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Formal Ontology and Principles of GOL

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Formal Ontology and Principles of GOL

Barbara Heller *Heinrich Herre*

Abstract. The *General Ontological Language* (GOL) is a formal framework for representing and building ontologies. The purpose of GOL is to provide a system of top-level ontologies which can be used as a basis for constructing domain-specific ontologies.

The present paper gives an overview about the basic categories and the principles of GOL. GOL is part of the work of the *Ontologies in Medicine* (Onto-Med) research group at the University of Leipzig, a collaborative research effort of the *Institute for Medical Informatics, Statistics and Epidemiology* (IMISE) and the *Institute for Computer Science* (IfI). It represents work in progress toward a proposal for an integrated family of top-level ontologies and will be applied to several fields of medicine, in particular to the field of *Clinical Trials*.

1 Introduction

In recent years research in ontology has become increasingly widespread in the field of information systems science. Ontologies provide formal specifications and computationally tractable standardized definitions of the terms used to represent knowledge of specific domains in ways designed to enhance communicability with other domains [Gruber, T.R., 1995]. The importance of ontologies has been recognized in fields as diverse as e-commerce, enterprise and information integration, qualitative modeling of physical systems, natural language processing, knowledge engineering, database design, medical information science, geographic information science, and intelligent information access [Guarino, N., Welty, C., 2002], [Guarino, N., 1998a]. In all of these fields a common ontology is needed in order to provide a unifying framework of communication. The GOL-project was launched in 1999 as a collaborative research effort of the *Institute for Medical Informatics, Statistics and Epidemiology* (IMISE) and the *Institute for Computer Science* (IfI). The project is aimed, on the one hand, at the construction of an ontological language powerful enough to serve as a formal framework for building models and representing complex structures of the world, and, on the other hand, at the development and implementation of domain-specific ontologies in several fields, especially medical science. [1]

The term *Formal Ontology* has its origin in philosophy but here we use it in a special sense to designate a research area in theoretical computer science which is aimed at the systematic elaboration of formalized axiomatic theories of forms and modes of being, and at the development of formal specification tools and methods to support the modeling of the complex structures of the world. Ontologies have different levels of generality, and there is a debate as to whether top-level ontologies, i.e. ontologies of the most general level, are needed in applications. Some researchers believe that top-level ontologies are important; others prefer to focus on domain-specific ontologies which are intuitively adequate for the needs of a particular group or community. We assume as a basic principle of our approach that every domain-specific ontology must use as a framework some upper-level ontology which describes the most general, domain-independent ontological categories of the world [Degen, W., Heller, B.et al., 2002], [Degen, W., Heller, B.et al., 2001a], [Degen, W., Heller, B., et al., 2001b], *General Ontological Language* (GOL) is a formal framework for building and representing ontologies. The purpose of GOL is to provide a system of formalized and axiomatized top-level ontologies which can be used as a basis for the construction of more specific ontologies. GOL consists of a syntax, and an axiomatic core which captures the meaning of the ontological categories introduced. GOL's system of top-level ontologies is called GFO (*General Formal Ontology*) [Degen, W., Heller, B.et al., 2003].

There is a debate as to whether the top-level ontology should be a single, consistent structure or whether it should be considered as a partial ordering of multiple theories, each of which may be inconsistent with theories that are not situated on the same path. The arguments for the multiple-ontology approach are, firstly, that there are numerous, incompatible, and – under certain assumptions – equally acceptable views on how to describe the world. Secondly, it seems to be possible that

[1] The ideas of the GOL-project were the basis for the foundation of the Institute for Formal Ontology and Medical Information Sciences (IFOMIS) at the Medical Faculty of the University of Leipzig in 2002.

the adequateness of a top-level ontology depends on the domain of application. Against a multiple-ontology, one might argue that such systems are more difficult to maintain and to use.

On the multiple-ontology approach, ontologies are distinguished in two ways. On the one hand, ontologies may differ with respect to the basic categories of entities postulated. On the other hand, even if two ontologies use the same basic categories they may differ with respect to the axioms pertaining to these categories. Our general strategy is to admit a restricted version of the lattice approach. We restrict the selection of top-level ontologies with different systems of basic categories but we are more liberal with respect to the systems of axioms admitted within a fixed system of ontological categories. In our opinion, the investigation of a system of axioms with respect to its possible consistent extensions is an important research topic in its own right. In what follows, we will discuss the ontologically basic entities and certain basic relations between them which are presently included in GFO. Furthermore, we discuss the axiomatic method and the principle of ontological reduction.

2 Hierarchy of GOL Categories

The following chapters discuss the top-level categories of GOL [Heller, B., Herre, H., 2003]. Figure 1 shows an excerpt of these categories.

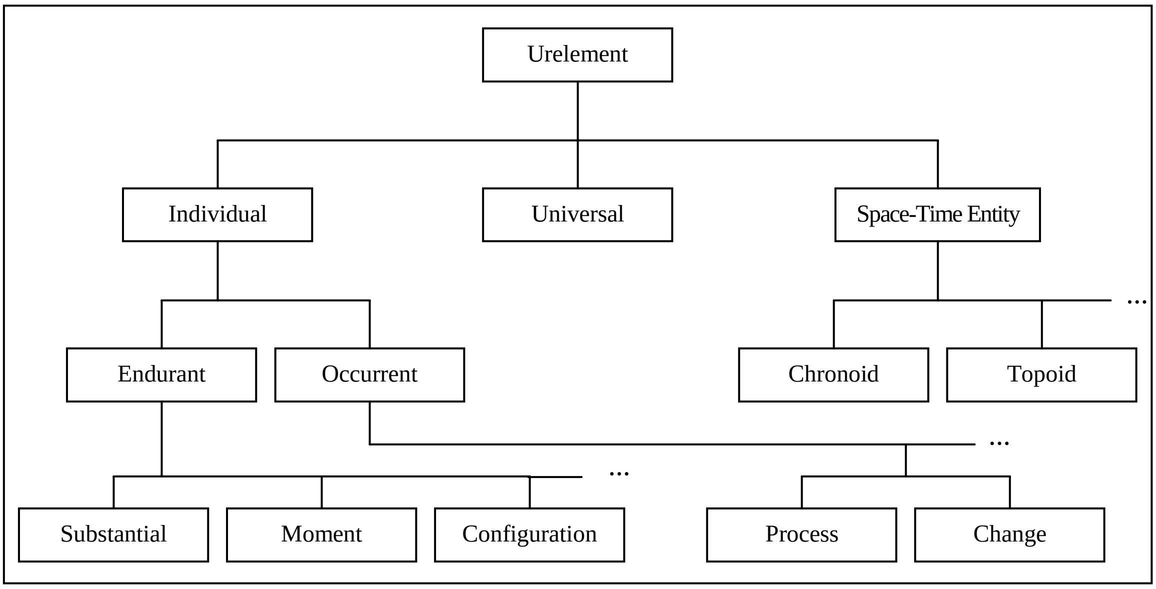

Figure 1: Excerpt of the Hierarchy of GOL Categories

3 Sets, Classes, and Urelements

The main distinction we draw is between *urelements*, *sets* and *classes*. ***Sets*** and ***classes*** constitute a metamathematical superstructure above the other entities of our ontology, but we also consider them to be entities in the world rather than merely formal tools.

