Do you still want to vote for your favorite politician? Ask Ontobella!

Pawel Garbacz, Marek Lechniak, Piotr Kulicki and Robert Trypuz
Department of Philosophy
The John Paul II Catholic University of Lublin

Abstract. The paper presents the preliminary version of Ontobella - a domain ontology of beliefs. The philosophical assumptions of this system are taken from the philosophy of Roman Ingarden and from the psychological results obtained in the Lvov-Warsaw school. Ontobella is applied as the conceptual framework for a computer system that collects information about political debates. We use it to retrieve and store beliefs expressed during sessions of the Polish parliament.

Keywords. ontology, belief, intentionality, politics

Representation of knowledge and beliefs plays a crucial role in Artificial Intelligence, especially in modeling artificial agents being able to carry out actions on the basis of their knowledge about environment and goals [12,8] and in automated planning [7]. Beliefs are largely studied in epistemic logic, where many formal systems of representation of private, public and common beliefs have been proposed. One special interest is a question of belief revision formally described by the well-known AGM model [1]. Finally, the important role of knowledge representation in argumentation and persuasion is evident.

Nonetheless, ontological foundations of these approaches remain unclear. The domain of beliefs did not attract a lot of attention in ontological engineering despite the substantial research in psychology and philosophy. The authors of this contribution are not aware of any domain specific ontology of beliefs except for the COM ontology. This paper presents a slightly different approach to modelling the domain of beliefs. Section 1 describes the results we have achieved so far in the form on the Ontobella ontology. Section 2 is devoted to one of the possible applications of such ontologies, while the last section compares Ontobella with the COM ontology. The formal shape of our system is outlined in the Appendix.

1. Main ontological assumptions of Ontobella

Our ontology of beliefs, Ontobella, has two main sources of inspiration:

1. R. Ingarden's ontology of intentional object (cf. [3]), in particular:
   - the distinction between autonomous and heteronomous entities,

- the conception of intentional objects as contents of mental acts,
- the definition of beliefs as those mental acts the represent situations together with his theory of situations/states of affairs (*Sachverhalten*).

2. the psychological legacy of the Lvov-Warsaw school (the so-called "descriptive psychology"–cf. [10]), in particular:

   - the conception of beliefs as perdurants,
   - the thesis that representational object exhibit (mental) content,
   - the distinction between assertions and rejections as non-reducible propositional attitudes,
   - the definition of memory and expectation.

However, due to the lack of space, we have not elaborated here on these threads and confine our presentation to the results we took over from these traditions.

1.1. Ontological neutrality of Ontobella

The Ontobella ontology is a domain-specific ontology, so it presupposes a number of general categories like those of endurant, state of affairs, time etc. Although we share the conviction that the precise understanding of these notions is crucial to the task of ontological engineering, we do not want to restrict our ontology of beliefs to some specific upper-level ontology. We believe that any sufficiently broad upper level ontology has concepts that subsume the most general concepts of Ontobella. The following table shows the correspondence between Ontobella and a sample of the upper-level ontologies. The correspondence shown is either of the type of subsumption (i.e. a given Ontobella category is subsumed by the respective category from an upper-level ontology) or identity.

Ontobella	**DOLCE**	**GFO**	**BFO ontology**	**SUMO**
SimpleThing	Particular	Individual	Entity	entity
Situation	Situation[a]	Configuration	-	-
occursIn	-	-	constituent of ($cpart$)	-
Endurant	Endurant	Presential	Continuant	Object
Perdurant	Perdurant	Occurent	Occurent	Process
dependsOn	specific constant dependence	dependence	specific constant dependence	
$\prec$	proper parthood	(abstract) part-of relation	proper parthood	properPart
participates	constant participation	exhibit	complete participation	-
Agent	Agentive Physical Object	-	-	cognitive agent

[a]The category of situations is to be found in an extension of DOLCE named "DOLCE+" (cf. [6]).

Table 1. Ontobella and upper-level ontologies

On the other hand, we use these upper-level notions to define certain less specific ones, usually following the standard patterns (see definitions 1, 2, 3).

