General Formal Ontology (GFO)
A Foundational Ontology for Conceptual Modelling

Heinrich Herre
Research Department Ontologies in Medicine und Life Scienes
IMISE University Leipzig

1. Introduction

Research in ontology has in recent years become widespread in the field of information systems, in distinct areas of sciences, in business, in economy, and in industry. The importance of ontologies is increasingly recognized in fields diverse as in e-commerce, semantic web, enterprise, information integration, qualitative modelling of physical systems, natural language processing, knowledge engineering, and databases. Ontologies provide formal specifications and harmonized definitions of concepts used to represent knowledge of specific domains. An ontology supplies a unifying framework for communication and establishes the basis of the knowledge about a specific domain.

The term *ontology* has two meanings, it denotes, on the one hand, a research area, on the other hand, a system of organized knowledge. A system of knowledge may exhibit various degrees of formality; in the strongest sense it is an axiomatized and formally represented theory. which is denoted throughout this paper by the term *axiomatized ontology*.

We use the term *formal ontology* to name an area of research which is becoming a science similar as formal or mathematical logic. *Formal ontology* is an evolving science which is concerned with the systematic development of axiomatic theories describing forms, modes, and views of being of the world at different levels of abstraction and granularity. Formal ontology combines the methods of mathematical logic with principles of philosophy, but also with the methods of artificial intelligence and linguistics. At the most general level of abstraction, formal ontology is concerned with those categories that apply to every area of the world.

The application of formal ontology to domains at different levels of generality yields knowledge systems which are called, according to the level of abstraction, *Top Level Ontologies* or *Foundational Ontologies*, *Core Domain* or *Domain Ontologies*. Top level or foundational ontologies apply to every area of the world, in contrast to the various *Generic*, *Domain Core* or *Domain Ontologies*, which are associated to more restricted fields of interest. A foundational ontology can serve as a unifying framework for representation and integration of knowledge and may support the communication and harmonisation of conceptual systems.

The current paper presents an overview about the current stage of the foundational ontology GFO[1]. GFO (General Formal Ontology) is a component of ISFO (Integrated System of Foundational Ontologies), and ISFO is intended to be a part of an Integrated Framework for Development and Application of Ontologies (IFDAO) whose predecessor

---

[1] A more detailed exposition of GFO is presented in [Her 2006b].

was the GOL project that was launched in 1999 at the University of Leipzig. GFO is a foundational ontology integrating objects and processes. It is being developed, after a deep revision of the original GOL-project, by the research group Onto-Med (Ontologies in Medicine)[2] at the University of Leipzig. GFO exhibits a three-layered meta-ontological architecture consisting of an abstract top-level, an abstract core level, and a basic level. Further unique selling propositions of GFO are the following:

- Includes objects (3D objects) as well as processes (4D entities) and both are integrated into one coherent framework,
- GFO presents a multi-categorial approach by admitting universals, concepts, and symbol structures and their interrelations,
- includes levels of reality,
- is designed to support interoperability by principles of ontological mapping and reduction,
- it is s presented by a set of formal axioms which might be added by meta-logical links to domain specific ontologies,[3]
- GFO is intended to be the basis for a novel theory of ontological modelling which combines declarative specifications with algorithmic procedures,
- it contains several novel ontological modules, in particular, a module for functions and a module for roles, and
- GFO is designed for applications, firstly in medical, biological, and biomedical areas, but also in the fields of economics and sociology.

We envision GFO to be a foundational ontology which is expressive enough to contain several other foundational ontologies as special cases. But, GFO is not intended to be the ultimate result of a foundational ontology; one may doubt whether a final and uniquely determined top level ontology can ever be achieved. For this reason, GFO is merely a component of the evolutionary system ISFO, which leaves room for modifications, revisions, adaptations that are triggered by the historical state of our knowledge, and the applications in nature and society.