At the bottom of the class hierarchy we have the entities of type 0, consisting of sets and urelements; the latter are conceived as the realm of existing things in the world which are not sets or classes.

3.1 Types of Classes

The entities of the world are classified according to *type*. Let *Set* be the class of all sets and *Ur* be the class of all urelements. The class of lists *List* is the smallest class containing the empty list [] and closed with respect to the following condition: if $l_1, \ldots, l_k \in List \cup Set \cup Ur$ then $[l_1, \ldots, l_k] \in List$. Sets, urelements or lists are entities of type 0, and C_0 is the class of all entities of type 0. Let $\tau_1, \ldots, \tau_n$ be types, and $C[\tau_i]$ the class of all classes of type τ_i, respectively. Then $C[\tau_1, \ldots, \tau_n]$ is the class of all classes of relations whose arguments are classes of types $\tau_1, \ldots, \tau_n$, respectively. A class is of finite type if it can be generated by a finite number of iterative steps.

3.2 Urelements

Urelements are entities of type 0 which are not sets. Urelements form an ultimate layer of entities lacking set-theoretical structure in their composition. Neither the membership relation nor the sub-class relation can reveal the internal structure of urelements.

We shall assume the existence of three main categories of urelements, namely *individuals, universals*, and *entities of space and time*. An ***individual*** is a single thing which is in space and time. A ***universal*** is an entity that can be instantiated by a number of different individuals. The individuals covered by a universal are similar in some respect. We assume that the universals exist in the individuals (*in re*) but not independently from them; thus our view is Aristotelian in spirit [Bonitz, H., Rolfes, E., et al., 1995]. On the other hand, humans as cognitive subjects conceive of universals by means of concepts that are in their heads. Hence we hold - in accordance with J. Sowa [Sowa, J., 2001] - that mental notions cannot be eliminated from ontology.

Alongside urelements there is the class of *formal relations*. We assume that formal relations are classes of certain types. Classes may be specified by definitions within a language *L*. We call such classes *L-definable relations* or *L-definable predicates*.

4 Space and Time

There are several basic ontologies about space and time. In the top-level ontology of GOL which is discussed in this paper, *chronoids* and *topoids* represent kinds of urelements. ***Chronoids*** can be understood as connected temporal intervals, and ***topoids*** as spatial regions with a certain mereotopological structure.

Chronoids are not defined as sets of points, but as entities *sui generis*. Every chronoid has boundaries, which are called ***time-boundaries*** and which depend on chronoids, i.e. time-boundaries have no independent existence. Every chronoid has exactly two *extremal* time-boundaries called the *left boundary* and the *right boundary*. The *inner* time-boundaries of a chronoid *c* are the extremal boundaries of proper sub-chronoids of *c*. The class *TE* of temporal entities consists of two disjoint sub-classes: the class *Chr* of chronoids and the class *TB* of time-boundaries. Let *TB(c)* denote the class of all time-boundaries of the chronoid *c*. By *temporal structure* we understand a sub-class of *TE,* i.e. the class *TS* of all temporal structures is defined by $TS = \{ K : K \subseteq TE \}$. We assume that temporal entities are related by certain formal relations, in particular the *part-of relation between chronoids*, the relation of *being a time-boundary of a chronoid*, and the relation of *coincidence between two time-boundaries.*

In this approach to an ontology of time, we adapt the ideas of F. Brentano [Körner, S., Chisholm, R.M., 1976] and R. M. Chisholm [Chisholm, R.M., 1983] and advance and refine the theory of J. Allen [Allen, J., Hayes, P.J., 1989]. Relevant aspects of granularity are considered in Becher [Becher, G., Clerin-Debart, F., et al., 2000].

A class *K* of chronoids is *bounded* if there is a chronoid *c* which contains every member of *K* as a temporal part. We stipulate a *continuity axiom* stating that for every bounded class *K* of chronoids there exists a least unique chronoid *c* containing every member of *K* as a temporal part. A *generalized chronoid* is the mereological sum of a class of chronoids. The *part-of relation* between chronoids is naturally extended to a part-of relation between generalized chronoids.

Our theory of topoids is based on the ideas of F. Brentano [Körner, S., Chisholm, R.M., 1976] and R. M. Chisholm [Chisholm, R.M., 1983] and discusses some attempts of B. Smith [Smith, B., Varzi, A., 2000] to formalize the Brentano-Chisholm approach. An important investigation of boundaries which plays a role in our theory is presented in [Kleinknecht, R., 1992]. Similar to Borgo [Borgo, S., Guarino, N., et al., 1996] we distinguish three levels for the description of spatial entities: the *mereological level* (mereology), the *topological level* (topology), and the *morphological level* (morphology). Topology is concerned with such space-relevant properties and relations as connection, coincidence, contiguity, and continuity. Morphology (also called qualitative geometry) analyses the shape, and the relative size of spatial entities.

5 Endurants and Processes

Individuals are entities which are in space and time, and they can be classified with respect to their relation to space and time. The main distinction in the present paper is between endurants and processes. According to the *endurantist* view there is a categorical distinction between objects and processes, while, according to the *perdurantist* view there are only processes in the most general sense of four-dimensionally extended entities. In the top-level ontology of GOL presented here, we assume the endurantist point of view. However, given our pluralist research commitments, we are also exploring perdurantist versions of top-level ontologies, as well as the “recurrence view of persistence,” a third option between endurance and perdurance [Seibt, J., 2003], [Seibt, J., 2001], [Seibt, J., 1997].