The only exception to our "ontological indifference" is the conception of time. The idea we refer to is borrowed from the ISO 15926 ontology where a time object (be it an instant or period) is the mereological sum of a set of perdurants (cf. [11]). In our ontology we assume that there exists a set of time objects (TimeThing) that are perdurants (axiom 6) and are ordered by means of the relation of being earlier than (axiom

7).[1] This solution allows us to define the ternary temporal relations with the help of their binary counterparts (cf. definitions 4, 36, 31, 34, and 35). We do not, however, accept the four-dimensional perspective of the ISO 15926 ontology.

1.2. Specific categories of Ontobella

Ontobella is a first-order theory that is determined by the axioms and definitions given in the Appendix. Here we briefly describe its most important tenets in the natural language. Moreover, there exists an OWL version of Ontobella, available at www.trypuz.ovh.org/ontobella/ontobella.owl.

We assume that beliefs are perdurants, i.e. that they extend in time. This ontological categorisation takes into account the following intuitions:

- our beliefs start and end at certain points in time,
- our beliefs have phases, i.e. they are not "fully-feathered" when that come into existence, but they develop in the course of time,
- our beliefs are parts of our mental lives,
- although some of our beliefs are composed of other beliefs, it is not the case that any collection of beliefs corresponds to a belief.

Beliefs are those perdurants in which certain agents participate. The current axiomatisation aims at modelling only individual beliefs, so any belief has exactly one agent which participates in this belief. This relation between the agent and his or her belief is represented by the "hasBelief" predicate. Except for axiom 26, we do not characterise the notion of agent in more detail.

A belief is a representational object, that is to say, due to its ontological status, it represents other objects. Among other representational objects, beliefs may be isolated as those objects that represent situations/states of affairs (Situation). As all representational objects, beliefs represent something because of their (mental, or even better intentional) content. The relation of representation is divided into two components: hasContent and directRepresents. The first relation links beliefs, and, for that matter, all other representational objects, to their contents.[2] Then, each piece of mental content directly represents (directRepresents) the respective piece of reality, i.e. situations/states of affairs in the case of beliefs. This informal description of beliefs as perdurants that represent situations is captured by definitions 13 and 16 together with axiom 13. Figure 1 outlines the main elements of this view on beliefs.

In sum, when an agent has a belief, then by means of this belief he or she refers towards a certain mental content (cf. definition 21) and thereby believes that a certain situation is the case (definition 18). Finally, if an object occurs in this situation, then we say that the belief at stake concerns the object (definition 15).

[1] The notion of time object is taken as primitive here, but one can define it provided that one is able to define the relation of simultaneousness on the set of all perdurants. Then each time object is the mereological sum of an abstraction class of this relation. Thus, a time object may be either an instant or a period. Our time objects coincide with the so-called historical closures from [11].

[2] We found that R. Ingarden's notion of intentional objects is particularly useful to define contents of beliefs, but the proper exposition of his theory goes far beyond the scope of the present paper. Nonetheless, the notion of specific content dependence might serve as the upper-level super-concept for hasContent (cf. axioms 10 and 11).

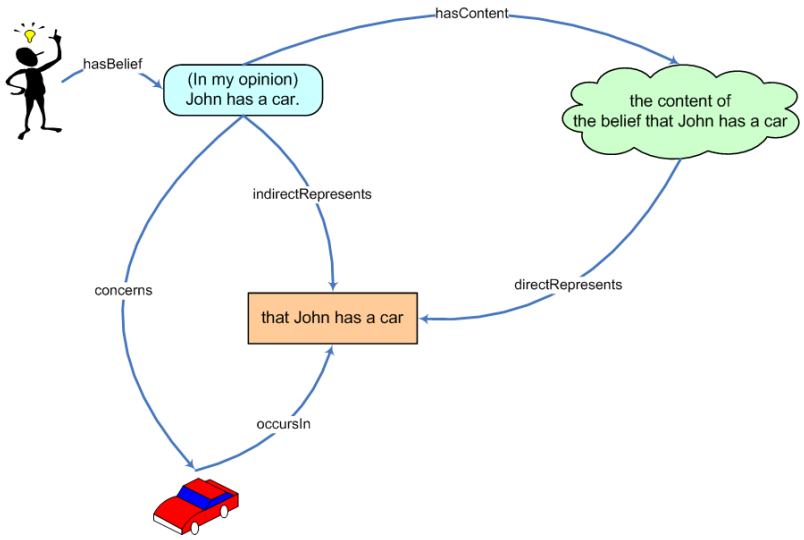

Figure 1. Representation of beliefs in Ontobella

Axiom 15 gives the criterion of identity for beliefs: one agent cannot have two different beliefs if these beliefs share content and have the same temporal span.