Foundational ontologies may differ with respect to their basic categories and relations (i.e., their vocabulary), with respect to the set of axioms formulated about their vocabulary or with respect to both the basic vocabulary and the axioms. If two ontologies have the same basic categories and relations, then the question arises which axioms should be included in the axiomatization. Here, we admit various different axiomatizations. The investigation of a system of axioms with respect to its possible consistent extensions and of other meta-logical properties is an interesting research topic of its own. It is our opinion that different views of the world can be sustained, though over time we expect that the number will be reduced to a few such views, mainly based on utility. According to our pluralistic approach ISFO is intended to be an integrated and evolutionary system of foundational ontologies. These ontologies are compared and interrelated using methods of translation and interpretation.

---

[2] http://www.onto-med.de

[3] The development of axiomatic systems for GFO is work in progress and will be published as Part II of the General Formal Ontology.

Domain-specific ontologies exhibit a much richer diversity than foundational ontologies. The notion of a domain specific ontology admits various interpretations. From a practical point of view, domain specific ontologies include, among others, terminologies, glossaries, thesauri and nomenclatures which are associated to specific domains. A terminology, for example, is a list of terms referring to concepts in a particular domain. Such a terminology is usually a result of consensus and agreement among the domain's experts. Hence, a terminology tends to converge to a unified and common basic vocabulary which is influenced and determined by utility and usage. A domain specific ontology in the stronger sense, i.e. understood as an axiomatized ontology, normally is based on a terminology. There are usually various axiomatized ontologies that may be built on a terminology[4] .

Several groups are tackling the development of top-level ontologies or certain aspects of top-level ontologies. The following approaches are fairly developed, and they are used, in part, as a source for our considerations. Nicola Guarino, an early proponent of the use of ontologies in the field of knowledge-based systems, is involved in the construction of DOLCE [Mas 2003]. Further, two other ontologies[5] are presented in [Mas 2003], following the idea of an ontology library in the WonderWeb project. DOLCE itself is presented as a hierarchy of categories and several relationships between them. The description is fairly extensive and an axiomatization is contained therein as well.

John Sowa in [Sow 2000] presents and extensively discusses a top-level ontology in the form of a polytree within a comprehensive book on knowledge representation issues, i.e., it is not a pure work introducing a top-level ontology. Sowa's ontology is based on ideas of the philosopher *Charles Sanders Peirce*. The Standard Upper Merged Ontology (SUMO) is an effort of the P1600.1 Standard Upper Ontology Working Group at IEEE [SOU 2004]. Several draft proposals have been made, one of the more developed suggestions of which is SUMO. SUMO adopts a polytree architecture of categories, in which there are cases of multiple super-categories, for example, Group is a subcategory of both Collection and Agent. Its development may have contributed to the multiplicative approach, as SUMO originates from a merge of several top-level ontologies (cf. [Nil 2001]), including one of Russell and Norvig [Rus 1995], one of John Sowa [Sow 2000], as well as several others. Another relevant ontology is a 4-dimensional ontology developed by M .West [Wes 1993]. Roberto Poli contributes an additional important account of ontology in the field of computer science [Pol 2001a]. In particular, Poli presents a theory of ontological levels (cf [Pol 2002 b],[Pol 2002] that is acknowledged and adopted in GFO. A further important contribution to top-level ontologies is the approach by Giancarlo Guizzardi and Gerd Wagner [Gui 2004a, 2004b] which is aimed

---

[4] These axiomatized ontologies of a domain are influenced by the assumed views and the Classification principles from which different conceptualizations can be derived. Furthermore, there is no sufficiently founded criterion to establish the equivalence of two ontologies. Hence,the orthogonality criterion, as expounded in [Smi 2007], must be rejected.

[5] One of these ontologies, called BFO (Basic Formal Ontology)[Gre 2003], has its source in the GOL- project which started in 1999 as a common project of the department of formal concepts (Institute for Computer Science) and the Institute for Medical Informatics of the University of Leipzig. GOL was the scientific basis for a research programme related to a Wolfgang-Paul Prize advertised in 2001. Since June 2002 GFO and BFO were independently developed.

at the development of a Unified Foundational Ontology (UFO). This ontology integrates several aspects of DOLCE and GFO.