The difference between endurants and processes is their relation to time. An ***endurant*** is an individual which is in time, but of which it makes no sense to say that it has temporal parts or phases. Thus, endurants can be considered as being wholly present at a time-boundary. We use the relation *at(x,y)* with the meaning ‘the endurant *x* exists at time-boundary *y*’. Let *Endur* be the class of all endurants and *TB* the class of all time-boundaries. We stipulate that *at* is a functional relation from *Endur* into *TB*, i.e. we assume the following axioms:

$$\forall x\, (Endur(x) \rightarrow \exists y\, (at(x, y))$$

$$\forall x\, y\, (at(x, y) \rightarrow Endur(x) \wedge TB(y))$$

$$\forall x\, y\, z\, (at(x, y) \wedge at(x, z) \rightarrow y = z)$$

These axioms raise the question of what it means that an endurant persists through time. We pursue an approach which accounts for the persistence of endurants by means of a corresponding universal whose instances are endurants. Such a universal might be called *abstract endurant*.

Processes, on the other hand, have temporal parts and thus cannot be present at a time-boundary. For processes, time *belongs to them* because they *happen in time* and the time of a process is built into it. The relation between processes and temporal structures is determined by the projection function *prt(x,y)* meaning that 'the process *x* is projected onto the chronoid *y*'. Again, *prt(x,y)* is a functional relation from the class *Proc* of all processes into the class *GC* of generalized chronoids, and we say also that *y frames x*. Thus,

$$\forall x\, y\, z\, (prt(x, y) \wedge prt(x, z) \rightarrow y = z).$$

There are yet two other projection relations; one of them projects a process *p* to a temporal part of the framing chronoid of *p*. The relation *pr(p,c,q)* has the meaning: '*p* is a process, *c* is a temporal part of the chronoid which frames *p*, and *q* is the projection from *p* onto *c*'. *q* can also be understood as the restriction of the process *p* to the generalized sub-chronoid *c*. The temporal parts of a process *p* are exactly the projections of *p* onto temporal parts of the framing generalized chronoid of *p*. The other relation projects processes onto time-boundaries; we denote this relation as *prb(p,t,e)* and call the entity *e* onto which *p* is projected the *boundary of p on t*; we introduce the notation *B(p,t)* to denote the endurant *e*. *Boundaries of processes* are dependent entities; they depend on the processes bound by them. A process *p* is not the aggregate of its boundaries; hence, boundaries of a process are different from the entities which are sometimes called *stages* of a process. A process cannot be understood on the basis of its boundaries. We postulate that the projection of a process to a time-boundary is an endurant. An important subcategory of processes is formed by the class of *coherent processes*. A process *p* is coherent if, intuitively, its boundaries (and temporal parts) are ontically connected by the basic relation *ontic(x,y)* (see section **Fehler! Verweisquelle konnte nicht gefunden werden.**) and if there are causal relationships between the temporal parts of *p*.

Processes belong to a category which we call ***occurrents***. The above projection relation *prt(x,y)* will be generalized to arbitrary occurrents *x*; then *y* is – in the most general case – a *temporal structure*. Other types of occurents are *histories, states, changes, locomotions,* and *boundaries of processes.* Boundaries of processes are projections of processes to time-boundaries. Histories are families of endurants which are indexed by time-boundaries.

6 Substances, Substantials and Objects

In our ontology, the notion of substance plays – in relation to time – three different roles. When we speak of *substances* simpliciter, we refer to endurants. *Abstract substances* are specific universals which have substances as instantiations. Finally, by *substance-processes* we refer to processes of a certain type. ***Substances*** are individuals which satisfy the following conditions: they are endurants, they are bearers of properties, they cannot be *carried by* other individuals, and they have a spatial extension. The expressions *x carries y* and *x is carried by y* are technical terms which we define by means of an ontologically basic relation, the *inherence relation* which connects properties to substances. Inherence is a relation between individuals, which implies that inhering properties are themselves individuals. We call such individual properties ***moments*** and assume that they are endurants. Moments include *qualities*, *forms*, *roles*, and the like. Examples of substances are an individual person, a house, the moon, a tennis ball (each considered at a time-boundary).

Every substance *S* has a spatial extension which is called the *extension-space* of *S*, and occupies a certain space region which is called the *spatial location* of *S*. Here we use the formal relation *occ(x,y)* which means ‘the substance *x* occupies the spatial location *y*’. We consider the extension-space of *S* and the spatial location of *S* to be different entities. The extension-space *e* of a substance *S* is an individual property of *S*, similar to, for example, the individual weight or individual form of *S*. The formal relation *exsp(S, e)* means ‘*e* is the extension-space of *S*’, and we assume the following condition on this relation:

$$\forall S\, e\, (exsp(S, e) \wedge exsp(S', e) \rightarrow S = S')$$

We assume that the spatial location occupied by a substance is a topoid which is a 3-dimensional space region. A *physical object* is a substance with unity, and a *closed substance* is a substance whose unity is defined by the strong connectedness of its parts. Substances may have (substantial) boundaries; these are dependent entities which are divided into *surfaces, lines* and *points*.

Substances are related to time by the relation *at(S, t)* having the meaning that ‘*S* exists at time-boundary *t*’. However, there is yet another relation between substance and time. What does it mean that a substance *persists through time* or that a substance *has a lifetime*? For this purpose we introduce the notion of an ***abstract substance***. To clarify the problem let us consider a term *Robert* which denotes a certain individual person *den(Robert)*. What kind of entity is *den(Robert)* ? If we consider it as a substance then there is a time-boundary *t* such that *at(den(Robert),t)*. Because *at(x,y)* is assumed to be a functional relation the entity *den(Robert)* depends on the time-boundary *t*, i.e. we have to add the parameter *t* to *den(Robert)*, which we denote by *den(Robert)(t).* Obviously - with respect to this interpretation - the term *Robert* denotes an endurant for certain time-boundaries. Let *TB(Robert)* be the class of all time-boundaries *t* at which the term *Robert* denotes the endurant *den(Robert)(t)* and let *E(Robert)* = {*den(Robert)(t)*: $t \in$ *TB(Robert) and at(den(Robert)(t),t)*}.

To ensure that all these different endurants *den*(*Robert)(t)* present the *same* Robert we introduce an ontologically basic relation with the meaning that the substances *x* and *y* are *ontically connected*, and a universal *U(Robert)* whose instances are just all elements of the class *E(Robert)*. Then we stipulate that two endurants *e(1)* and *e(2)* are equivalent with respect to *Robert*, i.e. represent the *same Robert*, if *ontic(e(1),e(2))* and both *e(1), e(2)* are instances of *U(Robert).* The relation *ontic(x,y)* should satisfy – at least – the conditions of *spatio-temporal continuity* which are discussed by R. Le Poidevin [Le Poidevin, 2000]. The universal *U(Robert)* is called an abstract substance.

