Frame Theory with First-Order Comparators: Modeling the Lexical Meaning of Punctual Verbs of Change with Frames

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Abstract. The first part of the paper proposes a formal foundation of a theory of frames. Frames are embedded into a general ontology. On this background, we introduce a formal model-theoretic semantics for frames and thereby an interface to formal semantics. The model-theoretic semantics allows us to define central notions of frame theory such as the "satisfaction type" for a node in a given frame, and a semantic definition of subsumption. The second part presents a case study of decomposition: frames for subtypes of intransitive punctual verbs of change, such as punctual 'grow' and 'go from A to B'. We introduce times, events, and time-dependent attributes in the ontology. A crucial element of the analysis is "comparators", a novel type of attribute in frame theory. Comparators are partial two-place attributes that compare two individuals of the same sort and return comparison values such as '=' vs. '≠' or '<' vs. '=' vs. '>'. Comparators allow us to model within frames and AVMs conditions in terms of basic abstract relations. The approach proposed offers simplifications of alternative proposals for the frame-theoretical decomposition of these types of verb: (i) standard PL1 is used as a frame description language; (ii) with comparators, the use of non-functional relations as additional components in frames can be avoided; (iii) meanings of punctual verbs of change can be represented within one frame.

Keywords: frames · ontology · comparator · mereotopology · time · time-dependence · degree achievement · verb of change · verb of locomotion · decomposition

1 Background

The work presented here has emanated from joint projects involved with a novel theory of frames (*see* Acknowledgments). The research initiative aims at a formally precise and cognitively plausible theory of frames as a general format of conceptual representation, in particular, but by no means exclusively, as a general format of semantic representation, including both, lexical and compositional meaning. The enterprise aims to test the 'Frame Hypothesis' that goes back to Barsalou's work ([2, 3]): that frames constitute the general format of representation in the human cognitive system.

The hypothesis has strong repercussions on the theory of language (see Löbner [9] for discussion concerning semantic and syntactic theory). This paper adds selected contributions to general frame theory that include the following points:

- relation of frames to a general frame ontology that provides a global model for admissible frames;

adfa, p. 1, 2011.

- inclusion of time and time-dependent attributes in the frame ontology, along with explicit time elements in frames;
- introduction of novel two-place "comparator" attributes that capture basic binary relations between entities of the same sort, e.g., equality or order relations.

Inclusion of time into frame representations addresses a basic challenge to frame theory: the representation of dynamic concepts such as the meanings of verbs of change (see Naumann [15] for introductory discussion). The apparatus developed will be applied in a decompositional representation of punctual change of state verbs such as degree achievement verbs (*grow*) and verbs of locomotion (*go from A to B*).

2 Frames related to a global frame ontology

2.1 A simple frame example

Frames in the sense of the frame hypothesis are recursive attribute value structures with exclusively functional relations; they will be given a formal definition in the next subsection. A simple example is the frame for a 'male person with blue eyes' given in Fig. 1. It is a frame for an entity typed as a person that is assigned values for two attributes: EYES and GENDER. The GENDER attribute is specified as 'male', which may be taken as standing for a type of gender, rather than just the individual gender ♂. The value of the attribute EYES is the eyes of the person (as one complex entity); these are specified with the attribute COLOR as blue. The value specification 'blue' is not a single discrete color value but stands for a range of color hues.[1] Fig. 1 displays two common formats of representing frames: the left part of the figure shows a frame diagram with labeled nodes and arrows; the right figure is an equivalent attribute-value matrix (AVM).

The frame diagram displays four circles, or nodes; these carry numbers as labels; the number label is essentially a variable for the individual represented by the node. The node labeled[2] with $\boxed{1}$ represents the entity which the frame is taken to describe; it is called the "central node" and is marked by a double line border. The arrows represent attributes as indicated by the labels; the arrows end in the nodes that represent the values of the attributes. Three nodes carry type information: **person**, **blue**, and **male** indicating that $\boxed{1}$ is a person, $\boxed{111}$ is a blue color, $\boxed{12}$ is a male gender.

The attribute value matrix in the right part of Fig. 1 contains the same information as the diagram. It represents the element $\boxed{1}$ as the entity described by the whole structure; $\boxed{1}$ is categorized as a person. That person has two attributes, EYES and GENDER. The attribute EYES takes the value $\boxed{11}$, further typed by the embedded matrix: it is **eyes** (a tautological categorization deriving from the fact that $\boxed{11}$ is the value of the EYES attribute), and it has the attribute COLOR with value $\boxed{111}$, categorized as **blue**. The GENDER attribute of $\boxed{1}$ has the value $\boxed{12}$, of type **male**.

It should be pointed out that in natural language, terms for attributes are systematically also used for their values. We talk of 'the color [attribute term] of the cocktail' but also of 'the colors [value term] red, blue, and pink'. This circumstance has caused

[1] For the sake of simplicity, the fact is ignored that it is not the whole eyes that are specified for color, but rather the iris. The complex aspects of color predication are not at issue here.

[2] The frame around the number is omitted when the label is written into a frame diagram node.

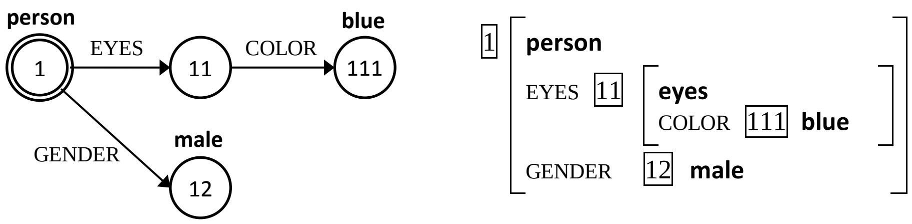

Fig. 1. Frame example in diagram and AVM representation

some confusion. In this article we will distinguish the two senses of attribute terms typographically, using SMALL CAPS for their use as attribute terms, and **special bold type** in their use as value, i.e. type, terms.[3]

Frames are essentially graphs in the mathematical sense, i.e. sets of pairs of things, called "nodes". The pairing is the result of relations obtaining between the paired elements. In the case of frames, the pairs are ordered, rendering a directed graph ("digraph" in mathematical jargon), and the relations are attributes. The first member of a pair is the bearer (argument) of the attribute, the second member of the pair is the value. In the use of graphs for frame representation, different attributes may connect nodes. Crucially, the attributes are functions: one node cannot be connected by the same attribute to two nodes representing different values.

The term 'graph' strongly appeals to network diagram representations like the left structure in Fig. 1; the connections between nodes are called "edges" or "arcs". Frame graphs have topological properties that also appeal to the network diagrams: for example, we will assume that frame graphs in general are connected. Still, in spite of their name, graphs are not drawings, but abstract mathematical structures. The diagrams are a means of *visualization*. The nodes carry identifying labels, or indices. The edges, too, carry labels that are read to define the attribute which an edge stands for. The nodes may carry predicative type information in addition to being indexed.

