Ontology of Time and Situoids in Medical Conceptual Modeling

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Abstract. Time, events, changes, and processes play a major role in medical conceptual modeling. Representation of time-structures and reasoning about time-oriented medical data are important theoretical and practical research areas. We assume that a formal representation of temporal knowledge must use as a framework some top-level ontology which describes the most general categories of temporal entities. In the current paper we discuss an ontology of time and situoids which is part of the top-level ontology GFO (General Formal Ontology) being developed by the Onto-Med research group [1]. The expressive power of GFO and its usability in conceptual modeling is tested by Onto-Med by carrying out a number of case studies in several fields of medicine and biomedicine. In the present paper we report on results of reconstructing the temporal-abstraction ontology presented by Y. Shahar [2] within GFO. In carrying out this investigation it turns out that a number of aspects in [2] needs further clarification and foundation.

1 Introduction

Time, events, changes, and processes play a major role in medical conceptual modeling. Representation of time-structures and reasoning about time-oriented medical data are important theoretical and practical research areas. We assume that a formal representation of temporal knowledge must use as a framework some top-level ontology which describes the most general categories of temporal entities. There is a growing body of work of ontologies in the sense of [3], i.e. as sharable conceptual specifications and its applications in several domains [4, 5]. These developments are closely related to conceptual modeling [6, 7] and may benefit from an interdisciplinary approach [8, 9, 10]. Testing and proving the usability of top-level ontologies in conceptual modeling of real domains is an important step in establishing them as an integral part of *Ontological Engineering*.

† The Onto-Med research group mourns the death of its founder Barbara Heller. She died after a long illness during the work on this paper.

The current paper reports on research which is aimed at testing the top level ontology GFO in several fields of medicine and biomedicine. We discuss an ontology of time and of situoids which is part of the top-level ontology GFO (General Formal Ontology) [11]. GFO will be included in an integrated library *LibOnt* of top-level ontologies which is intended to cover all of its basic types, among them several 4D and 3D+T ontologies [12, 13]. The main purpose of *LibOnt* is to provide an integrated system of axiomatized top-level ontologies which can be used as a framework for building and representing specific ontologies pertaining to some concrete domain. The time ontology of GFO is inspired by ideas of F. Brentano [14]; situoids resemble what is sometimes called histories, and GFO-situations are ontological versions of situations in the sense of Barwise and Perry [15, 16].

The paper is structured as follows. In section 2 we present the main ideas of GFO's ontology of time, and in sections 3, 4, and 5 those categories of GFO are outlined which are relevant for the conceptual framework of the present paper. Finally, in section 6 it is shown how the temporal-abstraction ontology of Y. Shahar [2] may be reconstructed in the framework of GFO. This reconstruction is conducted by principles of ontological mappings as expounded in [17]. It turns out that a number of aspects in [2] needs further clarification and foundation.

2 Brentano Time

The time ontology expounded in this section was inspired by the ideas of Brentano [14]. We assume that time is continuous and endorse a modified and refined version of the interval-based approach of time. Following this approach, chronoids – the intervals of the classical approach – 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. Besides chronoids we introduce time-regions which are mereological sums of chronoids. We assume that time entities are related by certain formal relations, in particular the part-of relation between chronoids and time regions, denoted by $tpart(x, y)$, the relations of being a (left, right) time-boundary of a chronoid, $lb(x, y)$ and $rb(x, y)$, and the relation of coincidence between two time-boundaries which is denoted by $tcoinc(x, y)$.

Dealing with boundaries and the relation of coincidence is especially useful if two processes are to be modeled as "meeting" (in the sense of Allen's relation "meets"). In our opinion there are at least three conditions that a suitable model must fulfill: (a) There are two processes following one another immediately, i.e., without any gaps (b) There is a point in time where the first process ends and (c) there is a point in time where the second process starts. If, as is common practice, intervals of real numbers are used to model time intervals with reals as time points, the desired conditions cannot be satisfied. In contrast, the approach presented in GFO allows for two chronoids following immediately after one another *and* having proper starting- and ending-"points" by letting their boundaries coincide. Thus (a), (b), and (c) are preserved. An axiomatization $B(Time)$ of this ontology of time – based on the relations $Chron(x)$, $tpart(x, y)$, $tcoinc(x, y)$, $tb(x, y)$ – is presented in

[18]. In [19] it is shown that the theory *B*(*Time*) and the theory in [20] have the same expressive power with respect to the interpretability relation, i.e. each of these theories is interpretable in the other.