The current paper is an exposition of main ideas of GFO and draws on the report [Her 2006]. In section 2 the basic assumptions and logical methods are expounded. Section 3 describes the meta-ontological architecture of GFO. Section 4 is devoted to a detailed exposition of the basic categories of individuals; this section presents the core of the current paper. In section 5 the basic relations of GFO are outlined. In section 6 a central idea of GFO is exposed: the object-process integration. Section 7 presents some ideas on principles of ontology development and ontological modelling.

2. Basic Assumptions and Logical Methods

In this section we summarize the basic assumptions and methods from philosophy and logic.

2.1 Philosophical Assumptions

Ontology is based on a particular view at the world: ontology asks what an entity is, what the essence of it is, and which mode of existence it has. We use the term “entity” for everything that exists where existence is understood in the broadest sense. In [Ing 1964] a classification of modes of existence is discussed that is useful for a deeper understanding of entities of several kinds. According to [Ing 1964] there are –roughly- the following modes of being: absolute, ideal, real, and intentional entities. This classification can be to some extent related to Gracia’s approach [Gra 1999] and to the levels of reality in the spirit of N.Hartmann [Har 1964] and R. Poli [Pol 2001]. We hold a realist view at the world and assume the existence of a real world which is independent from the subject. Appearances of this world are considered as actual realizations of the world’s dispositions within a subject. There is a mutual relation between the subject and object in the sense of [Blo 1985] which exhibits the most important and complex inter-relationship between man and nature.

Categories are entities that are expressed by predicative terms of a formal or natural language that can be predicated of other entities. Predicative terms are linguistic expressions T which state conditions Cond(T) to be satisfied by an entity. Categories are what predicative terms express, not the predicative terms themselves [Gra 1999]. There is a close relation between categories and language, hence the analysis of the notion of a category cannot be separated from the investigation of language. The predicative term T, the expressed category *C,* the conditions Cond(T) specified by T, and the satisfying entity e are mediated by two relations, *expr(T,C)* and *sat(Cond(T),e).* We stipulate that a category *C* is predicated of an entity e if an only if e satisfies the conditions that are associated to *C*. Summarizing the inter-relations between categories, conditions, and predicative terms we hold that an entity e instantiates the category C with respect to T if and only if *expr(T,C)* and e satisfies the conditions Cond(T) associated to the term T.

Individuals are entities which cannot be instantiated, hence, they cannot be predicated of other entities. There is a distinction between the property of being instantiable and of having instances. Individuals cannot be instantiated, on the other hand, there are categories without any instance. The expression “round square”, for example, presents a category without any instance. Such categories are called empty, and they are an extensional sub-category of every category. For a category C we introduce the *transitive closure* of C, denoted by trcl(C); this is the smallest set containing C as an element and which is closed with respect to the following condition: if $D \in$ trcl(C) and e::D then $e \in$ trcl(C). The *individual base* of a category C, denoted by IndBase(C), is the set of all individuals which are elements of the transitive closure trcl(C).

2.2 Concepts, Symbols, and Universals

We distinguish at least three kinds of categories: universals, concepts, and symbol structures. We hold that any reasonable foundational ontology must include these three types of categories.[6] *Universals* are constituents of the real world, they are associated to invariants of the spatio-temporal real world, they are something abstract that is in the things. Concepts are categories that are expressed by linguistic expressions and which are represented as meanings in someone’s mind. Concepts are a result of common intentionality which is based on communication and society [Sea 1995].[7] *Symbols* are signs or texts that can be instantiated by tokens. There is a close relation between these three kinds of categories: a universal is captured by a concept which is individually grasped by a mental representation, and the concept and its representation is denoted by a symbol structure being an expression of a language. Texts and symbolic structures may be communicated by their instances that a physical tokens.[8]

Sets play a particular role in GFO. We hold that a set cannot be predicated of its members, but there are, of course, specifications of sets expressing categories which can be predicated of sets. Concepts have a complex structure that consists of interrelated particular parts, which are called conceptual constituents. For concepts we introduce a basic relation catp(x,y) having the meaning that x is a categorial part of the concept. In the simplest case a concept can be represented as a set or aggregate of predicates or properties.