For later application, the general definition of a frame structure needs to admit n-place attributes (n≥1). N-place attributes result in a functional connection between an n-tuple $\vec{x}$ of argument nodes and an additional node for the value. We will represent such constellations as in Fig. 2. Edges that connect tuples of nodes are technically called 'hyperedges' in graph theory.

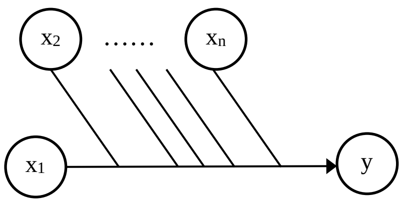

Fig. 2. Frame diagram for an n-place attribute assignment

3 For discussion of the relation and the difference between attribute concepts and concepts for their values see Petersen [16]: 162ff and Löbner [10]: 30–34.

Definition 1. Frame structure

A frame structure is a sextuple ⟨V, r, A, att, T, typ⟩, such that

a. V is a finite set of nodes.

b. $r \in V$ is a distinguished node, the "central node".

c. A is a finite set of edge labels.

d. att is a function that maps pairs of an n-tuple of nodes ($n \geq 1$) and an edge label on another node.

e. T is a set of type labels.

f. typ is a partial function that assigns type labels to nodes.

g. With $E =_{df} \{\langle \vec{x}, y\rangle \mid \exists a \in A\ \mathsf{att}(\vec{x}, a) = y\}$, ⟨V, E⟩ is a connected digraph with n-to-1 hyperedges ($n \geq 1$).

A digraph is connected if there is a connection along one or more edges, in either direction, between any two nodes of the graph. The frame represented by the diagram in Fig. 1 is connected. The central node is understood to represent the type of object, or the individual object, that the frame describes. In the example, the central node is the node 1; its status is indicated by the double-line border.

The above definition of frame structure is essentially equivalent to the definitions given in Petersen [16], except for the fact that the definition here is more general while Petersen distinguishes different, more specific types of frames, such as frames for sortal, relational, and functional nouns (see Löbner [1010]: 41–47). The frame structures used below for verb meanings / event concepts are relational concepts: they have a referential central node (the node representing the event described) and argument nodes for the verb's role arguments. The definition here is also compatible with the definition of frames in Kallmeyer and Osswald [8]; their definition, however, allows arbitrary relations between the nodes of a frame structure, in addition to the attributes.

2.2 Global frame ontologies

The two structures in Fig. 1 are both essentially two-dimensional *expressions*. Usually, these types of structure are used with a presupposed interpretation of the attribute and type labels. When applied in semantics, these labels are in need of a precise formal interpretation. We will define an underlying ontology for frame interpretation and relate all frames to it. In an additional step we will translate frame structures into first-order predicate logic in order to provide an interface to truth-conditional semantics.

Any framework of representation employing frames depends on ontological assumptions as to which attributes can plausibly figure in a frame and which types are available for the values they can take. The frame representations used here are primarily representations in terms of attributes of the entities represented and, secondarily, in terms of the types of attribute values. Therefore the frame ontology is based on attributes. This distinguishes the approach from frameworks like Carpenter's [5] theory of typed feature structures: these are based on a given system of types with a semi-lattice structure defined by type subsumption. The "types" in the theory proposed here correspond to Carpenter style "types" in that they subsume cases of the same description (like, for example, **blue-eyed man**). However, the types as introduced here are essentially derivative. In general, attributes are partial functions; they come with a domain of application, i.e. a type of things that are eligible for carrying this attribute, and they come with a codomain, the type of possible values. Being partial functions, they need not return a value for everything in their domain. The attribute COLOR, for example, is defined for physical bodies and it takes colors as values (including the value 'colorless').

The attributes of the human frame ontology form an infinite space. Attributes can form chains of arbitrary length, by applying an attribute to the value of the first attribute, another one to the value of the second, and so on. Also, arbitrary attributes can be defined ad hoc, drawing on existing concepts. Nevertheless, frame theory needs a consistent and plausible framework of available, well-defined attributes that constitute legitimate elements of frame representations.

In a really cognitive approach, the attributes and types would have to be attribute concepts and type concepts. This kind of approach is not spelt out yet. The frame ontology to be introduced here will be an "ontological" ontology, of functions and entities in the world as we refer to when using language. This decision enables a straightforward comparison with analyses in the truth-conditional semantic paradigm, which is based on an "ontological" ontology, too.

A frame ontology has a non-empty universe of individuals, a set U. U is partitioned into sorts: any individual is of exactly one sort; there is no overlap of sorts. In a hierarchy of types, the sorts are maximal types. To give a few examples: one will assume the sorts of persons, of physical objects, of numbers, of temperatures, of weights, of colors, of truth-values, and so on.

It is assumed that attributes are always restricted to one sort, but their domain need not exhaust the sort it is a subset of. Also, attributes return values of only one sort. This appears necessary for the ontological distinction of different attributes denoted by a polysemous attribute term. For example, the term *weight* can be used as denoting the weight attribute of physical objects having mass, but it can also be used for a particular aspect, roughly importance, of things like arguments or decisions. A frame ontology properly defined will provide different attributes for the 'weight' of physical objects, of arguments, and of decisions, respectively, because these three kinds of entity are of different ontological sorts as are the values returned by the 'weight' attribute.

Attributes may have more than one argument; for example, DISTANCE and RELATIONSHIP would be two-place attributes.

The attributes form a space which will be postulated to be closed under functional composition. For example, if HAIR is assumed to be an attribute of persons, and the attribute COLOR is applicable to human hair, functional composition yields the attribute HAIR COLOR for persons with hair. We will further postulate that for injective one-place attributes, the inverse is also in the ontology. Injective attributes are 1-to-1 mappings. For example, every person has a body, whence there will be the attribute BODY available for persons; conversely, every body belongs to exactly one person, and there will be the inverse attribute BODY^{-1} in the ontology; it returns the body-owner for every body.

Every attribute A is associated with the types that constitute its domain of application and the range of values it can take. We denote the domain as dom(A) and the codomain as cod(A). If A is n-place ($n>1$), its domain is the Cartesian product of n types $\text{dom}_i(\text{A})$, $i=1,\ldots, n$. We will assume that the set of types is closed under intersection and that for each individual in U there is a corresponding atomic type, an atom. If an attribute is applicable to all members of a type **t**, then the image of **t** is also a type in the ontology; conversely, if **t** is a subtype of the codomain of an attribute, then its preimage is a type in the ontology. For example, one will assume that there is a type **hair** included in the domain of the attribute COLOR; thus the ontology will contain the type **hair color** as the image of **hair** under the COLOR mapping. Conversely, there is the type **red** of red colors within the codomain of the COLOR attribute; its preimage is the type of red objects; it intersects with the type **hair** to form the type **red hair**. Due to the conditions on the ontology, the system of types is closed under attribute-related operations. It does not, however, exhaust the powerset of U – not if there is more than one sort in the ontology, which we will certainly want there to be.