The notion of an abstract substance and its instances is in accordance with the use of object diagrams in conceptual modelling. At any moment of time an object, say *Robert*, has a certain state consisting of the current individual properties inhering in him. Real objects cannot be stored in a computer, hence the real object *Robert* is denoted by an identifier, say by a name *id(Robert).* An object diagram consists of object identifiers, say *id(Robert)*, and a specification of a state which contains the current values of its attributes. The state may change during time; hence *id(Robert)* can be understood as a notation of the universal *U(Robert),* and the states can be interpreted as partial descriptions of the instances of *U(Robert).*

A universal *U* which is an abstract substance should satisfy the following conditions:

(a) every instance of *U* is a substance

(b) there exists a coherent process *p* such that

1) the boundaries of *p* equal the class of instances of *U*

2) every boundary *b* of *p* causally depends on a temporal part *q* of *p* which is bounded by *b* or which meets *b,* i.e. the time-boundary of *b* coincides with the right time-boundary of *q*

3) for every property *F* of a boundary *b* and property *G* of a boundary *c* such that *F* and *G* are different positions along a continuous dimension (e.g. spatial position, form, volume, mass, temperature) all properties between *F* and *G* along that dimension will be instantiated by boundaries between *b* and *c*

We say that an abstract substance persists through its instances. The approach of spatio-temporal continuity may be used to explain how things which have different properties and which exist at different times can nevertheless be the same.

A coherent process *p* satisfying the conditions 2) and 3) is called a ***substance-process*** if every boundary of *p* is a substance. The lifetime *y* of an abstract substance *x,* denoted by *lt(x,y),* is – by definition – the temporal projection of one of its corresponding substance-processes.

We use the term ***substantial*** to cover all individuals which are related to substances, i.e. *objects*, *substantial boundaries*, *masses, spatial parts of substances*, *mereological fusions of substances,* and *agents*.

7 Moments, Qualities and Properties

Moments are endurants; in contrast to substances, moments are entities which can exist only in another entity (in the same way in which, for example, an electrical charge can exist only in some conductor). Moments are property particulars.

Examples

this color, this weight, this temperature, this thought

According to our present ontology, all moments have in common that they are dependent on substances, where the dependency relation is realized by inherence. A more general approach may allow for moments which inhere in moments. In every case we assume an axiom of well-foundedness, i.e. there are only finite chains of the inherence relation.

Some moments are one-place *qualities*, for example color or temperature, but there are also *relational moments* – for example *relators* (discussed in section 10) founded on kisses or on conversations – which are dependent on a plurality of substances. Moments can be classified in *qualities*, *forms, roles*, *relators*, *functions*, *dispositions* and others.

The notion of *moment* – similar to that of *substance* – also plays the role of a universal (*abstract moment*) and of a process of a certain type. Such a *moment-process* is connected to a substance-process by a generalized (processual) inherence relation. Roles are elaborated in Loebe [Loebe, F., 2003]

Example

An individual red inhering in an apple during one hour.

8 Occurrents

To restate, we use the notion of occurrents to cover several categories of individual entities related to processes. ***Occurrents*** comprise *processes, histories, locomotions, changes, boundaries of processes*, and *states*. A *connected process* is an individual which has temporal parts and whose projection onto time is a chronoid (which is a connected time-interval).

A boundary of a process is – in general – the beginning or end of a process. An entity *e* is an inner boundary of a process *p* if *e* is the beginning or end of a temporal part of *p* whose framing chronoid is properly included in the chronoid which frames *p*. Two boundaries of a process *meet* if their associated time-boundaries coincide.

The boundaries of a process are – in general – parts of situations (to be considered in section 9).

A ***change*** is a pair *(e1, e2)* of meeting boundaries where one of them is the ending of a past process and one the beginning of a future process, and *e1*, *e2* instantiate different universals. To be more precise, changes are relative to a basic universal *u* such that the change is exhibited by certain proper sub-universals of *u*.

Example

Consider the universal color as the basic universal and red and blue as discriminating sub-universals. Obviously, a change in color from blue to red can be understood in this framework.

Changes between proper sub-universals are called *extrinsic changes*. In order to understand the essence of a change, the above-mentioned relation of ontological connectedness *ontic(x, y)* must be extended to moments and defined in such a way as to exclude the possibility that an individual color may change to an individual temperature.

We hold that *changes* are entities which depend on processes. Note that in our approach universals persist, and change means instantiation of different proper sub-universals by ontically connected endurants. *Intrinsic changes* cannot be captured by universals. We introduce the process category of *locomotions* covering the most important type of processes based on intrinsic changes.

Example

The movement of a body is an example of an intrinsic change.

A ***state*** is a connected process without any extrinsic or intrinsic changes. Obviously, this is a relative notion, because changes are related to universals. It might be that processes are states with respect to certain universals, but with respect to others they contain changes.

Histories are classes of endurants which are indexed by the time-boundaries at which they exist. We assume that histories *h* may be presented as partial functions from *Endur* into the class *TB(c)* of time-boundaries of a certain chronoid *c*. Let *TB(h)* be the class of time-boundaries which are associated to the history *h.* Then, a history is more precisely specified by a pair *(h, (TB(h), c))* where *c* is a chronoid and *TB(h)* is a sub-class of the boundaries of *c*. Not every history in this very general sense is a reasonable entity, because no connection between the constituents of some histories is postulated.

9 Situoids, Situations, and Configurations

Substances and moments presuppose one another, and both constitute complex units or wholes of which they are aspects. Such integrated wholes of substances and moments are themselves endurants, and we call them ***configurations***. A ***situation*** is a special configuration which can be comprehended as a whole and satisfies certain conditions of unity imposed by the particular universals associated with the situation. Situations present the most complex comprehensible endurants of the world and they have the highest degree of independence among endurants. Our notion of situation takes up situation theory of Barwise and Perry [Barwise, J., Perry, J., 1983] and advances their theory by analysing and describing the ontological structure of situations. Situations might be a suitable semantics for conceptual graphs which were introduced and advanced by J. Sowa [Sowa, J., 2000].