2.3 The Axiomatic Method

The axiomatic method comprises 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. If knowledge of a

---

[6] Our approach to categories is inspired by the ideas of Jorge Gracia [Gra 1999]. We consider Gracia’s approach as an important contribution to the philosophical foundation of conceptual modelling.

[7] The mental representation of a concept allows us to understand a linguistic expression. Concepts are outside of individual minds, but they are anchored, on the one hand, in individual minds by the concepts’ mental representation, and on the other hand, in society as a result of communication and usage of language.

[8] The ability to generate and use symbol structures seems to be the most basic assumption for complex communication. Here, an important aspect of the ability of humans to construct symbolic structures and to identify tokens as instances of symbols. The ultimate transmission of information must use spatio-temporal tokens as bearers.

certain domain is to be assembled in a systematic way, one can distinguish 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 use them without formally explaining their meanings through explicit definitions. Examples for primitive concepts are *identity* and *part*. New terms can be introduced by explicit definitions based on the primitive notions.

Given the basic terms, we can construct more complex sentences that can be understood as descriptions of certain formal interrelations between them. Some of these statements are chosen as *axioms*; we accept them as true without establishing their validity by means of a proof. The truth of axioms of an empirical theory may be supported by experimental data. By accepting such sentences as axioms, we assert that the interrelations described are considered to be valid in some domain and at the same time we define the given notions implicitly, i.e., the meaning of the basic terms is captured and constrained by the axioms.

Axiomatic theories should be studied with respect to meta-theoretical properties. It is important that the axioms of a foundational ontology are consistent, because domain-specific and generic axioms will be built on them.[9] Other important meta-theoretical properties are completeness, and the classification of complete extensions. If several theories are considered, their inter-relationships must be studied which will lead to questions regarding the interpretation of one theory in another, and identifying the more comprehensive or expressive theory.

2.4 Representation of Ontologies

An ontology must be represented and specified by expressions of a language. We assume that the general terms in these expressions denote concepts. An ontology *O* - understood as a formal knowledge base – is given by an explicit specification of a conceptualization [Gru 1993]. This specification must be expressed in a formal language, and there is a variety of formal specification systems. A main distinction is drawn between logical languages with model-theoretic semantics and formalisms using graph-theoretic notations.

2.5 Types of Realism

The type of realism on which GFO is based is called *integrative realism*; it fundamentally differs from the realism expounded in a number of papers by Barry Smith [Smi 2004], [Smi 2005],[Smi 2006a], [Smi 2006b]. This section expounds a critical comparative analysis between GFO-realism and *Smithian realism.*

Smith's position can be specified by the following conditions and assumptions, presented in [Smi 2004], [Smi 2006a], [Smi 2006b]:

---

[9] If the theory is sufficiently expressive then an absolute consistency proof, based on finitary methods, is impossible. Hence, consistency proofs have a relative character; they are based on the method of formally reducing the considered theory to another already established theory whose consistency has a higher degree of evidence.

- Universals have an observer-independent objective existence; they are invariants of reality.
- Bad ontologies are those whose general terms lack a relation to corresponding universals in reality, and thereby also to corresponding instances.
- Good ontologies are representations of reality. A good ontology must be based on universals instead of concepts.

Unfortunately, there is a gap and a fundamental obscurity pertaining to condition 3. No definition for *reality representation* is provided. This fundamental gap can never be closed without the use of concepts, i.e. there is no representation of reality without concepts.

To close this gap, let us construct an ontology Ont that may represent a part D of reality. Assume that there are universals U(1),…,U(k) in D having an observer-independent objective existence; they are related, by assumption, to certain invariants in D, say Inv(1),…,Inv(k), of reality. Consider, as an example, the universal *Ape,* denoted by A. There are individual instances a(1),…,a(m) of A being individual apes. The universal A may be analysed and discussed, and information about A may be communicated. Hence, this universal is used and included in natural language and must be represented by a term, denoted by a word w(A). w(A) is a string in a language (spoken or written string), but it is more than a senseless string, because it denotes something. If a person uses w(A), then this word has a meaning, and understanding a word implies to have access to its meaning. Let m(w) be the meaning of the word.

