collection of binary relations and a collection of unary relations on these nodes. A simple modal logic for talking about such structures can be defined in the usual way. The standard truth definition is as follows.

1. $M, n \models p_a \, iff \; n \in Q_a$
2. $M, n \models \neg\phi \, iff \; not M, n \models \phi$
3. $M, n \models \phi \vee \psi \, iff \; M, n \models \phi \, or M, n \models \psi$
4. $M, n \models < l > \phi \, iff \; \exists n' \, with \, (n, n') \in R_l \, and \, M, n \models \phi$

Kripke-models are basically used to represent ontologies like those of persistent object (Petersen-frames) and action/events. Many-sorted Kripke-models are used to represent relations between different ontologies where the entities are taken as atoms. In Petersen-frames the domain is a (non-empty) set of persistent objects. In addition, there is a distinguished node, called the central node (cn)[12]
The definition of an event-structure is given below.

[12] Missing from this definition is the condition that the interpretation of atomic formulas is constraint by a sort-hierarchy.

Definition 2 (event structure) *An event structure E is a sixtuple* $< E_{nb}, E_b, \alpha, \beta, \sqcup, \sqsubseteq >$ *where (i)* E_{nb} *is a non-empty set of non-boundary events, (ii)* E_b *is a non-empty set of boundary events, (iii)* α (β) *is a total function from* E_{nb} *to* E_b *that assigns to each non-boundary event e its left boundary* $\alpha(e)$ $(\beta(e))$.[13] $\sqcup$ *and* $\sqsubseteq$ *are the usual join and part-of relations on the domain of non-boundary events.*

Static event frames are defined as two-sorted Kripke structures with two disjoint domains: a domain of non-boundary and boundary events and a domain of persistent objects.

Definition 3 (static event frame) *A static event frame (SEF) of signature* $<T>$ *with* T *a non-empty set of thematic relation symbols is a triple* $< E, O, \{TR_t\}_{t \in T} >$, *where E is a non-empty set of non-boundary or boundary events, O is a non-empty set of persistent objects and each* TR_t *is a partial function on* $E \times O$.

Instead of having two domains; E and O, it is possible to work with a single domain W and two special unary constants, say *event* and *object*, in the underlying language. These constants are defined in such a way that the domain W is partitioned into two disjoint subdomains. Formally, this constraint can be enforced by axioms like (i) $event \vee object$ and (ii) $\neg(event \wedge object)$.
In order to model the dynamic dimension, it is necessary to use in addition to Kripke-models various operations on such models. A first operation that will be used is the combination of Kripke-models in the sense of Finger & Gabbay (1992) and Blackburn & de Rijke (1997). If $\mathcal{A}$ and $\mathcal{B}$ are two classes of Kripke-models (or, more generally, structures), and $\mathcal{Z}$ is a collection of relations between the elements of $\mathcal{A}$ and those of $\mathcal{B}$, the triple $< \mathcal{A}, \mathcal{Z}, \mathcal{B} >$ is called a *trio* with $\mathcal{A}$ and $\mathcal{B}$ the left and right continent, respectively, and $\mathcal{Z}$ the bridge between the two continents. In the present context, trios are used for refinement and temporalization.
In a refinement relation entities belonging to the domains of the elements of the left continent $\mathcal{A}$ are assigned a structure belonging to the right continent $\mathcal{B}$. For action and events, refinement will be defined as the relation between an action/event and its temporal developments (or evolutions). For example, an event of drying can be decomposed into its inchoation (the beginning of the drying), followed by a development portion (the theme becoming less and less drier) and a culmination (the theme is dry) followed by a consequent state during which the theme remains dry.[14] For events described by a verb like *send* a possible temporal decomposition consists of an action undertaken by the actor causing a

[13] It is possible to extend the definition to boundary events by setting $\alpha(e_b) = \beta(e_b) = e_b$, i.e. each boundary event is its own left and right boundary.
[14] Such a decomposition is similar to the concept of a nucleus structure in Moens & Steedman (1988).

movement of the theme to the recipient as its destination.[15] In both cases the occurrence of an event is described as an ordered sequence of different phases.[16]
Temporal event frames (TEFs) are defined in terms of the sequential decomposition of a non-boundary event e.