On the other hand, according to the basic assumptions of GOL, endurants have no independent existence; they depend on processes. Since configurations are endurants, they too depend on processes. We call such processes ***configuroids***. They are integrated wholes made up of substance-processes and moment-processes. We claim that substance-processes and moment-processes presuppose each other. Surely a moment-process depends on a substance-process; on the other hand we may assume that a substance-process needs an extension which includes a moment-process.

Finally, there is a category of processes whose boundaries are situations and which satisfy certain principles of coherence and continuity. We call these entities ***situoids***; they are the most complex integrated wholes of the world, and they have the highest degree of independence. As it turns out, each of the entities considered (including processes) is embedded into a corresponding situoid. A situoid is, intuitively, a part of the world that is a coherent and comprehensible whole and does not need other entities in order to exist. Every situoid has a temporal extent and is framed by a topoid.

Example

> An example of a situoid is John's kissing of Mary in a certain environment which contains the substances John and Mary and a relational moment kiss connecting them. Taken in isolation, however, these entities do not yet form a situoid; we have to add a certain environment consisting of further entities and a location to get a comprehensible whole: John and Mary may be sitting on a bench or walking through a park.

The notion of being a coherent and comprehensible whole is formally elucidated in terms of an *association relation* between situoids and certain universals. The relation *ass(s, u)* expresses that 'the universal *u* is associated to the situoid *s*'.

How are situoids related to time and space? Every situoid is framed by a chronoid and a topoid. We make use here of the two relations *chr(s, x)*, and *top(s, z)*, where *x* is the chronoid framing the situoid *s* and *z* is the topoid framing *s*. The topoid framing a situoid is a fiat object (i.e. given by convention); it can be understood – in a sense – as defined by a local coordinate system (also the boundaries of the framing chronoid are conventional, however). Note, that the relation *chr(s, x)* coincides with *prt(s, x)* if the situoid is considered as a process.

Every temporal part of a situoid is itself a situoid. The temporal parts of a situoid *s* are determined by the full projection of *s* onto a part of the framing chronoid *c* of *s*. This full projection relation is denoted by *prf(a, c, b)*, where *a* is a situoid, *c* is a part of the framing chronoid of *a*, and *b* is the situoid which results from this projection. Boundaries (including inner, fiat boundaries) of situoids are projections to time-boundaries. We assume that such projections, denoted by *prb(a, t, b)*, are endurants which are called ***situations***. In every situation there occurs a substance, and we say that an endurant *e* is a constituent of a situation *S* iff there is a time-boundary *t* of *S*, such that the projection of *S* onto *t* is a situation containing *e*. An endurant *e* is a constituent of a situoid *S* if there is a time-boundary *t* such that *e* occurs in the situation determined by *prb(S, t, b)*.

Let *P* be a connected process and *t* a time-boundary of a chronoid *c* which frames *P*, then *B(P, t)* denotes the boundary of *P* at *t.*

Situoids have a rich structure which can be analysed by using some additional concepts. A *substantial layer P* of the situoid *S* is a ‘portion’ of *S* satisfying the following conditions:

- *P* is a connected process
- *P* and *S* are framed by the same chronoid
- every boundary of *P* contains a substance
- For all time-boundaries *p, q* of *S*, it holds that if *a* is a substance which is contained in *B(P, p)* and *b* is a substance which is contained in *B(S, q), p is before q,* and *a, b* are ontically connected, i.e. *ontic(a, b)*, then *b* is contained in *B(P, q)* as well.

The notion of the *moment-layer* of a situoid is introduced in similar fashion.

A ***configuroid*** *c* in the situoid *S* is defined as the projection of a substantial layer of *S* onto a chronoid which is a part of the time-frame of *S*. In particular, every substantial layer of *S* is itself a configuroid of *S*. Obviously, every configuroid is a connected process. Not every connected process is a configuroid of a situoid, however, because not every process satisfies the substantiality condition.

We postulate as a basic axiom that every occurrent is – roughly speaking – a ‘portion’ of a situoid, and we say that every occurrent is embedded in a situoid. Furthermore, we defend the position that processes should be analyzed and classified in the framework of situoids. Also, situoids may be used as ontological entities representing contexts. A rigorous typology of processes in the framework of situoids is an important future project. Occurrents may be classified with respect to different dimensions, among which we mention the temporal structure and the granularity of an occurrent.

10 Relations

Relations are entities which glue together the things of the real world. Every relation has a number of *relata* or *arguments* which are connected or related by it. The number of arguments a relation connects is called its *arity*. We admit the possibility of anadic relations, i.e. relations with an indefinite number of arguments. Relations can also be classified according to the types of their relata. There are relations between sets, between individuals, and between universals, but there are also relations relating entities of different categories, for example urelements and sets, or sets and universals.

We divide relations into two classes, called material and formal, respectively. The relata of a *material relation* are mediated by individuals which are called relators. ***Relators*** are individuals with the power of connecting entities. One has to distinguish between the relator itself and its foundation.

Examples

> Kisses, contracts and conversations are individuals generating relators which connect individual persons. A conversation is the foundation for the relator of being connected by a conversation.

A *formal relation* is a relation which holds between two or more entities directly – without any further intervening individual.

Examples

> larger than, part-of, different from, dependent on

10.1 Holding Relation and Facts

One important formal relation is called the ***holding relation***. If r is a relator connecting the entities $a_1, ..., a_n$, $n \geq 1$, then we say that $r, a_1, ..., a_n$ (in this order) stand in the holding relation with one another, symbolized by $h(r, a_1, ..., a_n)$. The fact that h holds directly prevents the regression which would arise if a new material relation were needed to tie h to $r, a_1, ..., a_n$, and so on.

If r connects the entities $a_1, ..., a_n$, then this yields a new individual which is denoted by $\langle r\!: a_1, ..., a_n \rangle$. Individuals of this latter sort are called ***material facts.*** Note that the a_i are not necessarily individuals. We assume that at least one of the arguments of a material fact is an individual endurant. Material facts are in every case constituents of situations, and situations are collections of facts into wholes.

Example

> The fact 'Anne is speaking about anatomy' can be represented as the fact ⟨ speaking, Anne, anatomy ⟩, where the event speaking (in the sense of an individual speech act) founds a relator which connects Anne with the universal anatomy.

Complementary to the material facts there are *factual processes* $\langle r\!: a_1, ..., a_n \rangle$ where r is a relator process. Such a factual process $\langle r\!: a_1, ..., a_n \rangle$ has a duration which depends on the lifetime of the relator-process r. We write $\langle r\!: a_1, ..., a_n ; i \rangle$ if i is a chronoid which is a part of the lifetime of r, i.e. this fact exists at least during the interval i.