To clarify, the entities w(A), A and m(w(A)) exist and are pair-wise distinct. Obviously, w(A) exists, and A exists by assumption. The existence of m(w(A)) is demonstrated by the process of understanding. The perception of w(A)[10] is immediately connected to a meaning, and this meaning must be an entity of the mind. The meaning of w(A) allows for understanding the spoken announcement '*Yesterday an ape escaped from the Zoo*', independent from the actuality of this event. Since the universal A is separate and outside the mind, and the meaning m(w(A)) exists within the mind, it may be concluded that A and m(w(A)) are distinct. It is also clear that w(A) and m(w(A)) are distinct, because w(A) is merely a string, and one could, through a thought experiment, replace w(A) with any other string S by stipulating that S is connected to m(w(A)); this connection can be established by a learning process. Then, the string S plays the role of a designation as well as w(A). Now, we must clarify a further phenomenon: We must distinguish different (individual) meanings depending on different recipients; this can be illustrated and explained by a relation *intension*(*p,m(w*)) that is interpreted as: the person p grasps the meaning m(w(A)) in the course of perceiving the word w(A). Hence, the meanings are dependent on the individual subjects, and we use the expression m(p,w(A)) to denote the meaning of the word w(A) with respect to the person p. Hence, distinct recipients of a word possess distinct meanings. On the other hand, we assume that any speaker of this language who perceives the word w(A) relates it to the same meaning. But

---

[10] One must distinguish between symbols and tokens. Only tokens, being physical instances of symbols, can be perceived and transmitted through space and time.

these meanings must be different entities and we must clarify how the equivalence between different individual meanings is determined and how it is to be understood. In achieving this equivalence we need a further step and a new construct, the *common intentionality* which is the result of communication and society [Sea 1995]. The common intentionality constitutes an agreement between the subjects about the equivalence of the different individual meanings m(p,w(A)). This agreement forms the basis for a concept conc(A), which is an abstract, atemporal entity. In general, common intentionality establishes an equivalence relation between different individual meanings. Concepts are abstract entities which are associated to these equivalence classes, and conversely, individual meanings can be understood as mental representations of concepts.[11] The concept conc(A) is based on the one hand on individual meanings, and on the other hand on common intentionality which is related to the social stratum. Hence, a concept participates in the mental as well as in the social stratum of the world. Obviously, conc(A) is distinct from m(p,w(A), w(A), and A.

In sum, the nodes in an ontology are labeled by terms that denote concepts. Some of these concepts, notably natural concepts, are related to invariants of material reality. Concepts are represented in individual minds and are founded in society. The same is true for individuals to which individual concepts correspond. The interrelations between universals, concepts, symbols and society are realized by various relations, including the relation of correspondence (between concepts and universals, and individual concepts and real individuals), the relation of representation (between concept and individual mind), the relation of foundedness (between concept and society), and the instantiation relation. We summarize that the restricted view of Smithian realism cannot be an ontological-philosophical foundation for the field of conceptual modeling and, in particular, for computer-science ontologies.

2.6 Levels of Reality

We assume that the world is organized into strata, and that these strata are classified and separated into layers. We use the term *level* to denote both strata and layers. GFO distinguishes, according to Poli [Pol 2001], at least three ontological strata of the world: the material, the mental-psychological, and the social stratum. Every entity of the world participates in certain strata and levels. We take the position that the levels are characterized by integrated systems of categories. Hence, a level is specified by a meta-level category whose instances are categories of certain kinds. Every level includes individuals too; these belong to the individual base of those categories specifying the level.