According to the definition to follow, the sorts are an a priori part of the ontology, while the types (except of the sorts) should be considered derivative of the system of sorts and attributes. Equally a priori is the universe as such, a non-empty set whose elements are the individuals of the system and correspond to the atomic types. The types form hierarchical systems, but the hierarchies are each restricted to one sort.

Definition 2. Sorted frame ontology

A sorted frame ontology $\mathfrak{O}$ is a quadruple $\langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$ such that

a. U, the universe, is a non-empty set of individuals.

b. $\mathcal{S}$, the system of sorts, is a partition of U: every individual in U belongs to exactly one sort in $\mathcal{S}$.

c. $\mathcal{A}$, the set of attributes, is a set of non-empty partial functions $A: U^n \longrightarrow U$.
The attributes are restricted to sorts: for every $A: U^n \longrightarrow U$, there are sorts $\mathbf{s}_1, \ldots, \mathbf{s}_n, \mathbf{s} \in \mathcal{S}$ such that $\mathrm{dom}_i(A) \subseteq \mathbf{s}_i$ for $i = 1, \ldots, n$ and $\mathrm{cod}(A) \subseteq \mathbf{s}$.

d. $\mathcal{T}$, the set of types, is a proper subset of $\wp(U)$: every type **t** is a subset of U.
For every $\mathbf{t} \in \mathcal{T}$, there is an $\mathbf{s} \in \mathcal{S}$ with $\mathbf{t} \subseteq \mathbf{s}$: types contain individuals of only one sort.

Closure conditions on the set $\mathcal{A}$ of attributes

e. $\mathcal{A}$ is closed under functional composition.

f. If a one-place attribute $A \in \mathcal{A}$ is injective, there is a partial function $A^{-1} \in \mathcal{A}$, such that for every $x, y \in U$, $A^{-1}(y) = x$ iff $A(x) = y$.

Closure conditions on the set $\mathcal{T}$ of types

g. Every sort is a type: $\mathcal{S} \subseteq \mathcal{T}$.

h. For every $x \in U$, $\{x\} \in \mathcal{T}$. $\{\{x\}: x \in U\}$ is the set of atomic types in $\mathcal{T}$.

i. If $A \in \mathcal{A}$, $\mathbf{t} \in \mathcal{T}$, $\mathbf{t} \subseteq \mathrm{dom}(A)$, then the image of **t** under A, $A[\mathbf{t}]$, is in $\mathcal{T}$;
if $A \in \mathcal{A}$, $\mathbf{t} \in \mathcal{T}$, $\mathbf{t} \subseteq \mathrm{cod}(A)$, then the preimage of **t** under A, $A^{-1}[t]$ is in $\mathcal{T}$.

j. For every $\mathbf{t}, \mathbf{t'} \in \mathcal{T}$, $\mathbf{t} \cap \mathbf{t'} \in \mathcal{T}$.

k. $\mathcal{T}$ contains no other types than those defined by (h)–(k).

While this definition is completely abstract, we want to invest it with the informal constraint that the attributes to be postulated in any frame ontology used for the analysis of natural language are to be cognitively plausible, i.e. plausible candidates for attributes of which humans can be expected to be able to have cognitive representations in their minds.[4] We now introduce the notion of a frame structure related to a given ontology.

Definition 3. Frame structure related to an ontology

For a frame structure ⟨V, r, A, att, T, typ⟩ related to the ontology $\mathfrak{O} = \langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$

a. the elements of V are variables for individuals in U;

b. the elements of A are labels for attributes in $\mathcal{A}$;

c. the elements of T are labels for types in $\mathcal{T}$.

2.3 A formal semantics for frames

A frame structure related to an ontology receives a straightforward semantics by using identical constants as labels in the frame structure and as expressions in the metalanguage of the ontology. A frame structure describes a structure in the ontology with as many elements as there are nodes in the frame structure indexed with a variable. For example, the frame structure in Fig. 1 describes triples ⟨x, y, z⟩ such that x is a person of male gender, with eyes y of color z of a blue color. Hence it describes the type of blue-eyed male persons in the ontology. As a descriptor of a type, the frame *constitutes a concept.* Note that, unlike a predicate expression in a logic language under truth-conditional interpretation, a frame is not merely associated with a type to fit its truth conditions; rather it describes the type it represents by use of particular criteria (i.e. attributes and value assignments) which are irreplaceable components of the concept.

In order to provide an interface to truth-conditional semantics, we translate frame structures into an appropriate first-order predicate logic (PL1) language. The type of PL1 language needed for frame representation is considerably restricted: it has neither negation, nor disjunction, nor universal quantification.

Definition 4. PL1 frame language associated with an ontology

For a given frame ontology $\mathfrak{O} = \langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$, the associate language PL-$\mathfrak{O}$ is a first-order predicate logic language with the following elements:

a. individual terms, including individual variables and individual constants for individuals in U

b. type constants: terms for types in $\mathcal{T}$; type constants include expressions of the form '{i}' (i an arbitrary individual constant) for the atomic types in $\mathcal{T}$.

c. n-place function constants: terms for the attributes in $\mathcal{A}$

d. ∈ for statements of the form $\ulcorner i \in \mathbf{t} \urcorner$, with individual term i and type term **t.**

e. = for statements of the form $\ulcorner i_1 = i_2 \urcorner$ with individual terms i_1, i_2.

f. ∧ propositional conjunction

g. ∃ existential quantifier

[4] We will make use of an implicitly presupposed ontology when we discuss examples below. To come up with a concrete definition of a frame ontology for semantic analysis is a task for semantic and ontological theory for decades of research.

The model-theoretic interpretation of PL-$\mathfrak{O}$ is obvious: all constants are interpreted as denoting the individuals, attributes, and types they denote in the metalanguage of the ontology. Complex expressions are interpreted as usual. In the PL-$\mathfrak{O}$ applied here, we use framed symbols for natural numbers as individual variables. There is a straightforward way of translating a frame structure into a PL-$\mathfrak{O}$ representation, rendering a canonical satisfaction formula (SatFor) that is unique except for the order of conjuncts.

Definition 5. Canonical satisfaction formula

If $\mathfrak{f}$ = ⟨V, r, A, T, att, typ⟩ is a frame based on the ontology $\mathfrak{O}$ = ⟨U, $\mathcal{S}$, $\mathcal{A}$, $\mathcal{T}$ ⟩, the canonical satisfaction formula for $\mathfrak{f}$ – SatFor($\mathfrak{f}$) – is the conjunction of the following PL-$\mathfrak{O}$ statements:

a. for all $i_1, \ldots, i_n, j \in V$, all $A \in A$, ⌜$A(i_1, \ldots, i_n) = j$⌝ if $att(i_1, \ldots, i_n, A) = j$,

b. for all $i \in V$, $\mathbf{t} \in T$ ⌜$i \in \mathbf{t}$⌝ if $typ(i) = \mathbf{t}$.

c. for all $i \in V$, $u \in U$ ⌜$i = u$⌝ if $typ(i) = \{u\}$

d. If att and typ are empty and V={r}, then SatFor($\mathfrak{f}$) is ⌜$r = r$⌝.