10.2 Relator Universals and Relation Universals

A ***relator universal*** is a universal whose instances are relators. For every relator universal R there exists a set of facts, denoted by *facts(R)*, which is defined by the instances of R and their corresponding arguments. We assume the axiom that for every relator universal R there exists a *factual universal* $\boldsymbol{F}=\boldsymbol{F}(R)$ whose extension equals the set *facts(R)*.

Example

Take the relator universal U whose instances are individual kisses. Then we may form a factual universal $\boldsymbol{F}(U)$ having the meaning 'A person a kisses a person b' whose instances are all facts of the form $\langle\, k\!: a, b \,\rangle$, where k is a relator founded by an individual kiss and a, b are individual persons (k, a and b, here, are variable terms).

The factual universal $\boldsymbol{F}(R)$ is the basis for a material relation $R(\boldsymbol{F})$ whose instances are lists of entities. $R(\boldsymbol{F})$ is considered as a universal of a special type which is called ***relation universal*** (or simply relation).

Example (ctd.)

In our example $R(\boldsymbol{F})$ is defined as follows.

$$[a, b] : R(\boldsymbol{F}) \leftrightarrow \exists k\,(k :: U \wedge \langle\, k, a, b \,\rangle :: \boldsymbol{F}(R))$$

There are sub-universals $\boldsymbol{F}(U, J, M)$ of $\boldsymbol{F}(U)$, say, with the meaning 'John kisses Mary', whose instances are all facts of the form $\langle\, k\!: J, M \,\rangle$ where J, M are the individuals John and Mary. Natural language sentences of the form 'A man kisses a woman' or 'John kisses Mary' can be interpreted as referring to factual universals.

10.3 Formal Relations

A ***formal relation*** is a relation which holds between two or more entities directly – without any further intervening individual. We consider them as classes whose instances are lists. Note that the components of these lists are not necessarily individuals. If R is a formal relation and $[a, b] : R$ then $\langle\, R\!: a, b \,\rangle$ is called a formal fact.

10.4 Basic Relations

We can distinguish the following basic ontological relations, which are needed to glue together the entities introduced above.

Basic Relation	Denotation(s)	Brief Description
Membership	$x \in y$	set *y* contains *x* as an element
Part-of	*part(x, y)* *tpart(x, y)* *spart(x, y)* *cpart(x, y)* *part-eq(x, y)* *tpart-eq(x, y)* *spart-eq(x, y)* *cpart-eq(x, y)*	*x* is part of *y* *x* is temporal part of *y* *x* is spatial part of *y* *x* is constituent-part of *y (y contains x)* the reflexive version of *part* the reflexive version of *tpart* the reflexive version of *spart* the reflexive version of *cpart*
Inherence	*i(x, y)*	moment *x* inheres in substance *y*
Relativized Part-of	*part(x, y, u)*	*u* is a universal and *x* is a part of *y* relative to *u*
Instantiation	$x :: u$ $x : y$ $x ::_i y$	individual *x* instantiates universal *u* list x instantiates relation y higher order instantiation, $i \geq 1$
Participation	*partic(x, y)*	*x* participates in process *y*, where *x* is a substance, an abstract substance or a substance process
Framing	*chr(x, y)* *chr(x)* *top(x, y)* *top(x)*	situoid *x* is framed by chronoid *y* denotes the chronoid framing *x* situoid *x* is framed by topoid *y* denotes the topoid framing *x*
Location and Extension Space	*occ(x, y)* *exsp(x, y)*	substance *x* occupies topoid *y* substance *x* has extension space *y*
Association	*ass(x, y)*	situoid *x* is associated with universal *y*
Ontical Connectedness	*ontic(x, y)*	*x* and *y* are ontically connected
Denotation	*den(x, y)*	symbol *x* denotes entity *y*

Table 1 : Overview of Basic Relations of GOL

The ***membership relation*** $\in$ is the basic relation of set theory. $x \in y$ implies that either *x* and *y* are both sets, or that *x* is an urelement and *y* is a set. For every set *x* there is a least set *y* = *trans(x)* satisfying the conditions $x \subseteq y$, and for every $z \in y$, $z \subseteq y$. The set $\{a \mid a$ is an urelement and $a \in trans(y)\}$ is denoted by *supp(x)* and is called *support of x*. A set *x* is said to be *pure* if *supp(x)* = ∅. There is a kind of membership relation between classes. Assume *X* is a class of type $[\tau_1, \ldots, \tau_n]$, and $X(Y_1, \ldots, Y_n)$. We say that *X* holds of $Y_1, \ldots, Y_n$, and sometimes write $Y_1, \ldots, Y_n \in X$. Obviously, if $X(Y_1, \ldots, Y_n)$ then this implies that the classes $Y_1, \ldots, Y_n$ are of types $\tau_1, \ldots, \tau_n$, respectively.

Part-of is a basic relation between certain kinds of entities, denoted by *part(x, y)*. We assume that a set has no parts. Hence, only urelements can have parts. We introduce several part-relations: *tpart(x, y)*:= '*x* is temporal part of *y*'; *spart(x, y)* := '*x* is spatial part of *y*'; *cpart(x, y)* := '*x* is constituent-part of y'. The reflexive versions of these relations are denoted by *tpart-eq(x, y), spart-eq(x, y), cpart-eq(x, y).*

The *containment* relation *cpart* holds between the constituents of a situation and the situation itself. The constituents of a situation *s* include, among other entities, the pertinent substances and the moments inhering in them. Also, facts and configurations are constituents of situations. Note, that not every part of a constituent of a situation is contained in it.

The phrase ***inherence*** *in a subject* can be understood as the translation of the Latin expression *in subjecto esse*, as opposed to *de subjecto dici*, which may be translated as *predicated of a subject*. The inherence relation *i* – sometimes called ontic predication – glues moments to the substances which are their bearers.

Example

Inherence glues your smile to your face, or the charge in a conductor to the conductor itself.

The ***ternary part-whole*** relation *part(x, y, u)* has the meaning '*u* is a universal and *x* is a part of *y* relative to *u*'. Briefly, if *x is a u-part of y* in this sense, then *x* and *y* are parts of instances of the universal *u* and *part*(*x, y)*. More is involved, however, since again the notions of granularity and point of view are at issue. We propose the following axiom: for every universal *u* there are universals $u_1, ..., u_n$ such that *part(x, y, u)* implies that *x, y* are instances of one of the u_i's and every instance of one of the u_i's is part of an instance of *u*.