Among these levels specific forms of categorial and existential dependencies hold. For example, a mental entity requires an animate material object as its existential bearer. These levels are needed to describe adequately the entities of the world. Another problem is how the levels within of a single entity are organized, and how these levels are

---

[11] The study of mental representations of concepts is an important topic of cognitive psychology and cognitive linguistics. The theory of prototypes is an influential approach in this area of research [Rsc 1975].

connected and how they are separated. It turns out that the separation cannot be precisely defined, because the phenomenal world that can be immediately perceived is already cognitively influenced. We assume that there is a physical level, denoted by PhysW, that is completely independent from the subject. Then there is the phenomenal world, denoted by PhenW, which can be immediately experienced by perception.

Perception can be understood as realizing an immediate connection between the subject and the material, subject-independent, objective world. Natural concepts, based on perception, are the most primitive ones and additional concepts are constructed from them. The construction of more complex systems of subject-object interrelation [12], as, for example theories, increase the distance between the subject and the perceived material world; on the other hand, they provide a deeper understanding of the world. One may think of several ontological layers which connect the subject with the independent reality. We consider the layer of perception as the mediator between the subject and reality and stipulate that the phenomenal world belongs to the material level.

3. Meta-Ontological Architecture of GFO

GFO has a three-layered meta-ontological architecture comprised of (1) a basic level consisting of all relevant GFO-categories and relations, (2) a meta-level, called abstract core level containing meta-categories over the basic level, for example the meta-category of all categories, and finally (3) an abstract top-level including *set* and *item* as the only meta-meta-categories.

The notion of a meta-category is a generalization of the notion of a meta-set or a meta-class in the set-theoretical sense. Let X be a set of entities, then every category C having exactly the entities of X as its instances is called a *categorial abstraction* of X. Usually, there can be several distinct categorial abstractions over the same set of entities. If a set X of entities is specified by a condition C(x), then the expression C(x) expresses a category which can be understood as a categorial abstraction of X.

A *categorial similarity abstraction* of X specifies properties that are common to all members of the set X. The specification of such categorical similarity abstractions in a language uses conjunctions of atomic sentences representing – in many cases – perceivable properties. There are also disjunctive conditions, for example the condition *x is an ape or x is a bridge*; obviously, the set of instances of this condition cannot be captured by a similarity abstraction. More complicated are categorial abstractions over categories, for example the category *species* in the field of biology.

The *abstract top ontology* (ATO) of GFO contains two meta-categories: *set* and *item*. Above the abstract top level there is a non-formal level, which might be called *philosophical level*. On this level, several distinct, philosophically basic assumptions are presented, mainly around the notions of existence and dependency. The abstract top level

---

[12] There is the general problem where the cut is made and defined between the subject and the independent real world. Several options are possible. Our approach can be justified by interpreting the phenomena as realization of dispositions of the objective independent world. These dispositions need a subject to come to appearance, more precisely, these appearances are realizations of dispositions within a subject. Hence, the phenomenal world is, on the one hand, anchored and founded in the objective reality, on the other hand it is realized in the subjective world. This connection is the basis for GFO's *integrative realism*.

is used to express and model the lower levels of GFO by set-theoretical expressions. To the abstract top level two basic relations are associated: membership $\in$ and identity =. The abstract top level of GFO is represented by a weak fragment of set theory, and some weak axioms connecting sets with items. Among the axioms concerning sets belong the following:

$$\forall x\, y\, (Set(x) \wedge Set(y) \rightarrow (x=y \leftrightarrow \forall u\, (u \in x \leftrightarrow x \in y))$$

$$\forall x\, y\, (Set(x) \wedge Set(y) \rightarrow \exists\, z\, (Set(z) \wedge z = \{x,y\})$$

$$\forall\, x\, y\, (Item(x) \wedge Item(y) \rightarrow \exists z\, (\, z = \{x,y\} \wedge Set(z)))$$

The *abstract core level* of GFO, called *abstract core ontology* of GFO (abbreviated ACO), exhibits the upper part of GFO. The abstract core ontology of GFO must first be determined by their main entity types and the relations among them, for which a certain vocabulary must be introduced. The entities of the world – being represented on the ATO-level by the items – are exhaustively divided into *categories* and *individuals*, and individuals *instantiate* categories. Moreover, among individuals we distinguish *objects*, and *attributives.*

By introducing a vocabulary for the considered entities we obtain the following signature: Cat(x) denotes the meta-category of all categories, OCat(x) represents the category of all object categories, Prop(x) indicates the category of all properties, and Rel(x) identifies the category of all relations. Ind(x) is the category of all individuals, Obj(x) designates the category of all objects, Attr(x) represents the category of all attributives, Rol(x) identifies the category of all roles, and Rel(x) denotes the category of all relators. These categories are all presented as predicates, i.e., they occur on the ATO-level as sets of items.