Example. The frame structure in Fig. 1 yields the SatFor in (1), which can be simplified by variable elimination to the equivalent in (2):

(1) $\boxed{1} \in \textbf{person} \wedge \text{EYES}(\boxed{1}) = \boxed{11} \wedge \text{COLOR}(\boxed{11}) = \boxed{111} \wedge \boxed{111} \in \textbf{blue} \wedge$
$\text{GENDER}(\boxed{1}) = \boxed{12} \wedge \boxed{12} \in \textbf{male}$

(2) $\boxed{1} \in \textbf{person} \wedge \text{COLOR}(\text{EYES}(\boxed{1})) \in \textbf{blue} \wedge$
$\text{GENDER}(\boxed{1}) \in \textbf{male}$

Related to an appropriate ontology, a frame structure represents a type in the ontology for every variable/node it contains. The type is defined by existential closure applied to the remaining variables. For the three variables of the example frames, the types are:

(3) a. $\{ x : \exists y \exists z (x \in \textbf{person} \wedge \text{EYES}(x) = y \wedge \text{COLOR}(y) = z \wedge z \in \textbf{blue} \wedge$
$\text{GENDER}(x) \in \textbf{male})\}$
i.e. the type of male persons with blue eyes

b. $\{ y : \exists x \exists z (x \in \textbf{person} \wedge \text{EYES}(x) = y \wedge \text{COLOR}(y) = z \wedge z \in \textbf{blue} \wedge$
$\text{GENDER}(x) \in \textbf{male})\}$
i.e. the type of blue eyes of male persons

c. $\{ z : \exists x \exists y (x \in \textbf{person} \wedge \text{EYES}(x) = y \wedge \text{COLOR}(y) = z \wedge z \in \textbf{blue} \wedge$
$\text{GENDER}(x) \in \textbf{male})\}$
i.e. the type of blue colors of the eyes of male persons.

The resulting type may be empty, depending on facts given in the ontology. The “satisfaction type” of a frame is the type it describes with respect to the central node; in general, a satisfaction type can be defined for every variable/node in the frame:

Definition 6. Satisfaction type

Let $\mathfrak{f} = \langle V, r, A, T, \mathsf{att}, \mathsf{typ} \rangle$ be a frame based on the ontology $\mathfrak{O} = \langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$. The satisfaction type of $\mathfrak{f}$ is the type

$\mathrm{SatTyp}(\mathfrak{f}) =_{df} \{ r : \exists_{\neq r}\, \mathrm{SatFor}(\mathfrak{f}) \}$
where $\exists_{\neq r}\, \mathrm{SatFor}(\mathfrak{f})$ is the existential closure of $\mathrm{SatFor}(\mathfrak{f})$ for all variables in V except r.

More generally, if $i \in V$ is a node in $\mathfrak{f}$, the satisfaction type of $\mathfrak{f}$ for i is:

$\mathrm{SatTyp}(\mathfrak{f}, i) =_{df} \{ i : \exists_{\neq i}\, \mathrm{SatFor}(\mathfrak{f}) \}$

The notions defined so far allow for a semantic definition of frame subsumption.

Definition 7. Subsumption

Let $\mathfrak{f}_1$ and $\mathfrak{f}_2$ be frames related to the same ontology, let x and y be nodes in $\mathfrak{f}_1$ and $\mathfrak{f}_2$, respectively. $\mathfrak{f}_1$ for node x subsumes $\mathfrak{f}_2$ for node y if the satisfaction type for the first includes the satisfaction type for the second:

$\mathfrak{f}_1(x) \sqsubseteq \mathfrak{f}_2(y) \quad \mathrm{iff}_{df} \quad \mathrm{SatTyp}(\mathfrak{f}_1, x) \supseteq \mathrm{SatTyp}(\mathfrak{f}_2, y).$

In particular, $\mathfrak{f}_1$ subsumes $\mathfrak{f}_2$:

$\mathfrak{f}_1 \sqsubseteq \mathfrak{f}_2 \quad \mathrm{iff}_{df} \quad \mathrm{SatTyp}(\mathfrak{f}_1) \supseteq \mathrm{SatTyp}(\mathfrak{f}_2).$

The usual definition of subsumption for frames and AVMs relates to the structure of a frame: a frame subsumes another frame if there is a node in the second frame for every node in the first frame with compatible respective characteristics (cf., e.g., the definition in Kallmeyer and Osswald [8]: 280 ff.). The formal semantics defined for frames here allows a semantic definition of subsumption that is independent of the form in which the information in a frame is arranged. For example, we might replace the frame structure in Fig. 1 by the ones in Fig. 3. The three frame structures mutually subsume each other. The left frame contracts the attribute chain COLOR(EYES(…)) to the functional composition EYE COLOR; the respective parts of the SatFor's are logically equivalent. In the right frame, the attribute EYES is replaced by its inverse EYES-OWNER. Both replacements are legitimate due to the closure conditions on $\mathcal{A}$ in the general definition of ontologies. Thus defined, subsumption is basically logical entailment for frame structures or AVMs taken as logical expressions.

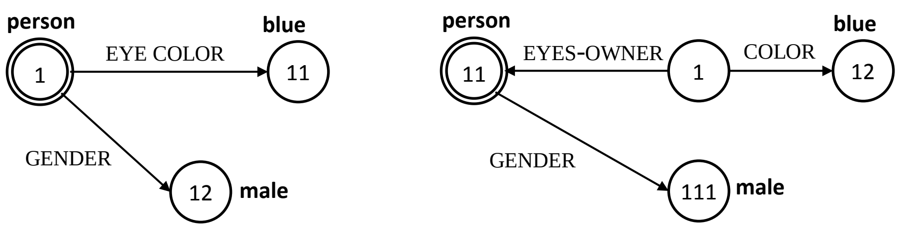

Fig. 3. Alternative frame structures for 'blue-eyed male person'

3 Comparators

One point of debate in frame theory is the question of how to model relations in a framework that is restricted to graphs with exclusively functional connections. This paper offers a proposal for modeling certain basic intrasortal relations. Kallmeyer and Osswald [8] proposed to model such relations by admitting non-functional relations as an additional type of component in a graph. This step is in conflict with the Frame Hypothesis mentioned in the beginning since Barsalou frames are supposed to employ exclusively functional attributes as relations in frames. We will introduce special two-place attributes to capture this type of intrasortal relation; we call them "comparators".