All beliefs are ephemeral objects, but some of them are stored by means of written or spoken utterances. We assume that belief storages (cf. definition 32) are created for the sake of storing beliefs, so the former store the latter as long as they exist (axiom 19). Moreover, since some belief storages are perdurants, we exclude the possibility that a belief is its own storage (axiom 20). Among such storage objects, we distinguish what we call transparent storage objects, i.e. those written or spoken utterances that exhibit such features by means of which certain agents are able to identify those of entities as storage objects. For example, the string "In my opinion Warsaw is more beautiful than London" is a transparent storage object in contrast to the string "Warsaw is more beautiful than London". We do not define the category TranspBeliefStorage of such transparent storage objects (see, however, axiom, 28), but we need it for the application purposes - see below. If a belief is stored in a storage object, we call the former a stored belief (definition 33).

When an agent entertains a certain belief, this belief is either accepted or rejected by him or her (cf. axiom 14). The notion of belief (definition 17) is broad as it includes all propositional doxastic attitudes, including those where we hardly believe or disbelieve something.

We are able to order both beliefs and belief storages according to their temporal position in time by means of the relation $\Rightarrow_{\mathsf{T}}$ that links our time objects.[3] Definitions 11, 7, 8, and 9 extend this relation to all entities that exist in time, including situations.

It is a psychological fact the beliefs support (or motivate) one another. Sometimes this relation is based on the deductive inference: I believe that every politician lies because I disbelieve some politicians do not lie. In most cases, however, the psychological fact that I believe so and so is supported by other beliefs (of mine) but the support at stake has little to do with logic. Moreover, it might be the case that my belief is supported

[3] $x \Rightarrow_{\mathsf{T}} y$ means that (time object) x is earlier than (time object) y.

not only by my other beliefs, but also by some other mental objects, e.g. emotions, or even external factors, e.g. someone's behaviour. In order to model this relation of support, we use the relation supports. We assumed the following minimal characterisation of this relation:

- all objects in the field of the supports relation are perdurants (axiom 21),
  - So neither John nor his suit can persuade Ann to buy a new model of Volvo. If she happens to be persuaded by John, we model this by selecting certain perdurant in which John participates, say his eloquent speech or his broad smile, and claim that it is this perdurant that supports Ann's new belief that she ought to buy this Volvo.
- other agents' beliefs do not directly support my beliefs; if they do, then it is mediated by the behaviour of those agents (axiom 22),
- direct supports does not span over time: if one perdurant directly supports a belief, then their temporal spans overlap (axiom 23),
- no belief can support itself (axiom 24),
- supports is transitive, at least over the belief set of one agent (axiom 25).

Axioms 24 and 25 presuppose that the relation of belief support has certain flavour of rationality. If you keep on repeating "p because p", you do not support anything in this sense.

1.3. Expressivity of Ontobella

Using the aforementioned primitive notions, we are able to define the following concepts and relations:

1. the relation that links beliefs with the objects these beliefs are about (definition 15),
2. the concept of second-order belief (definition 19),
3. the relation by means of which two beliefs have the same content (definition 14),
4. relation by means of which two agents believe in the same content (definition 22),
5. the concept of plain, i.e. non-ambiguous, belief (definition 23),
6. the concept of self-awareness (definition 25),
7. the concept of beliefs that represent past, present, and future situations (definitions, respectively, 26, 27, and 28),
8. the concept of memory and expectation (definitions 29 and 30).

2. Ontobella as a conceptualisation of political debate

We apply the Ontobella ontology to model the domain of political debate or rather the noetic aspect of this debate, i.e. we are interested in the beliefs expressed during such debates. As a case study, we choose to represent the debates that took place in the Polish Parliament (i.e. Sejm of the Republic of Poland).

We built a database that contains the representations of the beliefs expressed during the sessions of the Parliament. The schema of this database is shown in fig. 2.