Example

Consider the following example, taken from the domain of biology. Let u_T be the biological universal whose instances are those organisms called trees. Then: $part(x, y, u_T)$ describes the part-whole relation which imposes upon the parts it recognizes at a certain granularity, the granularity of whole trees. A biologist is interested in describing the structure of trees only in relation to parts of a certain minimal size. Thus she is not interested in atoms or molecules. There is a finite number of universals $\{u_1, ..., u_n\}$ by which the biologically relevant parts of trees are demarcated. All such parts of trees are either instances of some u_i, $1 \leq i \leq k$, or they can be decomposed into a finite number of parts, each of which satisfies this condition. Examples of relevant u_i would be branch of a tree, leaf of a tree, trunk of a tree, root of a tree, and so on.

The symbol :: denotes the ***instantiation*** relation. Its first argument is an individual, and its second a universal. If $x :: u$, then *u* is a certain time- and space-independent pattern of features and *x* is an individual in which this pattern of features is realized. The symbol : denotes *relation instantiation*. Its first argument is a list of entities, and its second a relation universal. Note that the components of the list are not necessarily individuals. *Higher order instantiation* is denoted by $::_i$, where $i \geq 1$.

Participation relates substances to processes. *partic(x, y)* has the meaning: 'the substance *x* participates in the process *y*'. Depending on the notion of substance there are three definitions of this relation. If *x* is an endurant, then *partic(x, y)* means that there is a boundary of the substantial closure *z* of *y* which has *x* as a constituent part. If *x* is an abstract substance then *partic(x, y)* means that every boundary of the substantial closure *z* of *y* contains an instance of *x*. If *x* is a substance-process, then *partic(x, y)* means that *x* is a substantial layer of the substantial closure *z* of *y*. The notion of substantial closure is at first defined for endurants *e.* The substantial closure of an endurant *e* is the collection of all substances carrying moments which occur in *e*. The substantial closure may be generalized to processes, details are presented in [Heller, B., Herre, H., 2003].

Every situoid, for example the fall of a stone in a certain environment, consumes an amount of time and a certain space. The binary relation of ***framing*** glues chronoids or topoids to situoids and is denoted by *chr(s, c)* and *top(s, t).* We presume that every situoid is framed by a chronoid and a topoid. The relation *chr(x, y) (top(x, y))* is to be read: 'the situoid *x* is framed by the chronoid (topoid) *y*'. Obviously, *chr(x, y), top(x, y)* are formal relations (no further entity is needed to link the chronoid with the situoid it frames). Let *s* be a situoid, then *chr(s)* denotes the chronoid framing *s*; *top(s),* similarly, denotes the topoid framing *s*.

The binary relation *occ(x, y)* describes a fundamental relation between substances and topoids. *occ(x, y)* can be read 'the substance *x* ***occupies*** the topoid *y*' (roughly, *x* is located in *y*). *exsp(x,y)* has the meaning: 'the substance *x* has the ***extension space*** *y*'.

The relation *ass(s,u)* has the meaning: '*s* is a situoid and *u* is a universal ***associated*** with *s*'. These universals determine which material relations and kinds of individuals occur as constituents within a given situoid and thus which granularities and points of view it presupposes.

Example

> A situoid *s* may be a part of the world capturing the life of a tree in a certain environment. If a tree is considered as an organism then the universals associated with *s* determine the point of view of a biologist and the associated granularity of included individuals (branches are included, electrons are not).

Individuals are connected by spatio-temporal and causal relationships. The relation *ontic(x, y)* connects the entities *x, y* by a system of such relationships. It is assumed that *x, y* are processes or endurants. The relation ***ontic*** should satisfy at least the conditions which are formulated in [Le Poidevin, R., 2000].

11 The Axiomatic-Deductive Method

Common-sense knowledge and reasoning is at the center of AI because human cognitive agents always start out from a situation in which the information available has a common-sense character. Although mathematical models of the traditional kind are contained, at least partially, in common sense, it seems to be impossible to reduce common sense to the usual mathematical theories which utilize only set-theoretical tools. This is for reasons of principle: set theory captures only a part of the ontology of the world. In spite of this ontological restriction of mathematics, its formal methods represent an ideal model for any science, in particular for the evolving science of axiomatic formal ontology. In what follows, the terms *formal theory* and *formal knowledge base* are used as synonyms. A formal theory is a set of formalized propositions. The axiomatic method contains several principles used for the development of formal knowledge bases and reasoning systems aiming at the foundation, systematization and formalization of a field of knowledge associated with a part or dimension of reality.

The axiomatic method deals with the specification of concepts and is motivated, as we conceive it, by the following considerations. A formal knowledge base uses, on the one hand, primitive notions, defined notions, and definitions, and includes on the other hand axioms, theorems, and uses proofs. It would be ideal if one were able to explain explicitly the meaning of every notion occurring in whatever the relevant domain is, and to justify each proposition in succession. When one tries to explain the meaning of a term, however, one necessarily uses other expressions, and in turn one has to explain these expressions. If, now, one wishes to avoid entering into a vicious circle, then one has to resort to yet further terms, and so on. We have thus the beginning of a process which can never be brought to an end. The situation is quite analogous for the justification of the statements asserted within a knowledge base, for in order to establish the validity of a statement, it is necessary to refer back to other statements, which leads again to an infinite regress.

The axiomatic-deductive method contains the principles necessary to solve this problem. When we set out to assemble in a systematic way the knowledge we have in regard to a given field of knowledge, then we can distinguish, first of all, a certain small set of concepts in this field that seem to be understandable of themselves. We call the expressions in this set *primitive* or *basic*, and we employ them without formally explaining their meanings by explicit definitions.

Examples are the concepts of *identity* or of *part*. At the same time we adopt the principle of not employing any other term taken from the field under consideration unless its meaning has first been determined with the help of the basic terms and of expressions whose meanings have been previously explained. The sentence which determines the meaning of a term in this way is called an *explicit definition*.

How, then, can the basic notions be described; how can their meaning be characterized? Given the basic terms, we may construct more complex sentences which may be understood as descriptions of certain formal interrelations between them. Some of these statements are chosen as *axioms*; we accept them as true without in any way establishing their validity by means of a proof. By accepting such sentences as axioms we assert that the interrelations described are considered to be valid and at the same time we define the given notions in a certain sense implicitly, i.e. the meaning of the basic terms is to some extent captured and constrained by the axioms. On the other hand, we agree to accept any other statement as true only if we have succeeded in establishing its validity from the chosen axioms via admissible deductions. Statements established in this way are called *proved statements* or *theorems*.