Comparators are binary attributes that apply to arguments of the same sort. Their values are the outcome of comparison with respect to certain basic criteria. For example, a comparator might compare two real numbers and return one of the comparison values '=', '>' and '<'. The three values are mutually exclusive alternatives, whence the comparator is a functional relation. (Note that there is no comparator function which could in addition also return '≤' and '≥'; there are however comparators that return either '>' or '≤', or either '<' or '≥'.) The comparison values are individuals returned as values by the comparison function; they are not to be confused with the general relations usually denoted with the same symbols. Comparator values are ontologically of their own sort, depending on the domain of comparison.

Comparators are cognitively highly plausible conceptual operations. Even the most primitive organisms are capable of comparisons. For humans, comparators are involved in recognition and categorization to name only a few cognitive functions.[5]

Depending on the sort applied to, there may be more than one comparator definable. The basic equality comparator is defined for every sort. If there are partial or linear orders defined within a sort, there are corresponding comparators; partial orderings include part-whole relations.

Definition 8. First-order comparators[6]

First-order comparators in an ontology $\mathfrak{O} = \langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$ are two-place attributes with both arguments of the same sort; they return comparison values.

For every sort $\mathbf{s} \in \mathcal{S}$, the **standard comparator** $©_\mathbf{s}$ is defined as
$©_\mathbf{s}(x, y) =_{df}$ '≠' / '=' iff $x \neq y$ / $x = y$

When we use comparators, we will express the comparisons in the satisfaction formulae in the conventional way; we will write '$x = y$' instead of '$©_\mathbf{s}(x, y) = 1$', and so on.

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5 Barsalou [4]: 601 uses comparators (although not called so) in his model of truth and falsity for propositions. Comparators check whether an internal simulation [roughly, a frame] can be "map[ped] successfully into a perceived scene". Truth and falsity is envisaged in our approach as a further application of comparators, probably of second order and hence outside the scope of frame theory sketched here.

6 These comparators are first-order in that they compare individuals.

4 Time and tensed ontologies

We will now integrate time into the ontology, a step that allows the modeling with frames of time dependence by using explicit time representations. In their frame analysis of temporal situation structure, in Kallmeyer and Osswald [8], Naumann [15], and Gamerschlag, Geuder, and Petersen [7], the authors relate to time implicitly by employing attributes such as RESULT; their frames do not contain times explicitly. The approach taken here follows a strategy of maximizing explicitness in frame representation; in particular, it tries to represent all arguments of attributes in the frame structure. In addition to this aspect of expressivity, the incorporation of explicit time parameters in verb meanings is also probably necessary for modeling tense and aspect in a frame theory of composition. I take it, along with many theories of tense, that tense is a predication about times, more specifically about the time occupied by an event e, if e is the event referred to, and aspect is perfective.[7]

Independently, the question arises if the assumption that times rather than just events figure in human cognitive representations is psychologically realistic. According to experimental evidence (Roberts, Coughlin, and Roberts [17]) there is positive evidence of time representation in cognition even for pigeons. This justifies the assumption of the sort **time** in our ontology.

We extend the definition of the ontology by introducing the sort **time**, where times are understood as being intervals on the time axis. For the comparison of times we apply the system of temporal relations introduced in Allen [1] which are mutually exclusive; we will use only two of them, the relation 'm' (meet) and its inverse 'mi'. Two times x and y "meet" iff x is earlier than y and immediately adjacent to y; mi obtains between x and y iff y m x. Rather than the traditional $\mathbb{R}^1$ topology assumed e.g. by Dowty [6] for the time axis, it appears psychologically more adequate to apply a topology where two time intervals can be connected without overlapping or with one being open and the other one closed. In such a mereotopology, it would be possible to model two consequent days as two closed time intervals that meet without overlap, the first one ending with 12:00 p.m. and the next one beginning with 0:00 a.m.; 0:00 a.m. would be the point in time immediately following 12.00 p.m. Other units of time like years, months, weeks, hours, and so on would be modeled analogously. This appears to me more in accordance with intuition than assuming that either 0:00 a.m. or 12:00 p.m. does not belong to a full day. A topology that allows for connection without overlap is even more plausible for the cognition of physical space where we are obviously willing to assume that it is possible that, say, two boxes with plane surfaces can be piled upon each other with nothing in between and no parts shared. Mereotopologies that implement the notion of connection without overlap are introduced in Varzi [18] or Muller [14] for systems of spatio-temporal reasoning. Allen's temporal relations can be defined for such a mereotopology if we take 'adjacent' as 'connected without overlap'.

Introducing time into the ontology involves two major changes and additions: (i) certain attributes will be defined as being time-dependent, i.e. two-place attributes with an additional time argument; (ii) events will be related to times by means of certain event attributes. As to the first point, it is to be observed that according to common

[7] See Löbner [11], Ch. 6, for a basic outline of the theory of tense and aspect supposed here.

ontological understanding the values of some attributes are time-dependent, while the values of other attributes are not. In general, attributes relating things to their origin are not time-dependent; most property attributes, however, are, since properties can change during the lifespan of things.

Definition 9. Tensed ontology

A tensed ontology $\mathfrak{O}^t = \langle U, \mathcal{S}, \mathcal{A}, \mathcal{T} \rangle$ fulfills the following conditions in addition to conditions a.–k. in Definition 2:

l. There is a sort **time** in $\mathcal{S}$, of non-empty time intervals (including points in time) with the properties and relations as to be defined in an appropriate mereotopology of **time**.

m. There is a comparator $©_{\mathbf{time}}$ in $\mathcal{A}$, defined for the sort **time** that assigns values for the Allen relations to pairs of times.

n. There is a sort **event** in $\mathcal{S}$, of events.

o. Three attributes map events on time:
TE(e) = the time occupied by the event e,
TB(e) = the time before the event e,
TA(e) = the time after e;
for every event e: TB(e) < TE(e) < TA(e); the three times need not be adjacent.

p. Time-dependent attributes: There are two-place attributes A: $\mathbf{t}_1 \times \mathbf{time} \longrightarrow \mathbf{t}_2$, for some types $\mathbf{t}_1$, $\mathbf{t}_2$.

q. Homogeneity condition for attributes with a time argument:
If an attribute A assigns the value v to a time t and possibly further arguments, then A returns the same value v for all non-empty subintervals of t.

The homogeneity condition is a novel kind of constraint. It is also necessary for other attributes, e.g. COLOR: COLOR does not yield a unique value for a would-be argument in case it is of more than one color like, for example, most flags. In general, an attribute A underlies a homogeneity condition with respect to an argument x iff a value assignment to x by A is true iff the same assignment holds for all relevant parts of x. This is tantamount to the condition that the predication $\lambda x\ A(x)=y$ (for any $y \in cod(A)$) is summative in the sense of Löbner ([12]: 237): $\forall x \forall y\ (A(x)=y \leftrightarrow \forall x'(x' \sqsubseteq x \rightarrow A(x')=y)$.