The *basic level ontology* of GFO contains all relevant top-level distinctions and categories. All basic relations and categories are presented as set-theoretical relations and set-theoretical predicates. Categories which are not contained within the basic level we call domain categories. Domain categories are related to a certain domain D of the world, and on the domain level they are not presented and considered as sets, but as entities of its own. Formally, the vocabulary at the basic level of GFO is extended by additional constants denoting proper categories or individuals. If, for example, C denotes a domain category we write x::C instead of C(x), indicating that x is an instance of C. Domain categories may be linked in a simple way to the basic level predicates of GFO, using domain-upper linking axioms.

4. The Basic Categories of Individuals of GFO

In this section the basic classification of individuals is expounded. Full GFO is intended to include also an ontology of categories; this topic is outside the scope of the current paper.

4.1 Space-Time

The GFO approach of time is inspired by Brentano's ideas [Bre 1976] on continuum, space and time. Following this approach, chronoids are not defined as sets of points, but as entities *sui generis*.[13] Every chronoid has exactly two extremal and infinitely many inner *time boundaries* which are equivalently called *time-points*. Time boundaries depend on chronoids (i.e., they have no independent existence) and can *coincide*. Starting with chronoids, we introduce the notion of *time region* as the mereological sum of chronoids, i.e., time regions consist of non-connected intervals of time. Time entities, i.e., time-regions and time-points, share certain formal relations, in particular the part-of relation between chronoids and between time-regions, denoted by tpart(x,y) the relation of being an extremal time-boundary of a chronoid, denoted by the relations lb(x,y) (x is left-boundary of y), rb(x,y) (x is right boundary of y, and the relation of coincidence between two time-boundaries, denoted by tcoinc(x,y).

Dealing with the coincidence of time boundaries is especially useful if two processes are to be modeled as "meeting" (in the sense of Allen's relation "meets"). In GFO there are at least three conditions that a correct model must fulfill:

there are two processes following one another immediately, i.e., without any gaps,
there is a point in time where the first process ends, and
there is a point in time where the second process begins.

If, as is common practice, intervals of real numbers are used for modeling time intervals (with real numbers as time points), then these conditions cannot be simultaneously satisfied. In contrast, the Brentano approach allows for two chronoids to follow immediately, one after another, *and* to have proper starting- and ending-"points" by allowing their boundaries to coincide. The coincidence relation entails that there is no time difference between the coinciding time boundaries, while maintaining their status as two different entities. This way, conditions (a), (b) and (c) are fulfilled.

Many temporal concepts are based on a measurement function μ for chronoids. Then value $\mu(C)$ is called the duration of the chronoid C. Using μ we classify chronoids with respect to their duration, we may say that this chronoid has a certain duration α. Using a measurement function we may introduce a number of temporal concepts, for example days, minutes, and years. Analogously to chronoids and time boundaries, the GFO theory of space introduces *topoids* with *spatial boundaries* that can coincide. *Space regions* are mereological sums of topoids.[14] To describe the structure of space (or of regions, respectively) we employ the basic relations *spatial part-of*, *boundary-of*, as well as the *coincidence of boundaries*. Formally, we use spart(x,y) x is a spatial part of y , *bd*(x,y) , if x is a boundary of y, and *scoinc*(x,y) if two (spatial) boundaries x and y coincide. This approach may be called *Brentano space*, and it is important to understand, that spatial boundaries can be found in a greater variety than point-like time-boundaries: Boundaries of regions are *surfaces*, boundaries of surfaces are *lines*, and boundaries of lines are *points*. As in the case of time-boundaries, spatial boundaries have no independent existence, i.e., they depend on the spatial entity of which they are boundaries.