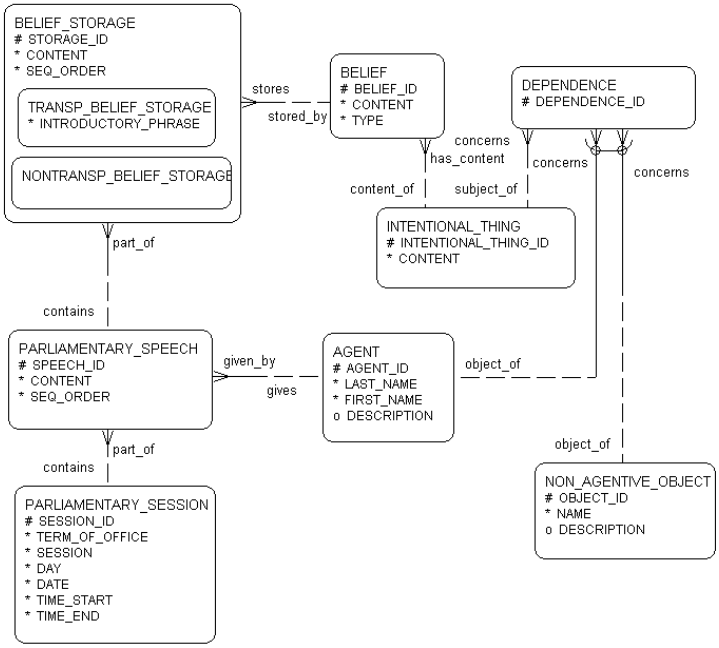

Figure 2. Schema of the Ontobella database.

It is in the form of an entity-relationship diagram presented using Barker's "crow foot" notation. Entities BELIEF_STORAGE, BELIEF, INTENTIONAL_THING and AGENT are directly translated from Ontobella categories. Entity DEPENDENCE is a result of the technically motivated reification of the Ontobella's concerns relation. Entity NON_AGENTIVE_OBJECT along with entity AGENT plays the role of a dictionary of objects that may occur in situations that beliefs indirectly represent. Entities PARLIAMENTARY_SESSION and PARLIAMENTARY_SPEECH represent the structure of parliamentary processes and their documentations from which the information is retrieved. The schema has been defined on the base of the Ontobella ontology, however, we deployed only a tiny part of the whole theory.

The database in question will be part of the computer system that retrieves the information about the beliefs expressed in the political debate, stores them in the database, and allows the user to find the information he or she needs. The architecture of this system is shown in fig. 3. The source of the relevant data are the parliamentary reports published at http://orka2.sejm.gov.pl. In order to automate this process, we defined an algorithm that finds within those reports the pertinent TranspBeliefStorage and stores them in the database. This algorithm is based on the notion of text pattern, which was successfully employed in the automated classification of sentences in legal documents (see [4]). However, the implementation of this algorithm is still ahead of us.

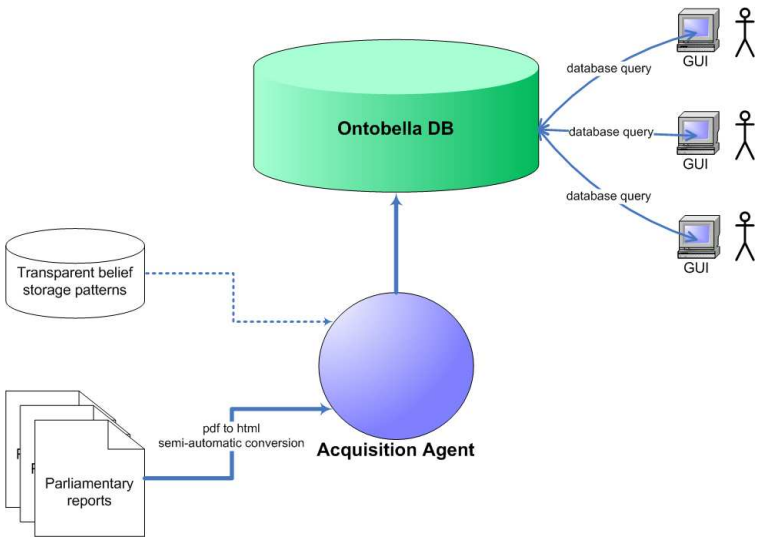

Figure 3. Computer system retrieving the information about the beliefs expressed in the political debate.

3. Ontobella vs COM

Computed Ontology of Mind (in short COM) [5] is a formal ontology developed by two researchers, R. Ferrario and A. Oltramari, from the Laboratory for Applied Ontology. As far as we know it was the first ontology of mental states built with the intention of application in information systems and, until Ontobella has been created, it remained the only one. Thus it seems appropriate to compare these two ontologies.