5 Lexical frames for intransitive punctual verbs of change

We will now present proposals for representing the lexical meaning of certain subtypes of punctual verbs of change. Verbs of change have been a topic in decompositional analysis since Dowty [6]. Modeling change is a particular challenge to frame theory since the original notion of frame is static. The proposal differs from existent alternatives in various ways.

- Unlike the proposals in Kallmeyer and Osswald [8], Gamerschlag et al. [7], and Naumann [15], it employs explicit time reference.

- Unlike in Gamerschlag et al. [7], and Naumann [15], the meanings of verbs of change are represented in a single frame.
- Unlike in Kallmeyer and Osswald [8], dynamic verb meanings are modeled with comparators rather than by adding non-functional relations to the frames used; also the logical language used for frame description here is more conventional.

The frame model to be proposed represents punctual verbs of change: the event consists of a change in time relating to the time before and the time after the event e. There is a condition that holds at the time before e and does not hold at the time after, or vice versa. The frame imposes no conditions on the time TE(e) that the event itself occupies. The transition may be continuous or an instantaneous change; it may be temporally extended or not. It is in this sense that these verbs are punctual: the time TE(e), for all the verb concept tells us, might as well be just a point in time. We need to assume that the criterial times TB(e) and TA(e) are immediately adjacent to TE(e). Otherwise, there might be more than one change of the kind between TB(e) and TA(e). We also need to assume that the times TB(e) and TA(e) are homogeneous with respect to the criterial condition in order to prevent there being further changes *within* TB(e) or TA(e); this constraint will be captured by the general homogeneity condition q in Definition 9 as the criterial condition will be in terms of the values of a time-dependent attribute. Note that TB(e) and TA(e) can be just points in time; the homogeneity condition does not require that there be extended time intervals of no change before or after the event. The question whether or not TE(e) itself should be imposed a condition to the extent that e must not host further changes back and forth will be left open here. I take it that we ought to allow for this; for example, the sentence *the light went on* may be about a neon light that goes on and off and on again several times until it is permanently on; to give a different example, we may say *the price of the share rose today* after a day of the price constantly changing up and down.

5.1 A general frame for punctual change

These conditions still leave the proper determination of TB(e) and TA(e) to the individual context of interpretation. Even so, I assume that 'the time before the event' and 'the time after the event' are pragmatically admissible determinate notions, i.e. legitimate time-dependent attributes in the underlying ontology. TB(e) and TA(e) are determined by the conditions that they "meet" TE(e) and are homogeneous with respect to the criterial condition. If, and how far, TB(e) extends into the past and TA(e) into the future does not make any difference.

The constellation of the event and its attributes TB, TE, and TA is depicted in Fig. 4. The arrow labeled 'time' is not part of the frame; it is only added for illustrating the temporal relationships. Comparators define the Allen relation from TA(e) to TB(e) as 'm' and the Allen relation from TB(e) and TE(e) as 'mi', the inverse of 'm'.

From now on, we will write the atomic values of comparator attributes right into the nodes of the frame diagrams, as is done in Fig. 4 with the value nodes for the two temporal comparison attributes. Thus, the node inscription 'cv' replaces the type annotation '{cv}' and overwrites the variable labeling the node. We will render the respective conjunct in the SatFor as '$©_{..}(i, j) = cv$' rather than as '$©_{..}(i, j) = k \wedge k \in \{cv\}$'. We

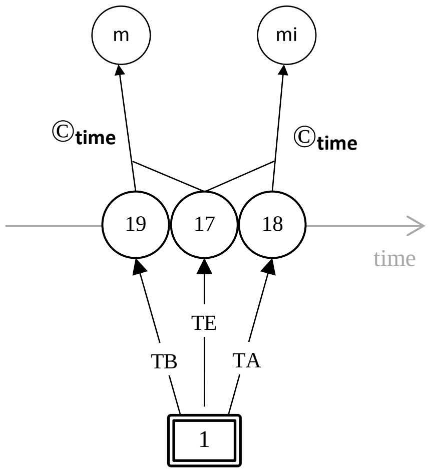


Fig. 4. Frame for an event and the related times

will simplify '$©_{..}$(i, j) = cv' further to 'i cv j', using the symbols for the comparator values as relation symbols between individual terms in the associated PL1 language.

For the subtypes of verbs of change considered here, the criterial condition of change is in terms of a time-dependent attribute of the theme argument that takes on different values for TB and TA. We will represent the theme argument by a rectangular node in the frame diagram, thereby indicating that it represents an open argument. Argument nodes can be considered providing an interface to syntax, but they do not receive a different interpretation than the other nodes in the frame.

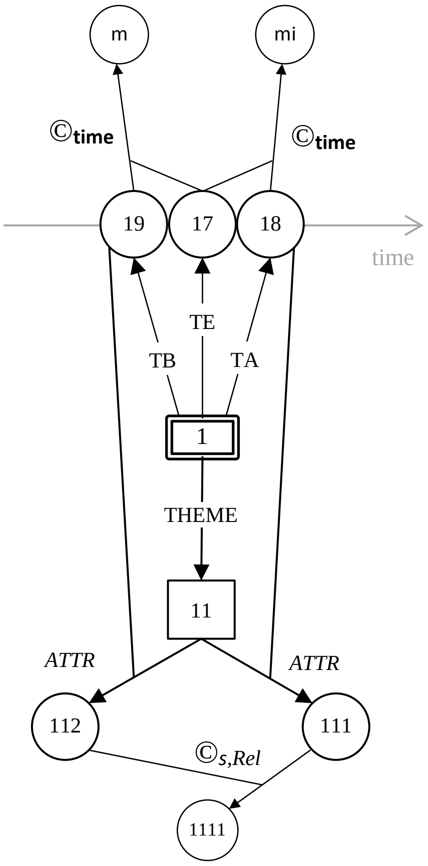
Fig. 4 displays the general schema of a frame for a verb that denotes a punctual change of its theme argument in terms of the attribute *ATTR*;[8] the difference between the state before and after the change is captured by the value of some comparator $©_{s,Rel}$ that is defined on the sort **s** of entities which the attribute *ATTR* takes as values. The value of the comparator has to be such that it entails inequality, as does e.g. '<'. The change is punctual in the sense that it does not impose any conditions on the time TE itself.

Discussion

The frame in Fig. 4 models a variant of Dowty's BECOME operator in its second version related to time intervals (cf. the discussion in [6], pp. 139ff.). BECOME operates on a proposition φ; [BECOME φ] is true at an interval I if there are intervals J and K such that ([6], p. 141, (11')):

(i) ¬φ is true in J and J contains the initial bound of I,
(ii) φ is true in K and K contains the final bound of I,
(iii) I is the smallest time interval that fulfills the conditions (i) and (ii).