The method of establishing a body of knowledge relating to a given field in accordance with these principles is called the axiomatic-deductive method. An axiomatic-deductive system is a set of propositions in which each proposition is either one of the set of initial propositions or it is a proposition which is generated from the set of initial propositions by deduction.

A knowledge base usually contains different (sometimes hidden) levels of generality. Thus, a knowledge base will make use of a basic logic which provides the principles of deduction. The basic logic includes all the deductive principles of the system. None of the latter is specific to the system itself and the deductive power of the system is achieved only with the addition of the system's axioms.

The axioms can be classified into three main groups, one group consisting of those axioms required for basic logic. These logical axioms are true in every possible world. General ontological axioms are concerned with axioms about the ontologically basic relations. They describe those laws of the ontologically basic entities and relations which are true in every part of the world in which those entities exist and those relations obtain. General ontological axioms present what is sometimes called the top-level ontology. Finally, domain-specific axioms are tailored to a given concrete area of the world. In summary, we distinguish *the logical level*, *the general ontological level*, and *the domain-specific level*.

Axiomatic theories have to be studied with respect to meta-theoretical properties. It is important that the basic axioms are consistent, because domain-specific axioms are built on them. With respect to a system of basic categories and basic relations $\mathbf{\Sigma = \Sigma(}\text{Cat}\mathbf{)} \cup \mathbf{\Sigma(}\text{Rel}\mathbf{)}$ axiomatic theories $\mathbf{T(\Sigma)}$ have to be formulated. Such formalized theories $\mathbf{T(\Sigma)}$ should be proved to be consistent. Other important meta-theoretical properties are completeness and the classification of complete extensions.

12 Ontological Reductions

An *ontological reduction* of an expression *E* is a definition of *E* by another expression *F* which is considered as *ontologically founded*. Hence, ontological reductions may be understood as translations *tr* of sets of expressions from a source language *L* to sets of expressions of the target language *TL* whose expressions are assumed to be ontologically founded.

To make the idea of an ontological reduction more precise, we introduce at first several notions. By a *constant* we understand a symbolic structure which can be used to denote other entities. We assume a denotation relation *den(s, a)* having the meaning: '*s* is a symbolic structure which denotes the entity *a*'. In the sequel we use the notion of an *ontological signature* **Σ = (***IndConst, UnivConst, TempConst, SpaceConst, ClassConst, RelConst*); here, *IndConst* is a set of individual constants, *UnivConst* a set of constants denoting universals. *TempConst* and *SpaceConst* are constants denoting entities of space and time, respectively; the constants from *ClassConst* are used to denote classes, and, finally, the constants from *RelConst* denote relations. Let *BasicRel* be a set of symbols denoting the basic relations described in section 10.4. On the set $\mathbf{\Gamma} = \mathbf{\Sigma} \cup$ *BasicRel* we may define several languages, the most simplest of which is the language of predicate logic PC(**Γ**)**.** In what follows we assume the language PC(**Γ**) to be the target language of the ontological reductions. Ontological reductions, then, are translations *tr* of sets of expressions from a source language *L* to sets of expressions of the target language PC(**Γ**)**.** A formula from PC(**Γ**) is considered as ontologically founded because it is built up from atomic formulas from PC(**Γ)** whose ontological meaning is inherited from the underlying top-level ontology of GOL.

In modeling a concrete domain ***D***, we may use as a formal source language one of the well-known knowledge representation languages, e.g. KIF [Genesereth, M.R., Fikes, E.R., 1992], Description Logics, Conceptual Graphs, Semantical Networks, but also modelling languages like UML (Unified Modeling Language) or OPM (Object Process Methodology). For our purposes we consider first order predicate logic over a certain classical signature **Δ =** *(Const, Rel)*, denoted by FOL(**Δ),** as the source language**.** Then, *Const* is a set of symbolic structures denoting elements of a universe, and the symbols from *Rel* denote (extensional) relations, i.e. sets of n-tuples of elements of a certain universe. The result of modeling the knowledge of ***D*** is a certain set KB(***D***) of formulas within the language FOL(Δ). The ontological reduction of KB(***D***) consists of constructing a set Ax(KB) of formulas of the target language PC(**Γ)** such that Ax(KB) captures more precisely the ontological content of KB(***D***); we call Ax(KB) an *ontological reduction* (or *ontological foundation*) of KB(***D***).

13 Summary and Future Research

One of the aims of the *Onto-Med* group is the application of the GOL-ontology in the field of medical science, among other domains [Heller, B., Herre, H., et al., 2003a], [Heller, B., Herre, H., et al., 2003b]. GOL is intended to provide a formal framework for building, representing and evaluating domain-specific ontologies. One of the computer-based applications is the development and implementation of software tools to support the standardization and reusability of terms in the field of clinical trials, e.g. the *Onto-Builder* [Heller, B., Kuehn, K., et al., 2003].

The basic categories and basic relations of GOL will be characterized – in the spririt of the axiomatic-deductive method – by a family Ax(GFO) of axiomatic systems. The aim of the ontological investigations is the selection, description and analysis of ontologically basic categories which will found a top-level system called GFO (General Formal Ontology). The present task is that of defining and specifying theoretically those most basic types of entities and relations which constitute the world. We admit a restricted version of the lattice approach, i.e. we limit the selection of top-level ontologies with different basic systems but we are more liberal with respect to the sets of axioms allowed within a fixed system of categories. Here, we are testing several philosophical theories with respect to their usability in conceptual modeling. Of particular interest is the study of the relations between GOL to other knowledge representation formalisms, in particular to SnePS, Shapiro [Shapiro, S.C., et al., 2002], [Shapiro, S.C., 2000].

By adding new categories and relations from the field of medicine, GOL will be extended in the future to GOL-Med and GOL-ClinTrials. The axioms and categories of GOL-ClinTrials, for example, refer to the class of all clinical trials. Another area of application is the ontological foundation of conceptual modeling in particular Unified Modeling Language (UML) [Booch, G., Rumbach, J., et al., 1999]. The first examples of applying GOL to UML (Unified Modeling Language) are demonstrated in [Guizzardi, G. Herre, H. et al., 2002a], [Guizzardi, G. Herre, H. et al., 2002b].

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