Let us start with a short introduction to COM. The authors of COM claim that it is inspired by J. A. Fodor's Computational Representation Theory of Mind and the BDI approach. COM is grounded in DOLCE [9] and shares its ontological choices. Moreover, all predicates present in COM—except two temporal relations of *precedence* and *start* taken from the theory of time of Allen and Hayes—come from DOLCE. Thus the authors constructed COM by means of two methods:

- by introducing definitions of new predicates using the existing ones,
- by proposing axioms "deepening" the characterization of DOLCE categories.

In COM the main two categories are *Mental State* and *Mental Object*. The second one is a subcategory of *Non-physical Object* and its main characteristic is such that its instances do not "generically dependent [on] a community of agents" [9].

They are two kinds of *Mental Object* postulated in COM: *Percept* and *Computed Object*. Any instance of the first one does *not* depend on any mental object. The second category is defined in the following way: x is *Computed Object* if and only if it is *Mental Object* and there is always some *Percept* or another *Computed Object* y such that x is proceeded by (historically depends on) y. Instances of *Computed Object* "are indirect, namely they are the result of the computational processes that occur every time that an input (external or internal) is processed" [5]. The four subcategories of *Computed Object* are *Computed Belief*, *Computed Desire* and *Computed Intention*.

All kinds of *Mental State*—there are four of them: *Perceptual State*, *Desire*, *Intention* and *Belief*—are defined in COM by means of reference to some subcategory of *Mental Object* and to relation *aboutness*. For instance *Belief* is defined in the following way (see D11 in [5]):

> x is a belief if and only if there exists the agent a, a time t and a computed belief object y such that the mental state x of the agent a is about y at t.

Formally *aboutness* is a four-place predicate defined by means of DOLCE predicates as follows (see D9 in [5]):

> "a state y of the intentional agent x is about a mental object z at time t if and only if the agent x participates to the state y at t and the mental object z also participates to y at t, being z one-sided specific constant dependent on x".

The temporal extension and existence of mental objects are bound to the duration of mental states that are about them in such a way that: percepts, computed intentions and desires exist as long as the mental states that are about them exist, whereas the computed belief is required to start at the beginning of the belief that is about it.

The main differences between Ontobella and COM:

1. Ontobella is an ontology of beliefs and does not characterize other mental states such as intentions or desires which COM does. On the other hand, there are many interesting categories concerning beliefs in Ontobella such as: past, present and future beliefs, expectations, memory, self-awareness or second order beliefs. None of them are present in COM.
2. *Belief* in COM is a *(Mental) State* which is a subcategory of *Perdurant*. In Ontobella Belief is a direct subclass of Perdurant.
3. COM's mental states are connected by aboutness with objects *internal* to the agent. COM does not provide any way to go from the "content" of belief (i.e. computed belief) to the objects represented by this content. Ontobella joins beliefs with their contents by means of primitive relation hasContent. Contents represent something "external" (directRepresents). By the relation indirectRepresents in Ontosbella we link a belief with a situation represented by its content. Contents of beliefs (and indirectly beliefs themselves) can be linked to objects which occur in the situations represented by them.
4. Contents of beliefs are not "private" in Ontobella—in the sense that two beliefs (of two distinct agents) may share the same content (see definition 22)—whereas they are "private" in COM. A common feature of the two ontologies in question is that every belief belongs to one and only one agent. Additionally in COM it is also required that for every agent present at time t there is a computed belief dependent on it. Ontobella does not take a position on this issue.
5. It can be proved in COM that belief is always preceded by another mental state. In Ontobella beliefs may be supported by other perdurants, e.g. percepts, emotions, other beliefs, desires, etc. (cf. axioms 21–25).

4. Further work

As the reader can easily appreciate, our research is still at an initial phase. Except for the implementation tasks described above, we envisage to pursuing the following problems:

1. In a number of context, including politics, beliefs are role-dependent: an agent has or expresses a belief because he plays a certain role. For example, a MOP presents a certain opinion not as his or her view, but as a view of his or her party. Thus, the adequate ontology of beliefs should account for this dependence.
2. The philosophical theories of beliefs tend to look at them from the point of view of epistemology or logic. Thus, the results obtained may oversimplify the obscure nature of beliefs. Although we tried to avoid this trap, we perceive the need to compare the assumptions we made to the more empirical psychological type of research. In particular, we want to investigate whether one can build software applications to support psychotherapy. The cognitive therapy developed by Aaron Beck [2] seems to be a promising field in this respect.