3 Processes and Endurants

Material individuals are entities which are in space and time, and there is the well-known philosophical distinction between endurants and processes which is determined by their relation to time. An endurant is an object which is in time, but of which it makes no sense to say that it has temporal parts or phases; hence it is wholly present at every time-boundary of its existence and it persists through time. In our approach we make a more precise distinction between *presentials* and *processes* because it turns out that the philosophical notion of endurant combines two contradictory aspects. Based on a different distinction, there are entities which characterize others: *properties*. Furthermore, with presentials, processes and properties at hand, several "derived" categories can be discussed, among them more complex entities like *situoids* and *situations*.

Persistence is accounted for by two distinct categories: presentials and persistants. A *presential* exists wholly at a time-boundary and the relation $at(x, y)$ has the meaning "the presential x exists at time-boundary y". We assume that "at" is a functional relation, i.e. the following axiom is stipulated: $at(x, y) \wedge at(x, z) \rightarrow y = z$. This axiom raises the question of what is meant by the claim that an endurant (seemingly a philosophical analogue of our presentials) persists through time. We pursue an approach which accounts for persistence by means of a suitable universal whose instances are presentials. Such universals are called *persistants*. These do not change and they can be used to explain how presentials which have different properties at different times can nevertheless be the same.

Processes have temporal parts and develop over time, unfold in time, or perdure, and thus cannot be present at a time-boundary. Time belongs to them, because they happen in time and the time of a process is built into it. The relation between a process and a chronoid is determined by the projection function $prt(x, y)$ stating that "the process x is projected onto a chronoid y". Again we stipulate that $prt(x, y)$ is a functional relation. Yet there are two more projection relations: the relation $prt(p, c, q)$ is to be understood as follows: p is a process, c is a temporal part of the chronoid which frames p, and q is that part of p which results from the projection of p onto c. The temporal parts of a process p are exactly the projections of p onto temporal parts of the framing chronoid of p. The third relation projects processes onto time-boundaries; we denote this relation by $prb(p, t, e)$ and call the entity e, which is the result of this projection, the boundary of p at t. We postulate that the projection of a process to a time-boundary is a presential.

4 Relations, Facts, and Propositions

Relations are entities which glue together the things of the real world whereas *facts* are constituted by several related entities together with their relation. Every relation has a finite number of *relata* or *arguments* which are connected or related. Let us first consider the connection between a relation and its arguments (referring to facts on an intuitive basis). At this point, a particular fact seems to involve a relation and particular arguments. "John's being a patient of hospital A" is one fact, whereas the same "John's being a patient of hospital B" amounts to a different fact. Different particular arguments are involved in these facts, but the same relationship appears, namely "being a patient of". For this reason we assume that relations exhibit a universal character. In contrast to the extensional definition of relations in a mathematical reading, we do not consider the mere collection of the arguments with respect to a single fact as an instance of a relation. For example, the pair (John, hospital A) is not an instance of the relation "being a patient of". Instead, we assume that there are concrete entities with the power of connecting other entities (of any kind). These connecting entities are called *relators*, and they are the instances of relations. Relators themselves offer an "internal" structure which allows one to distinguish the differences in the way the arguments of a relation participate in a fact. Returning to the example, John is involved differently in the fact of being a patient of hospital A as compared to the hospital B. Exchanging John and the hospital would result in a strange sentence like "the hospital A is a patient of John". We say that John and the hospital play different roles in that relationship. Formally, this leads us to the introduction of a further type of entity: *relational roles*. A relator can be decomposed into relational roles, such that each role is a mediator between exactly one argument and the relator [21].