8 Note that $\mathfrak{F}_{\mathbf{PunCh}}$ is not a frame structure in accordance with Definition 1 as it contains the attribute *variables* '*ATTR*' and '$©_{s,Rel}$'; $\mathfrak{F}_{\mathbf{PunCh}}$ is a frame schema.



$$
\begin{aligned}
& \text{TE}(\boxed{1}) = \boxed{17} \\
\wedge\ & \text{TB}(\boxed{1}) = \boxed{19} \\
\wedge\ & \boxed{19}\ \text{m}\ \boxed{17} \\
\wedge\ & \text{TA}(\boxed{1}) = \boxed{18} \\
\wedge\ & \boxed{18}\ \text{mi}\ \boxed{17} \\
\wedge\ & \text{THEME}(\boxed{1}) = \boxed{11} \\
\wedge\ & \mathit{ATTR}(\boxed{11}, \boxed{18}) = \boxed{111} \\
\wedge\ & \mathit{ATTR}(\boxed{11}, \boxed{19}) = \boxed{112} \\
\wedge\ & \copyright_{s,Rel}\,(\boxed{111}, \boxed{112}) = \boxed{1111}
\end{aligned}
$$

Fig. 5. Frame schema $\mathfrak{F}_{\mathbf{PunCh}}$ for a punctual change of state of the theme in the attribute *ATTR* , canonical satisfaction formula

The frame schema $\mathfrak{F}_{\mathbf{PunCh}}$ represents a BECOME event where φ is defined in terms of the value of the attribute *ATTR* of the theme changing into what it becomes. The three times $\boxed{19}$ (time before), $\boxed{17}$ (time the event occupies), and $\boxed{18}$ (time after), correspond to Dowty's time intervals J, I, and K, respectively. As is common practice in many variants of Montague Grammar, Dowty uses a logical language without expressions that refer to times; time-dependence is spelt out in the model-theoretic interpretation. It is therefore not possible to express in the formal frame language used here what would be Dowty's φ for the frame in Fig. 5. If we omitted the time argument of the attribute of the theme, we would get '$\mathit{ATTR}(\boxed{11}) = \boxed{111}$' as the operand φ of Dowty's BECOME.

There are differences, though, between the analysis proposed here and Dowty's. One concerns the minimality condition (iii). Dowty's definition of BECOME aims at exactly delimiting the interval in which the change takes place. In view of examples like those mentioned above (the neon light and the share price examples), I consider this condition possibly too strong. The second difference concerns the comparison between the two states; Dowty's BECOME operator models a change from $\neg\varphi$ to φ, while the comparator model allows for a wider range of relationships between the state before and the state after. The third difference is the respective topology of time assumed.

5.2 Punctual degree achievements

The general frame $\mathfrak{F}_{\textbf{PunCh}}$ can be spelt out for different types of intransitive punctual verbs of change. One such type is punctual degree achievements[9] with a lexically specified scale of change. Examples are cases like punctual intransitive 'grow':

(1) *the number of participants in my seminar grew by 2*

The lexical frame for 'grow' has SIZE as the attribute *ATTR* of change. The respective comparator is $©_{\textbf{size},<}$ where **size** is the sort of sizes, i.e. the sort of things that can be values of the attribute SIZE; this sort carries a linear ordering >; in the case of *grow*, the comparator returns '>'.

Punctual verbs cannot be used in the progressive[10] as they do not denote an event that can be parted into subevents of equal kind. In addition to the punctual use of *grow* illustrated in (1), there are senses of English *grow* where the verb denotes a continuous change on the size scale. These are not captured with the frame in Fig. 5. Modeling continuous change would require TE(e) to be temporally extended and would call for imposing a monotonicity condition on TE(e) to the extent that the value of SIZE is monotonically increasing during TE(e).Other punctual verbs denoting degree achievements on specific scales would be represented with a different instantiation of *ATTR*: *rise* with HEIGHT, *widen* with WIDTH, and so on.

In Japanese, there are degree achievement verbs which in general defy progressive use, i.e. a progressive reading with the continuative *-te iru* form.[11] These include for example *hutoru* 'get fat(ter)' and *yaseru* 'get thin(ner)'.

In general, punctual degree achievements are characterized by relating to a theme attribute *ATTR* that takes values of a sort that is ordered and therefore has a comparator that returns corresponding values such as '>' or '<'.

5.3 Punctual verbs of change into a specific state

Consider *go on* (of lamps etc.) in the sense of changing into the change of being [switched] on. The criterial attribute (to be named properly) can take either of two values, 'on' and 'off'. The value of that attribute at TA(e), i.e. $\boxed{18}$, is specified as 'on', the comparator is the standard © for this sort and returns '≠'. Japanese punctual verbs of change into a specific state include *aku* 'come open', *kowareru* 'break' (intransitive), or *sinu* 'die'. In general, this group of verb can be modeled with the frame in Fig. 5 with a specification of *ATTR* and its value $\boxed{111}$, and the comparator value being '≠'.

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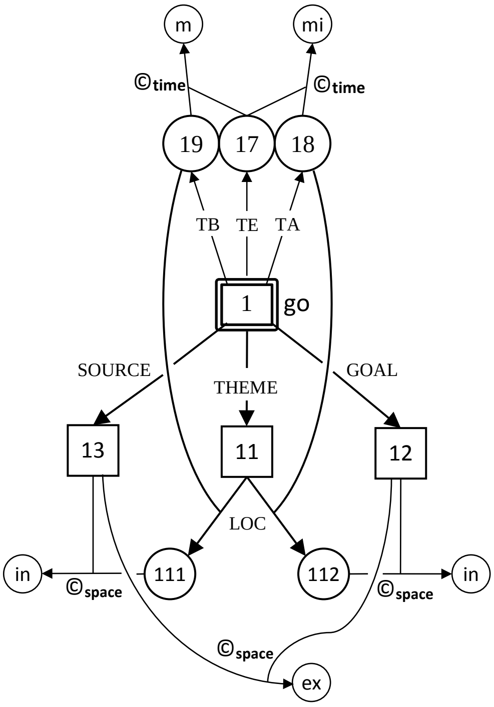
9 See Dowty [6]: 88ff for the notion of degree achievement verb.

10 The notion 'progressive' is to be taken in the functional, semantic sense, as relating to a certain variant of imperfective aspect, not in the morphological sense.