Nevertheless, we believe that the current state of the art in the ontological analysis of beliefs justifies the certain sketchiness of our results.

5. Appendix - Ontobella's formal outlook

Mereology

(D1) $\mathsf{Perdurant}(x) \wedge \mathsf{Perdurant}(y) \rightarrow [x \preccurlyeq y \triangleq x \prec y \vee x = y]$
(D2) $x \circ y \triangleq \exists z(z \preccurlyeq x \wedge z \preccurlyeq y)$

Occurrence

(A1) $\mathsf{occursIn}(x, y) \rightarrow \mathsf{SimpleThing}(x) \wedge \mathsf{Situation}(y)$
(A2) $\mathsf{Situation}(x) \rightarrow \exists z \mathsf{occursIn}(z, x)$
(A3) $\mathsf{SimpleThing}(x) \rightarrow \exists z \mathsf{occursIn}(x, z)$

Participation

(A4) $\mathsf{Endurant}(x) \rightarrow \exists y \mathsf{participates}(x, y)$
(A5) $\mathsf{Perdurant}(x) \rightarrow \exists y \mathsf{participates}(y, x)$
(D3) $\mathsf{Endurant}(x) \rightarrow [\mathsf{life}(x) \triangleq \sigma(y)\mathsf{participates}(x, y)]$[4]
(D4) $\mathsf{participatesAt}(x, y, z) \triangleq \mathsf{participates}(x, y) \wedge \mathsf{TimeThing}(z) \wedge y \prec z$
(D5) $\mathsf{agentIn}(x, y) \triangleq \mathsf{Agent}(y) \wedge \mathsf{participates}(y, x)$

Time Thing

(A6) $\mathsf{TimeThing}(x) \rightarrow \mathsf{Perdurant}(x)$
(A7) $\Rightarrow_{\mathsf{T}}$ is a strict partial order in set TimeThing.
(D6) $\mathsf{hasTemporalSpanOf}(x, y) \triangleq [\mathsf{TimeThing}(y) \wedge x \preccurlyeq y] \wedge$
$\forall z[\mathsf{TimeThing}(z) \wedge x \preccurlyeq z \rightarrow y \preccurlyeq z]$
(A8) $\mathsf{Perdurant}(x) \rightarrow \exists y \mathsf{hasTemporalSpanOf}(x, y)$
(D7) $\mathsf{Perdurant}(y) \rightarrow [x = \mathsf{span}_{\mathsf{perd}}(y) \triangleq \mathsf{hasTemporalSpanOf}(y, x)]$
(D8) $\mathsf{Endurant}(x) \rightarrow [\mathsf{span}_{\mathsf{sim}}(x) \triangleq \mathsf{span}_{\mathsf{perd}}(\mathsf{life}(x))]$
$\mathsf{Perdurant}(x) \rightarrow [\mathsf{span}_{\mathsf{sim}}(x) \triangleq \mathsf{span}_{\mathsf{perd}}(x)]$

[4] '$\sigma(\alpha)\phi$' denotes the mereological sum of the set of all entities α that satisfy the condition ϕ. The consistency of 3 is guaranteed by the formal properties of relation $\prec$.

(D9) $\mathsf{Situation}(x) \rightarrow [\mathsf{span}_{\mathsf{sit}}(x) \triangleq \mathsf{span}_{\mathsf{perd}}(\sigma(y)[\mathsf{Perdurant}(y) \wedge \mathsf{occursIn}(y, x)])$
(D10) $\mathsf{SimpleThing}(x) \rightarrow [\mathsf{span}(x) \triangleq \mathsf{span}_{\mathsf{sim}}(x)]$
$\mathsf{Situation}(x) \rightarrow [\mathsf{span}(x) \triangleq \mathsf{span}_{\mathsf{sit}}(x)]$
(D11) $x \Rightarrow y \triangleq \mathsf{span}(x) \Rightarrow_{\mathsf{T}} \mathsf{span}(y)$
(A9) $x_1 \prec x_2 \rightarrow [\mathsf{hasTemporalSpanOf}(x_1, y_1) \wedge \mathsf{hasTemporalSpanOf}(x_2, y_2) \rightarrow y_1 \prec y_2]$