Definition 4 (sequential decomposition of a non-boundary event) *A sequential decomposition (SD) of a non-boundary event e is a finite sequence of non-boundary events* $e_1...e_n$ *for some n s.t. (i)* $\sqcup E = \{e_1, ..., e_n\}$*, (ii)* $\alpha(e_1) = \alpha(e)$ *, (iii)* $\beta(e_n) = \beta(e)$ *and (iv)* $\beta(e_i) = \beta(e_{i+1})$ *for* $1 \leq i < n$.

Two subtypes of SD of non-boundary events are distinguished: *type-identical* and *non-type identical* SDs. For a type-identical SD, each event in the sequence is of the same type as e. Thus, if P_v is the set of all events of type v (e.g. if $v = dry$, P_v is the set of all drying-events), then if $e \in P_v$ one also has $e_i \in P_v$ for $1 \leq i \leq n$. By contrast, for a non-type identical decomposition, the e_i are not of the same type as e. This is the case for events like *sending*, for instance, where the event is decomposed into a causing event and a resulting effect event, which both are not sendings.
A second dimension with respect to which SDs can be classified is the way the postcondition is evaluated on it. To take a drying-event of a shirt as an example: the shirt is only dry at the left boundary of the event. Thus, the postcondition only holds at the end of the event but at no stage preceding it. This dimension can be represented by using program constructs from Dynamic Logic. For example, the above example of a drying in which the postcondition only holds at the right boundary of the event, can be modelled by a *while-loop*. Other types of how the postcondition is evaluated can be defined in terms of (combinations of) other programs. How this can be done, in particular for aspectual distinctions, has been shown in Naumann (2001).
The SD of an event is in general not unique. It is always possible to set $\sqcup E = \{e\}$. This is the coarsest SD. For a drying-event, the finest SD consists of atomic drying events, i.e. one has: $\forall e'(e' \sqsubset e_i \rightarrow e' \notin P_{dry}))$.
Given the definition of an SD of an event, a temporal event frames is defined as follows.

Definition 5 (temporal event frame) *A temporal event frame (TEF) is quadruple* $< E_b, E_{nb}, R, e >$ *s.t. (i)* $E_b \sqcup E_{nb} = E$ *is a sequential decomposition of e and (ii) R is defined by* $R(e_a, e_b, e)\, iff\, \alpha(e) = e_a \wedge \beta(e) = e_b$.

Finally, refinement for events is defined as given below.

[15] Such a temporal decomposition is similar to event templates like *x CAUSE z GO_ TO y)*. This is not the only decomposition for *send*; see section(5) for details.
[16] Thus, in the domain of action and events refinement can also be regarded as a special form of temporalization.

Definition 6 (refinement for events) *Refinement for events is a trio* $< E_{nb}, Z, \{TEF_q\}_{q \in Q} >$ *s.t. (i)* E_{nb} *is a non-empty set of non-boundary events, (ii) each* TEF_q *is a temporal event frame and (iii)* Z *is defined by:* $(e, TEF_q) \in Z$ *iff* TEF_q *is a sequential decomposition of* e*.*

Temporalization is used for the domain of persistent objects. Although elements of this domain persist through time, they usually undergo changes. For example, a wet shirt becomes dry or Bill gets sent a book by John and therefore now possesses this book whereas the book changed its location. Temporalization is defined in two steps. First, a persistent object is assigned a frame which partially describes what holds at the object at a particular stage during the occurrence of an event. Taken in isolation, this step can be seen as an instance of refinement because the object is described as having an internal structure given by the property/value pairs of the frame. By repeating this assignment for each phase of the event, one arrives at a sequence of frames for the object which depicts its temporal development during the occurrence of the event, in particular how some of its properties change as an effect of the object participating in the event. The first step is captured by temporalized static event frames.