The simplest combinations of relators and relata are *facts*. Facts are considered as parts of the world, as entities sui generis, for example "John's being an instance of the universal Human" or "the book B's localization next to the book C" refer to facts. Furthermore, facts are frequently discussed in connection with other abstract notions like propositions (cf. [22]). However, propositions make claims which may be true or false. Therefore, truth-values are assigned to propositions and they can be logically combined. Neither is the case for facts. In analogy to atomic formulas in logic, a special type of propositions is introduced which reflects a single fact and which is called an *infon*, similar to the notion of infons in [23, 16]. We write $\langle\langle R: a_1, \ldots, a_n\rangle\rangle$ for the fact that a relator, i.e., an instance, of the relation R connects the entities $a_1, \ldots, a_n$. Preliminarily, we use $\langle R: a_1, \ldots, a_n\rangle$ for the corresponding infon about the same situation. Infons are the simplest type of *elementary propositions.*

To make the difference between facts and infons clear let us consider the above example. The fact of "John's being a patient of hospital A" is denoted by the symbolic structure ⟨⟨Patient-of: John, A⟩⟩. In contrast, the symbolic structure ⟨Patient-of: John, A⟩ denotes an infon with the meaning "John is a patient of the hospital A." The difference is that the latter is a claim about the world which has an assigned truth-value and which can be logically combined with other propositions. The former simply denotes a part of the world. A deeper elaboration of the interconnections of facts, factual representations, infons, elementary propositions and propositions in general and agents in terms of an analysis of the denotation relation is to be developed in the future.

5 Situations and Situoids

Physical structures, qualities, and relators presuppose one another, and constitute complex units or wholes. The simplest units of this kind are, obviously, facts. A general configuration is an aggregate of facts. We consider a collection of presential (concrete) facts which exist at the same time-boundary. Such collections may be considered themselves as presentials, 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 certain universals, relations and categories associated with the situation. According to the basic assumptions of GFO, presentials have no independent existence, they depend on processes. Since configurations are presentials, too, they depend on processes. We call such processes *configuroids* [11].

Finally, there is a category of processes whose boundaries are situations and which satisfy certain principles of coherence, comprehensibility, 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 considered entities (including processes) is embedded into a suitable 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. The notion of being a coherent and comprehensible whole may be formally elucidated in terms of an *association relation* between situoids and certain categories. The notion of a *comprehensible whole* is captured in [24] by using terms of Gestalt Theorie. Furthermore, propositions are interpreted in situoids; to make this precise a basic relation |= between situoids and propositions is introduced, and "*S* |= *p*" has the meaning that the proposition *p* is satisfied (or true) in the situoid *S*. An outline of this approach is presented in [24].

6 Temporal Abstraction Ontology in the GFO-framework

The reconstruction of ontologies in the GFO-framework is guided by the principle of ontological mappings as expounded in [17]. Ontological mappings are semantic translations which are based on top-level ontologies.

We give an overview about some aspects of the abstraction ontology in [2], which is denoted in the sequel by *AbstrOnt*, and then we sketch how these concepts/entities may be re-interpreted (reconstructed) in the framework of the time and situoid ontology of GFO. The current paper does not contain a complete analysis of all aspects of the ontology *AbstrOnt*. A full analysis of *AbstrOnt* as of other ontologies is work in progress and will be published elsewhere.

According to the GFO-approach we assume that a particular medical domain *D* is modeled by a class *Situ*(*D*) of situoids which capture all relevant entities, relations, facts, temporal and spatial extensions of those coherent parts of the world which are related to *D*. We may describe *Situ*(*D*) by a certain formal description *Desc*(*D*) which can be understood as a GFO-category (a class in the modeling practice) whose instances contain – among others – the elements of *Situ*(*D*). The pair (*Situ*(*D*), *Desc*(*D*)) is a kind of reference frame which is assumed to be fixed in all further considerations. Furthermore, we assume the existence of a formal language which allows to formulate the descriptions *Desc*(*D*) and a set *Prop*(*D*) of the relevant propositions pertaining to the class *Sit*(*D*), and hence to the domain *D*.