Content and representation

(A10) $\mathsf{hasContent}(x, y) \rightarrow \mathsf{dependsOn}(y, x)$.
(A11) $\mathsf{hasContent}(x, y) \rightarrow \mathsf{IntentionalThing}(y) \wedge \exists z \mathsf{agentIn}(x, z)$.
(A12) $\mathsf{directRepresents}(x, y) \rightarrow \mathsf{IntentionalThing}(x)$
(D12) $\mathsf{IntentionalThing}(x) \triangleq \exists y \mathsf{hasContent}(y, x)$
(D13) $\mathsf{indirectRepresents}(x, y) \triangleq \exists z[\mathsf{hasContent}(x, z) \wedge \mathsf{directRepresents}(z, y)]$
(D14) $\mathsf{shareContent}(x, y) \triangleq \exists z[\mathsf{hasContent}(x, z) \wedge \mathsf{hasContent}(y, z)]$
(D15) $\mathsf{concerns}(x, y) \triangleq \mathsf{Belief}(x) \wedge \forall z[\mathsf{indirectRepresents}(x, z) \rightarrow \mathsf{occursIn}(y, z)]$

Belief

(A13) $\mathsf{hasBelief}(x_1, y) \wedge \mathsf{hasBelief}(x_2, y) \rightarrow x_1 = x_2$.
(D16) $\mathsf{hasBelief}(x, y) \triangleq \mathsf{agentIn}(y, x) \wedge \exists z \mathsf{hasContent}(y, z) \wedge \forall z[\mathsf{indirectRepresents}(y, z) \rightarrow \mathsf{Situation}(z)]$
(A14) $\mathsf{hasBelief}(x, y) \equiv \mathsf{asserts}(x, y) \vee \mathsf{rejects}(x, y)$.
(A15) $\mathsf{hasBelief}(x, y_1) \wedge \mathsf{hasBelief}(x, y_2) \wedge \mathsf{shareContent}(y_1, y_2) \wedge \mathsf{span}_{\mathsf{perd}}(y_1) = \mathsf{span}_{\mathsf{perd}}(y_2) \rightarrow y_1 = y_2$.
(A16) $\mathsf{hasBelief}(x, y) \equiv \exists z[\mathsf{ThatAgentHasBelief}(z) \wedge \forall v(\mathsf{occursIn}(v, z) \rightarrow v = x \vee v = y)]$.
(D17) $\mathsf{Belief}(x) \triangleq \exists y \mathsf{hasBelief}(y, x)$
(A17) $\mathsf{Belief}(x) \rightarrow \neg \mathsf{TimeThing}(x)$.
(D18) $\mathsf{believesThat}(x, y) \triangleq \exists z[\mathsf{hasBelief}(x, z) \wedge \mathsf{indirectRepresents}(z, y)]$

Second order, self and shared belief

(D19) $\mathsf{SecondOrderBelief}(x) \triangleq \mathsf{Belief}(x) \wedge \exists y[\mathsf{Belief}(y) \wedge \mathsf{concerns}(x, y)]$
(D20) $\mathsf{selfBeliefOf}(x, y) \triangleq \mathsf{hasBelief}(y, x) \wedge \mathsf{concerns}(x, y)$
(D21) $\mathsf{believesIn}(x, y) \triangleq \exists z[\mathsf{hasBelief}(x, z) \wedge \mathsf{hasContent}(z, y)]$
(D22) $\mathsf{shareBelief}(x, y, z) \triangleq \mathsf{believesIn}(x, z) \wedge \mathsf{believesIn}(y, z)$

Self-awareness

(D23) $\mathsf{PlainBelief}(x) \triangleq \mathsf{Belief}(x) \wedge \exists! y \mathsf{indirectRepresents}(x, y)$
(D24) $\mathsf{PlainBelief}(x) \rightarrow [y \triangleq \mathsf{representedby}(x) \equiv \mathsf{indirectRepresents}(x, y)]$
(D25) $\mathsf{PlainBelief}(x) \rightarrow \{\mathsf{SelfAware}(x) \triangleq \mathsf{ThatAgentHasBelief}(\mathsf{representedby}(x)) \wedge \wedge \forall y[\mathsf{hasBelief}(y, x) \rightarrow \mathsf{occursIn}(y, \mathsf{representedby}(x))]\}$

Past, present and future belief

(D26) $\mathsf{PastBelief}(x) \triangleq \mathsf{Belief}(x) \wedge \forall y(\mathsf{indirectRepresents}(x, y) \rightarrow y \Rightarrow x)$.