Definition 7 (temporalized static event frame) *A temporalized static event frame (t-SEF) is triple* $< SEF, Z, \{P_f\}_{f \in F} >$ *where* SEF *is a static event frame based on a domain of boundary events and a domain* O *of persistent objects,* $\{P_f\}_{f \in F}$ *is a set of Petersen-frames having cardinality* $|O|$ *and* Z *is an injective function that assigns to each element of* O *a Petersen-frame from* $\{P_f\}_{f \in F}$*.*

The second step consists in assigning to each $e_x \in E_b$ of a TEF its corresponding t-SEF. More formally: For a given TEF, let Z' be a function from E_b that assigns to $e_x \in E_b$ its corresponding t-SEF. The corresponding trio is then defined by $< TEF, Z', range(Z'(E_b)) >$
Refinement and temporalization relate structures to each other. In order to model the dynamics proper, mappings (or transformations) between Kripke-models are needed. For Kripke-models, either the domain (the set of states), the accessibility relations or the valuation can be changed. For modelling the change brought about by an action or an event, only the valuation needs to be changed. Changes in the valuation are defined using the notion of a *substitution*. The following definition is taken from Van Benthem et al. (2006). Let $\mathcal{L}$ be an appropriate language for talking about Petersen-frames.

Definition 8 (substitutions) $\mathcal{L}$ *substitutions are functions of type* $\mathcal{L} \rightarrow \mathcal{L}$ *that distribute over all language constructs, and that map all but a finite number of basic propositions to themselves.* $\mathcal{L}$ *substitutions can be represented as sets of bindings* $\{p_1 \mapsto \phi_1, ..., p_n \mapsto \phi_n\}$ *where all the* p_i *are different. If* σ *is a substitution, then the set* $\{p \in P \,|\, \sigma(p) \neq p\}$ *is* *called its domain, notation dom(σ). The identity substitution is denoted by ϵ. $SUB_{\mathcal{L}}$ is the set of all substitutions.*

Using the notion of a substitution, the notion of a *Petersen-frame under a substitution* is defined as follows.

Definition 9 (Petersen-frame under a substitution) *If $P =< W, V, \{TR_t\}_{t\in T} >$ is a Petersen-frame and σ is a substitution (for an appropriate language $\mathcal{L}$, then V_P^σ is the valuation given by $\lambda p.[[\sigma(p)]]^M$. In other words, V_P^σ assigns to p the set of worlds w in which $\sigma(p)$ is true. For $P =< W, V, \{TR_t\}_{t\in T} >$, M^σ is the model given by $P =< W, V_M^\sigma, \{TR_t\}_{t\in T} >$.*

The idea underlying a substitution and a Petersen-frame under it can be illustrated by the following example. Let *is_zero* be an atomic proposition that is true of a node of type *dryness* just in case the value of the corresponding property of an object (say a shirt) is the maximal element of the dryness-scale (i.e. 0). Suppose furthermore that there is a single node, say n, in the Petersen-frame of that type. Then for a drying-event the input Petersen-frame M has $\neg is\_zero$ for the node n that is the value of the path $< THEME >< DRYNESS >$ so that $V(is\_zero) = \emptyset$ in the frame M. The required substitution is $\sigma(is\_zero) = \phi$ with $V(\phi) = \{n\}$. If $dom(\sigma)$ is a singleton, this means that there is exactly one postcondition. If there is more than one postcondition, $|dom(\sigma)| > 1$ (this is the case for events like sending; see section(5) for details).
Update models for events specify the pre- and postconditions for each event in the model, where the latter are defined using the notion of a substitution.

Definition 10 (event update model) *An event update model with language $\mathcal{L}$ is a triple $< E, pre, post >$ where (i) E is a non-empty set of non-boundary events, (ii) $pre : E \rightarrow \mathcal{L}$ assigns a precondition to each event and (iii) $post : E \rightarrow SUB_{\mathcal{L}}$ assigns an $\mathcal{L}$ substitution to each event.*

Update execution is now modelled by the following construction.