11 See Martin [13], p. 518 for the punctuality of the Japanese verbs mentioned here and below.



$$\begin{aligned}
& \mathrm{TE}(\boxed{1}) = \boxed{17} \\
\wedge\ & \mathrm{TB}(\boxed{1}) = \boxed{19} \\
\wedge\ & \boxed{19}\ \mathsf{m}\ \boxed{17} \\
\wedge\ & \mathrm{TA}(\boxed{1}) = \boxed{18} \\
\wedge\ & \boxed{18}\ \mathsf{mi}\ \boxed{17} \\
\wedge\ & \mathrm{THEME}(\boxed{1}) = \boxed{11} \\
\wedge\ & \mathrm{GOAL}(\boxed{1}) = \boxed{12} \\
\wedge\ & \mathrm{SOURCE}(\boxed{1}) = \boxed{13} \\
\wedge\ & \boxed{13}\ \mathsf{ex}\ \boxed{12} \\
\wedge\ & \mathrm{LOC}(\boxed{11}, \boxed{19}) = \boxed{111} \\
\wedge\ & \boxed{111}\ \mathsf{in}\ \boxed{13} \\
\wedge\ & \mathrm{LOC}(\boxed{11}, \boxed{18}) = \boxed{112} \\
\wedge\ & \boxed{112}\ \mathsf{in}\ \boxed{12}
\end{aligned}$$

Fig. 6. Frame for punctual ‘THEME go from SOURCE to GOAL’, canonical satisfaction formula

5.4 Punctual verbs of locomotion

Verbs of locomotion from one location to the other can be represented with a frame very similar to $\mathfrak{F}_{\mathsf{PunCh}}$ – provided the verbs are conceived as punctual. It is not clear, if English has such verbs, but Japanese does, e.g. *iku* ‘go’, *kuru* ‘come’, *kaeru* ‘return’, *otiru* ‘fall’, *deru* ‘emerge from’, *hairu* ‘enter’, and others. The attribute of change is the location of the subject referent. For the construction ‘x *ga* [NOM] B *ni* [LOC] *ik*-’[12], we assume that both x, the theme, and B, the goal, are arguments of the verb. The goal attribute will usually be specified as a region that covers more than the space taken in by the theme when it is there. We cannot, therefore, identify the referent of the goal specification with the location of the theme that results from the motion; rather, we have to model the resulting state as the location of the theme being *within* the specified goal region. For the spatial relation, we can again use a comparator ©$_{\mathsf{space}}$ based on an appropriate mereotopology. We will use two comparator values, ‘in’ for x being within y and ‘ex’ for x being outside of y. These two are admissible values of the same comparator because the two spatial relations exclude each other.

[12] *ik*- is the bare stem of the verb, not inflected for tense. The citation form of Japanese verbs carries the present tense ending *-u* or *-ru.*

We will model the Japanese punctual verb *iku* 'go' in the full construction 'x *ga* [NOM] y *kara* [SOURCE] z *ni* [GOAL] *ik*-', meaning 'x go from y to z' in a punctual sense. The verb meaning is modeled as 'LOCATION(THEME(e)) be within SOURCE(e) at TB(e) and within GOAL(e) at TA(e), where SOURCE(e) is outside of GOAL(e)'. Thus the frame involves three applications of the spatial comparator; they encode (i) the relation between the location of the theme and the source, (ii) the relation between the location of the theme and the goal, and (iii) the relation between source and goal. The latter is necessary because this type of verb is not applicable to situations where the source is inside the goal region or overlaps with it: A statement like *John went from Tokyo to Japan* violates a presupposition of 'go from SOURCE to GOAL'. This presupposition is modeled explicitly by the third comparator condition. Fig. 6 displays the frame and the corresponding canonical satisfaction formula.

The frame can be accommodated to simpler cases such as the punctual Japanese *hair-u* 'enter'. This verb has only two arguments, theme and goal. There is a condition on the location of the theme at TA(e): it is within the goal, and a second condition on the location of the theme at TB(e): it is outside of the goal. Switching these two conditions yields a frame for the verb *de-ru* 'leave, emerge from'.

The canonical satisfaction formulae can be considerably simplified; if one omits the general conditions on TB, TE, and TA, and the general condition on the spatial relation between SOURCE and GOAL, the remaining conjuncts can be reduced to two, if one makes use of variable elimination. For the sake of comparability with other approaches, we replace the variable '[1]' by the conventional event variable 'e'. The remaining two conjuncts capture the idiosyncratic meaning components of punctual *go*/*iku*.

(4) punctual '*go from* SOURCE *to* GOAL', Japanese 'SOURCE *kara* GOAL *ni ik*-'
LOC(THEME(e), TB(e)) in SOURCE(e) $\wedge$
LOC(THEME(e), TA(e)) in GOAL(e)

The respective meaning components of *hairu* and *deru* are given in (5) and (6):

(5) punctual '*enter* GOAL', Japanese 'GOAL *ni hair*-'
LOC(THEME(e), TB(e)) ex GOAL(e) $\wedge$
LOC(THEME(e), TA(e)) in GOAL(e)

(6) punctual '*leave* SOURCE', Japanese 'SOURCE *o de*-'
LOC(THEME(e), TB(e)) in SOURCE(e) $\wedge$
LOC(THEME(e), TA(e)) ex SOURCE(e)

6 To be continued

The proposal developed here introduces further modules of the 'Düsseldorf frame theory'. Major points are (i) the definition of a global frame ontology, (ii) the introduction of times, events, and time-dependent attributes in the ontology, a step paving the way for explicit representation of time, time-dependence, and time parameters of events in frames, and (iii) the introduction of two-place comparator attributes.

The latter enable the modeling of basic intrasortal relations within a framework with exclusively functional frame-internal relations. Comparators are waiting for further applications, e. g. to mereological relationships, or to the modeling of degrees.

The inclusion of time-dependent attributes raises the general logical and ontological question as to which attributes are time-dependent and which are not. In particular the question arises if, for principal reasons, dynamic verbs involve at least one time-dependent attribute of a verb argument.

Time-dependent attributes require a homogeneity constraint on the assignment of values. This raises another general question: which attributes in general underlie a homogeneity constraint?

In view of the range of possible application of these general theoretical considerations, the proposed lexical analysis of verb meanings is, of course, very selective. Further extensions would have to address non-punctual verbs of change, as well as all the other well-known aspectual classes.

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Acknowledgments. The theory presented here arose from joint work at Düsseldorf University in the Research Unit RU 600 'Functional Concepts and Frames' (2005–2011), continued in the Collaborative Research Centre CRC 991 'The Structure of Representations in Language, Cognition, and Science' (2011–2019 or later), both financed by the German Science Foundation; see http://www.sfb991.uni-duesseldorf.de/en/ for the CRC. The author profited tremendously from extended discussion with Ralf Naumann Wiebke Petersen, Henk Zeevat, and Timm Lichte. I owe the reference to Roberts et al. [17] to Tobias Kalenscher; Christopher Habel referred me to the work on mereotopology mentioned above.

To appear in:
Helle Hvid Hansen, Sarah Murray, Mehrnoosh Sadrzadeh, Henk Zeevat (eds.), *Proceedings of the Eleventh International Tbilisi Symposium on Language, Logic and Computation, Tbilisi, 21-26 September, 2015.* Springer: Heidelberg & New York, LNCS series.