(D27) $\mathsf{PresentBelief}(x) \triangleq \mathsf{Belief}(x) \wedge \forall y(\mathsf{indirectRepresents}(x,y) \rightarrow \neg x \Rightarrow y \wedge \neg y \Rightarrow x)$.

(D28) $\mathsf{FutureBelief}(x) \triangleq \mathsf{Belief}(x) \wedge \forall y(\mathsf{indirectRepresents}(x,y) \rightarrow x \Rightarrow y)$.

Memory and expectation

(D29) $\mathsf{remembersThat}(x,y) \triangleq \exists z, v\{[\mathsf{hasBelief}(x,z) \wedge \mathsf{indirectRepresents}(z,y) \wedge \mathsf{PastBelief}(z)] \wedge [\mathsf{hasBelief}(x,v) \wedge \mathsf{indirectRepresents}(v,y)] \wedge v \Rightarrow z\}$

(D30) $\mathsf{expectsThat}(x,y) \triangleq \exists z[\mathsf{hasBelief}(x,z) \wedge \mathsf{indirectRepresents}(z,y) \wedge \mathsf{FutureBelief}(z)]$

Storage

(A18) $\mathsf{isStoredIn}(x,y) \rightarrow \mathsf{Belief}(x) \wedge [\mathsf{Endurant}(y) \vee \mathsf{Perdurant}(y)]$

(A19) $\mathsf{isStoredIn}(x,y) \rightarrow \mathsf{isStoredAt}(x,y,\mathsf{span}_{\mathsf{sim}}(y))$.

(A20) $\mathsf{isStoredIn}(x,y) \rightarrow x \neq y$.

(D31) $\mathsf{isStoredAt}(x,y,z) \triangleq \mathsf{isStoredIn}(x,y) \wedge \mathsf{TimeThing}(z) \wedge \wedge [\mathsf{Endurant}(y) \rightarrow \mathsf{life}(y) \circ z] \wedge [\mathsf{Perdurant}(y) \rightarrow y \prec z]$.

(D32) $\mathsf{BeliefStorage}(x) \triangleq \exists y \mathsf{isStoredIn}(y,x)$.

(D33) $\mathsf{StoredBelief}(x) \triangleq \exists y \mathsf{isStoredIn}(x,y)$

Ternary expansions of binary relations

(D34) $\mathsf{assertsAt}(x,y,z) \triangleq \mathsf{asserts}(x,y) \wedge \mathsf{TimeThing}(z) \wedge y \prec z$

(D35) $\mathsf{rejectsAt}(x,y,z) \triangleq \mathsf{rejects}(x,y) \wedge \mathsf{TimeThing}(z) \wedge y \prec z$

(D36) $\mathsf{hasBeliefAt}(x,y,z) \triangleq \mathsf{hasBelief}(x,y) \wedge \mathsf{TimeThing}(z) \wedge y \prec z$

Support

(A21) $\mathsf{supports}(x,y) \rightarrow \mathsf{Perdurant}(x) \wedge \mathsf{Belief}(y)$.

(A22) $\mathsf{supports}(x,y) \wedge \mathsf{Belief}(x) \rightarrow \exists z[\mathsf{hasBelief}(z,x) \wedge \mathsf{hasBelief}(z,y)]$.

(A23) $\mathsf{supports}(x,y) \wedge \neg\exists z[\mathsf{supports}(x,z) \wedge \mathsf{supports}(z,y)] \rightarrow \mathsf{span}(x) \circ \mathsf{span}(y)$.

(A24) $\neg\mathsf{supports}(x,x)$.

(A25) $\mathsf{Belief}(x) \rightarrow [\mathsf{supports}(x,y) \wedge \mathsf{supports}(y,z) \rightarrow \mathsf{supports}(x,z)]$.

Other taxonomical relations

(A26) $\mathsf{Agent}(x) \rightarrow \mathsf{Endurant}(x)$.

(A27) $\mathsf{ThatAgentHasBelief}(x) \rightarrow \mathsf{Situation}(x)$.

(A28) $\mathsf{TranspBeliefStorage}(x) \rightarrow \mathsf{BeliefStorage}(x)$.

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