Definition 11 (update execution) *Given a Petersen-frame $P =< W, V, \{TR_t\}_{t\in T} >$ with central node $w \in W$ and an update model $< E, pre, post >$, with $P, w \models pre(e)$, the update triggered by e in P, w is the model M^σ.*

Thus, for a single postcondition the occurrence of an event e has the effect of transforming the Petersen-frame at its left boundary to another Petersen-frame at its right boundary that differs from the former only in the value that is assigned to the node specified by $e's$ postcondition.

A schematic overview of the theory is depicted in Figur (12) (R = refinement; T = temporalization). The event e at the root of the SEF on the left is refined to the TEF on the right, yielding a temporal sequential decomposition of e. Each boundary event e_x in this decomposition is the root of a t-SEF the Petersen-frame of which gives a (partial) representation of the object bearing Tr to e (or e_x) at the stage e_x of the event e. On This perspective the object $TR(e)$ gets temporalized. Viewed from $TR(e)$, the Petersen-frame is a refinement, describing one of its stages. Each e_i brings about a partial change with respect to $TR(e)$. This change is modelled by the update construction $\otimes$ between the Petersen-frame at $\alpha(e_i)$ and the update model corresponding to e_i, yielding the (updated) Petersen-frame at, modelled by a Petersen-frame under substitution, $\beta(e_i)$. When taken together, one gets the overall change effected by the event e (w.r.t. $Tr(e)$). The correspondinmg update construction is shown at the bottom of the figure.

4 Simulations in a dynamic theory of frames

In this section we will relate our dynamic theory of frames to Barsalou's main motivation for introducing the frame concept. According to Barsalou (1999), perceptual representations rather than amodal logic-based propositions are the building blocks of cognition. Perceptual representations (or simulations) are the key concept in a theory of grounded cognition. During the interaction with the world traces of perceptions and experiences of objects and events become associated with words (e.g. verbs and nouns) and are stored in the memory repository of the brain. During language comprehension those traces are retrieved from memory and are reactivated to produce a perceptual representation (or simulation) of the situation described by the sentence or discourse. For example, when reading the sentence *The ranger saw an eagle in the sky* comprehenders will simulate the eagle as having its wings outstretched (as opposed to having them drawn) because it was flying and not, say, perched in a nest. In a series of experiments Zwaan and his colleagues (Zwaan & Stanfield 2001, Zwaan et al. 2002) tested this approach to language comprehension They predicted that there should be a mismatch effect when subjects are presented with the above sentence followed by a picture of an eagle with its wings drawn. This hypothesis was tested in two experiments. After reading a sentence, comprehenders were presented with a line drawing of the object in question. In the first experiment they had to judge whether the object had been mentioned in the sentence whereas in the second experiment they had to simply name the object. The authors found that in both experiments responses were faster when the shape of the pictured objects matched the shape implied by the sentence compared to when there was a mismatch.

These experimental findings can be taken as evidence that the amodal (propositional) representation of the sentence *The ranger saw an eagle in the sky* given in (2) does not capture the fact that the eagle is represented with its wings outstretched.