6.1 Time Stamps

Time stamps, according to *AbstrOnt*, are introduced as structures which are mapped into an integer amount of an element of a set of predefined temporal granularity units. Furthermore, a zero-point time stamp must exist, with relationship to which the time stamps are measured by using the units. This zero-point should be grounded in each domain to different absolute, real world time points. The reconstruction within GFO is carried out within a situoid *S* from *Situ*(*D*). Let *time*(*S*) = *T* be the chronoid onto which *S* is projected (which frames *S*). A granularity system *GS*(*T*) of *T* is a set of chronoids being temporal parts of *T*, one element *c*(0) of *GS*(*T*) is fixed as a "zero point chronoid". Furthermore, we may assume a measure-function *m* which attaches to any chronoid *c* (which is a part of *T*) a positive real number capturing the duration of *c*. The set *TS* of time stamps can be understood as a set of symbolic structures which are interpreted by elements from *GS*(*T*). All of this information can be captured in a system *TimeStamp*(*S*) = (*S*, *TS*, *f*, *GS*(*T*), *c*(0), *m*) which is called time-stamp structure. Furthermore, we may assume a uniform way to associate to any situoid *S* from *Situ*(*D*) a system *TimeStamp*(*S*). The other conditions described in *AbstrOnt* may be defined by adding further constraints to *TimeStamp*(*S*).

6.2 Time Interval

A *time interval I* in *AbstrOnt* is an ordered pair of time stamps representing the interval's endpoints. Time points are represented as zero-length intervals. In the GFO-framework there are no chronoids (intervals) of zero length but for any chronoid there exist exactly two time-boundaries. Hence time intervals are modeled by chronoids, points by time-boundaries. Since time stamps are data structures (say symbolic structures), the definition in *AbstrOnt* allows attaching time points to time stamps. In the GFO-framework it is sufficient to consider the case of associating chronoids to time stamps. Every chronoid defines two unique time-boundaries, hence, there is no need to define an interval by a pair of time stamps. In [2] it is stated that propositions are interpreted over time intervals. This seems to have no clear meaning. In our opinion propositions are interpreted in situoids (or configuroids) which themselves have a temporal extension. That means, the notion of "being interpreted over an interval" may be derived from the more fundamental notion of "being interpreted in a situoid/configuroid".

6.3 Interpretation Context

An *interpretation context*, according to *AbstrOnt*, is a proposition that, intuitively, represents a state of affairs. An example is the "drug insulin has an effect on blood glucose during this interval". And it is stated: "When interpreted over a time interval it can change the interpretation of one or more parameters within the scope of that time interval."

One problem with these definitions is that they need a sufficiently general and precise notion of "proposition" and of what it means "to be interpreted over an interval". In the GFO-framework a situoid semantics is under development which introduces so-called elementary propositions on which general propositions are built upon. In this framework the proposition "the drug has an effect on blood glucose during this interval" is an example of an elementary proposition. Propositions are interpreted, can be satisfied, in situoids *S* which contain as part a certain system of facts, called configuroid. Hence, the notion of context should include: a definition of the set *Prop*(*D*) of (relevant) propositions pertaining to the domain *D*, and a precise relation of truth (satisfiability) of the propositions with respect to the systems in *Situoids*(*D*). The pair (*Prop*(*D*), *Situoids*(*D*)) is said to be a semantic context. A step forward in carrying out such a program is presented in [24]. In *AbstrOnt* there is, furthermore, introduced the notion of a subcontext relation which is a binary relation between contexts. The subcontext relation is not clearly expounded.

6.4 Context Interval

A *context interval* is a structure <*p*, *I*> consisting of an interpretation context *p* and a temporal interval *I*. Context intervals represent an interpretation context over a time interval; within the scope of that interval, it can change the interpretation of one or more parameters. *P* is a proposition and one has to clarify of what it means that *p* is interpreted over an interval *I*. The GFO-framework provides concepts and methods to make all these notions clear.

6.5 Event Proposition

An *event proposition* represents, according to *AbstrOnt*, the occurrence of an external volitional action or process such as "administering a drug". Events have a series of event attributes $a(i)$, and each attribute $a(i)$ must be mapped to an attribute value. There exists an is-a hierarchy of event schemas (or event types). Event schemas have a list of attributes $a(i)$ where each attribute has a domain of possible values $v(i)$. An event proposition is an event schema in which each attribute $a(i)$ is mapped to some value $v(i)$ belonging to the set $V(i)$. A part-of relation is defined over a set of event schemas. If the pair $(e(i), e(j))$ belongs to the part-of relation, then the event $e(i)$ can be a subevent of the event schema $e(j)$ (example: a clinical protocol event can have several parts, all of them are medication events). An event interval is a structure <*e*, *I*> consisting of an event proposition *e* and a time interval *I*. Intuitively, *e* is an event proposition (with a list of attribute-value pairs), and *I* is as time interval over which the event proposition *e* is interpreted. The time interval represents the duration of the event.