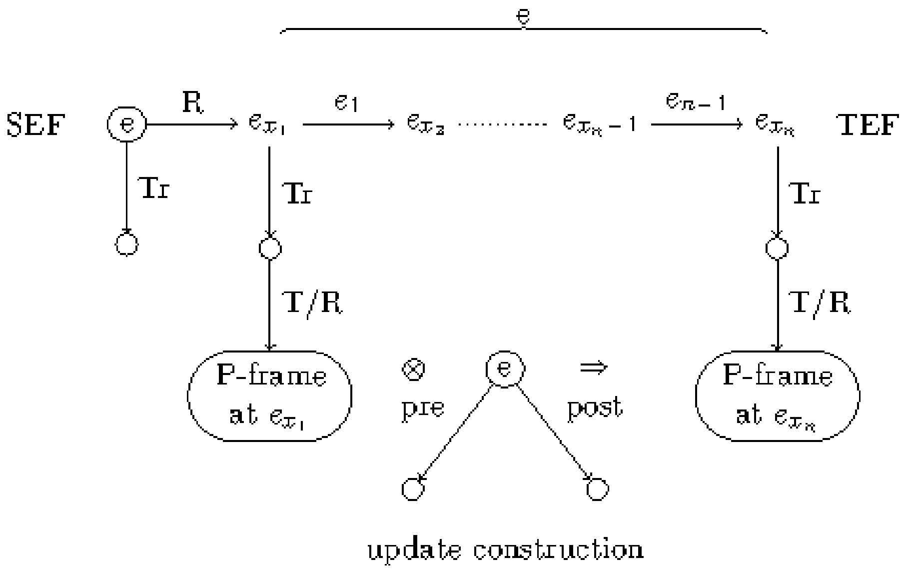

Fig. 12. schematic overview of the theory

(2) $\lambda e[See(e) \wedge Eperiencer(e, man) \wedge Theme(e, eagle) \wedge Location(eagle) = sky]$

Despite its weakness the logic representation in (2) captures the aspect that the eagle is the constant theme of the seeing event and the constant actor of the flying event. This aspect is important for the identity of persistent objects over time. Consider e.g. the short discourse in (3).

(3) The eagle was flying in the sky. After a few minutes it arrived at its nest and began to feed its offspring.

In this discourse the simulated shape of the eagle changes as a function of its location and, more importantly, the action it is involved in. But despite those differences it is the *same* eagle that is talked about and that has to be simulated (a fact which is, among other things, reflected in the use of the pronouns *it* and *its*).
In our approach the aspect of identity over time (or across sentences) is captured by SEFs which relate an event to a set of objects taken as atoms that persist over time. The aspect of a modal perceptual representation is captured by t-SEFs in which the persistent object is related to a boundary event and represented as having certain properties together with the corresponding values that can undergo a change due to external forces and events.
The results of Zwaan and colleagues also show that in the Petersen-frame of an object in a t-SEF not all of the object's properties need to be represented (or activated) but only a certain subset consisting of those properties that are related to the type of event described by the sentence. Thus, we get the following thesis:

> What is represented in a Petersen-frame of an object in a t-SEF depends on the type of the event that is described.

The way an object participating in an event is simulated depends, at least partly, on the type of the event. For example, although all three events in the discourse in (3) (flying, arriving and feeding) are related to the same eagle, the Petersen-frames used in the corresponding t-SEFs differ. For example, the shape of the eagle's wings will be simulated differently in the flying and in the arriving event (difference in the value of the attribute describing the shape of the wings of the eagle)[17] and in the feeding event the shape of the wings need not be represented at all. Instead the shape of its head (mouth) will be represented simulating the feeding activity.[18] Thus, a verb not only imposes a constraint on the type of object (e.g. the ability to fly) but it also primes the values of some of its properties, like the shape of its wings, for example. As a consequence, the semantic representation of a verb cannot be restricted to SEFs but

[17] Of course, other aspects of a simulation depend on additional factors like past experiences and/or the preceding linguistic context.

[18] This dependency of how an object is simulated on the object it participates in is one argument for defining t-SEFs with boundary events as roots and not with time points. This makes it possible to have an object being simulated in different ways when it is involved in several events at the same time.

must in addition also contain t-SEFs in which those constraints on how the object is simulated during the event are expressed.

The above considerations show that simulation and refinement are closely related. Refinement is needed in order to have access to those aspects of an object that change due to the event. But such aspects are also needed to account for the way an object is simulated during sentence comprehension. With respect to the different levels of frames, one gets the following correlations:

SEF $\rightarrow$ represented as an atom $\rightarrow$ identity over time

t-SEF $\rightarrow$ represented as having an internal structure $\rightarrow$ simulation + refinement + temporalization

5 The dative alternation with *send* verbs in English

In this section it is shown how the theory presented in the preceding sections can be applied to the frame-based analysis of *send*-verbs in Kallmeyer & Osswald (2012). In English, *send* occurs both in the double object (DO) and the prepositional object (PO) construction as exemplified by (4).

(4) a. John sent Mary the book.
    b. John sent the book to Mary.

Using decompositional schemas (see e.g. Levin & Rappaport-Hovav 2005), the two interpretations can be represented as shown in (5).

(5) a. $[[x\, ACT]\, CAUSE\, [y\, HAVE\, z]]$
    b. $[[x\, ACT]\, CAUSE\, [z\, GO\, TO\, y]]$

In both cases *send* is analyzed as having a causal component: the actor x does something which causes a change in the theme z. In the DO construction the effect of the causation is a change of possession whereas in the PO construction it is a change of location (the theme is at (or arrives at) the recipient conceived of as the destination). However, neither in the DO nor in the PO construction is the effect lexically entailed as shown by the non-contradictory examples in (6).

(6) a. John sent Mary the book. But she never got it.
    b. John sent the book to Mary. But it never arrived there.

Send only lexicalizes a caused motion towards the destination. By contrast, the arrival at the destination and the change of possession are only prospective (see Kallmeyer & Osswald 2012 and Beavers 2011 for details). Based on this analysis, Kallmeyer & Osswald (2012) propose the frame representation in Figure (13) for *send*.

The frame representation in Figure (13) not only captures the fact that *send* expresses a causation whose effect is a change of location but also

$$\begin{bmatrix} \textit{sending} & \\ \text{EFFECTOR} & \boxed{8} \\ \text{THEME} & \boxed{9} \\ \text{GOAL} & \boxed{10} \\ \text{CAUSE} & \begin{bmatrix} \textit{activity} & \\ \text{EFFECTOR} & \boxed{8} \end{bmatrix} \\ \text{EFFECT} & \begin{bmatrix} \textit{change-of-loc} & \\ \text{THEME} & \boxed{9} \\ \text{DESTINATION} & \boxed{10} \end{bmatrix} \end{bmatrix}$$

Fig. 13. lexical frame for *send*

the fact that the theme (prospectively) arrives at the destination.[19] The other meaning components, that are not lexicalized, are given by constructions which are also modelled as frames. For example, the frame for the DO construction is shown in Figure (14).[20]

$$\begin{bmatrix} \textit{causation} & \\ \text{THEME} & \boxed{2} \\ \text{GOAL} & \boxed{3} \\ \text{CAUSE} & \begin{bmatrix} \textit{activity} & \\ \text{EFFECTOR} & \boxed{1} \end{bmatrix} \\ \text{EFFECT} & \begin{bmatrix} \textit{change-of-poss} & \\ \text{THEME} & \boxed{2} \\ \text{RECIPIENT} & \boxed{3} \end{bmatrix} \end{bmatrix}$$

Fig. 14. lexical frame for the DO construction

Let us relate Kallmeyer & Osswald's analysis to the approach developed in the preceding sections. The EFFECTOR, THEME, GOAL part of the frame representation corresponds to an SEF. An event of type *sending* is related to different objects participating in it. The attributes CAUSE and EFFECT describe a particular type of TEF: it is a non-type identical sequential decomposition of the sending event. The types of those decompositions describe particular kinds of programs and are therefore

[19] Thus, the lexical contribution of *send* already comprises that of the PO construction, except for aspects like those related to the influence of *to* on possible recipients (Rainer Osswald p.c.). For example, consider the difference between *John send the package to Mary/London* and *John gave the package to Mary/*London*.