In the GFO-framework we get the following interpretation. A volitional action or process *proc* is a individual which belongs to a certain situoid *S*. As part of reality the entity *proc* may be rather complex; surely, *proc* has a temporal extension and participants which are involved in *proc*, e.g. physicians, patients, and other entities. For the purpose of modeling we need only selected, relevant information about *proc*. This selected information is presented by a list of attributes $a(i)$ and values $v(i)$, and this list, denoted by – say – *expr*(*proc*), is considered as an event proposition. In GFO *expr*(*proc*) is not a proposition (because it has no truth-value), but a symbolic representation of partial information about *proc*. A *event schema* can be understood, in the framework of GFO, as a category (the GFO-term for class/universal) whose instances are event expressions of the kind *expr*(*proc*). Event schemas themselves are, hence, also presented by certain symbolic expressions *schemexpr*. Attributes are interpreted in GFO as property-universals whose instances have no independent existence but are associated to – are dependent on – individual entities as, e. g. objects or processes. GFO provides a framework for analyzing all possible properties of processes. In many cases so-called properties of processes are not genuine process-properties but only properties of certain presentials which are derived from processes by projecting them onto time boundaries. Since GFO provides several formal languages to represent information about real world entities, there might be information, specified in one of these languages, which cannot be represented as a list of attribute-value pairs. This implies that GFO provides means for expression of information which exceeds the possibilities of the *AbstrOnt*-framework. Furthermore, the part-of relation mentioned above is not clearly described. Part-of is defined for event-schema, i.e. in the GFO-framework, between categories (universals/classes). But what, exactly, is the meaning of that a schema expression $schemexpr_1$ is a part of the schema expression $schemexpr_2$? In GFO there is the following interpretation: every instance e_1 of $schemexpr_1$, which refers to a real world event $event_1$, is a part of an instance e_2 of $schemexpr_1$ referring to a real world event $event_2$. The final understanding of this part-of relation should be reduced to the understanding of what it means that the $event_1$ is a part of the $event_2$. The GFO-framework allows to analyze and describe several kinds of part-of relations, among them – the most natural – that $event_1$ is a temporal part of $event_2$.

6.6 Event Interval

An *event interval*, according to *AbstrOnt*, is a structure <*e*, *I*> consisting of an event proposition *e* and a time interval *I*. Intuitively, *e* is an event proposition (with a list of attribute-value pairs) and *I* is a time interval over which the event proposition *e* is interpreted. The time interval represents the duration of the event. In GFO this can be interpreted as follows, which shows that in the above description there is a hidden subtle ambiguity. Let *e* be the expression *expr*(*proc*) which refers to a real world process *proc*. If *e* is interpreted over the interval *I* then the natural meaning is that the associated process *proc* has the uniquely determined temporal extension *I* (as a chronoid). But then it is not reasonable to say that *proc* is interpreted over the duration of *I*. The other meaning is that *proc* has a temporal extension (a framing chronoid *I*) which has a certain duration *d*. But in this case the expression *e* does not refer to a unique single process *proc* but to any process satisfying the attribute-value pairs and having a temporal extension of duration *d*. In this case the expression *e* does not represent a unique process but exhibits a GFO-category (a universal/class) whose instances are individual real world processes. This consideration uncovers that we may find the same ambiguity for the notion of an event proposition as introduced above. The GFO- framework is sufficiently expressive to find the correct disambiguations of the above notions.

The remaining notions of *AbstrOnt*, like parameter schema, parameter interval, abstraction functions, abstraction, abstraction goal and others are analysed in the extended paper.

7 Conclusion

The current paper presents some results of a case study which is carried out to apply and test the GFO-framework to existing ontologies, in particular to the ontology *AbstrOnt* [2]. We hope that already our preliminary results

a) indicate that GFO is an expressive ontology which allows for the reconstruction of other ontologies like *AbstrOnt*,
b) show that several concepts and notions in *AbstrOnt* are ambiguous and are not sufficiently founded,
c) demonstrate that GFO can be used to disambiguate several definitions in *AbstrOnt* and to elaborate a better foundation for existing ontologies.

The future research of the Onto-Med group includes the reconstruction of other ontologies of the medical and biomedical domain within the framework of GFO.

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