[20] Thus, Kallmeyer & Osswald's analysis separates the contribution of the lexical meaning from the contribution of a construction in the sense of construction grammar.

related to the second dimension at which a sequential decomposition can be described (the way a postcondition is brought about). Thus, adapting the Kallmeyer & Osswald analysis to our framework the relevant part of the representation of the DO construction is as in Figure (15) (where *nti* is the type of non-type identical TEFs).

$$\begin{bmatrix} \text{TEF} & \begin{bmatrix} \textit{nti} & \\ \text{CAUSE} & \begin{bmatrix}\textit{activity} & \\ \text{EFFECTOR} & \boxed{1}\end{bmatrix} \\ \text{EFFECT} & \begin{bmatrix}\textit{change-of-poss} & \\ \text{THEME} & \boxed{2} \\ \text{RECIPIENT} & \boxed{3}\end{bmatrix}\end{bmatrix}\end{bmatrix}$$

Fig. 15. alternative DO construction

What is missing in this representation is the constraint on the way an object is simulated. Therefore, the values of the attributes CAUSE and EFFECT should themselves be TEFs in which the values of attributes like EFFECTOR are Petersen-frames capturing the required constraints. The distinction between the lexical contribution of a verb and those of a construction is related to the fact that an event is in general related not to a single but to a set of TEFs. In the case of *send* at least the following temporal decompositions can be distinguished.

- type 1: caused change of location
- type 2: caused change of location plus a movement to the destination
- type 3: caused change of location plus a change of possession

The first type defines that part of a sequential decomposition which is common to all sending-events, thus reflecting the fact that it expresses the semantic contribution of the verb. The second and third type can be distinguished by making use of the fact that the two kinds of changes are related to different scales: a path-scale for the change of location to the destination and a (binary or simplex) 'possession'-scale for the change of possession (see Beavers 2011). These two types of changes are, however, not independent of each other: whenever the theme arrives at the destination (type 2), the recipient comes to possess it. One way of modelling this relationship consists in having a temporal decomposition which is of both types (or a common subtype of those two types). This combination yields a fourth type.

- type 4: caused change of location plus a movement to the destination plus a change of possession

The lexical contribution of *send* is a type 2 TEF whereas the DO construction contributes a type 3 TEF. In a sentence like *John sent Mary the book* both TEFs are combined to yields a type 4 TEF. For *send* this combination can be defined as follows. Since the 'possession'-scale, on which the type 3 TEF is built, is binary, i.e. there are only two values, the decomposition consists only of e_a and e_b related by the sending-event. At e_a $\neg Have(y, z)$ holds (precondition), whereas at e_b one has $Have(y, z)$

(postcondition). In the combined type 4 TEF the preconditions of both TEFs are combined at e_a and the same is done for the postconditions at e_b.

6 Conclusion and directions for future work

In this article we presented a dynamic theory of frames in which (basic) frames are defined as Kripke-models. In order to model the dynamic dimension of concepts for actions and events, not only basic frames but also combinations of and transformations between such frames must be considered. The dynamics proper is modelled by an update construction between a simple frame and an update frame.
There are at least the following two important issues that haven't been addressed in this article:

1. How is the meaning of verbs built in terms of the different levels of frames? An answer to this question depends, at least in part, on results from psycholinguistics and brain science. Some preliminary results of how a dynamic theory of frames can be combined with recent results in the latter areas are presented in Naumann(2012).
2. What are appropriate logics (or languages) for talking about the structures defined in section(3)? At present, we are using some form of extended modal logics like arrow logic or hybrid logic.

Let me close by mentioning some further questions: (i) How can the concept of a scale be integrated into the theory? (ii) How is the concept of causation modelled in the theory? The update construction used in the theory only changes the valuations of Kripke-models. However, other operations on Kripke-models are possible. Löbner (2011), for example, mentions: adding or deleting attributes (level of Petersen-frames), saturating arguments and relocating the central node. With respect to linguistic applications Löbner refers to metaphors: attributes with values are transferred from one frame to another one, forming a new concept. Other examples include shifts, for example from *play* to *player*, where the central node of a frame for a verb is shifted to the actor node. Finally, in order to model non-factual, for instance, epistemic changes triggered by communicative acts like announcements, further strategies from Dynamic Epistemic Logic must be incorporated into the theory.

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