---

[13] The GFO approach to time is related to what P. Hayes calls the *glass continuum* [Hay 1995]. Furthermore, we advance and refine the theory of [Bre 1976].

[14] Again, we use ideas of Brentano [Bre 1976] and Chisholm [Chi 1983] for our theory.

4.2 Principal Distinctions

In this section we consider the most basic distinctions between individuals. Individuals are entities that are not instantiable, they are divided into space-time entities, concrete and abstract individuals. Concrete individuals exist in time or space whereas abstract individuals do not. Concrete individuals include this *cup,* or this *hundred meter run*, abstract individuals include the real number π or idealized prototypical individuals as, for example, canonical anatomical structures [Ros 2003]. With regard to the relationship between individuals and time and space, there is the well-known philosophical distinction between endurants and perdurants. An endurant is an individual that exists in time, but cannot be described as having temporal parts or phases; hence it is entirely present at every time-point of its existence and it persists through time. Perdurants, on the other hand, are extended in time and cannot be wholly present at a time-point. The definition of endurant and perdurant is based on [Joh 1987], and [Lew 1986] where the notion of persistence is analysed and discussed.

According to this theory an entity persists if it exists at various times. The existence at various time can be understood - according to [Joh 1987] - in two different ways. Something perdures if it persists by having different temporal parts at different times, though no one part of it is wholly present at more than one time; whereas it endures if it persists by being wholly present at more than one time. It turns out that the notion of endurant combines two contradicting aspects. If, for example, an endurant x is wholly present at two different time-points t and s, then there are two different entities "x at t" and "x at s", denoted by x(t) and x(s) , respectively. Now let us assume that x persists from x(t) to x(s). For example, newborn Caesar exists at time t, x(t) , while Caesar at age of 50 at s, x(s) . Then, persistence of implies that x(t) and x(s) are identical.

Unlike the vague notion of an endurant and perdurant we make a more precise distinction between *presential* and *process*. A presential is an individual which is entirely present at a time-point. The introduction of the term "presential" is motivated by the fact that presentials are individuals that may exist in the presence, where we assume that the presence has no temporal extension, hence, happens at a time-point. We introduce the relation at(x,y) with the meaning the presential x exists at time-point y. In our approach we separate endurants into wholly present presentials and persisting persistants or perpetuants.

We pursue an approach which accounts for persistence using 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 that have different properties at different times can, nevertheless, be the same. They satisfy a number of conditions, among them the following: (a) every instance of a persistant is a presential; (b) for every time-boundary there is at most one instance which exists at this time-boundary; and (c) there is a chronoid c such that for every time-boundary of C the persistant has an instance at this time-boundary; and (d) every persistant is maximal, i.e. there is no proper categorial extension of it having the same extension. Further conditions should concern the relation of ontical connectedness and the relation of persistants to processes.

Persistants are special categories that can be instantiated. Are there individuals that correspond to persistants and take over some of its properties? We claim that for every persistant *P* of a certain subclass of persistants there exists an individual q called *perpetuant*, satisfying the conditions that it persists through time, and that it is related to the time-points of its duration by a relation *exhib*(q,a,t). The relation *exhib*(q,a,t) has the meaning that q exhibits the presential a at time-point t. A perpetuant is related to time by a set of time-points at which it exhibits presentials. A certain class of perpetuants, called material perpetuants, correlate to individuals which are sometimes called continuants. Unlike continuants - as a type of endurants - perpetuants are consistently presented.[15] The existence of perpetuants are justified and supported by results of Gestalt theory [Wer 1912],[Wer 1922].

Processes have a temporal extension thus cannot be wholly present at a time-point. The relation between a process and time is determined by the projection function *prtime(p,c)*, having the meaning that the process p has the temporal extension C. C is called the framing chronoid of P. There is another basic relation for processes, denoted by . The relation has the meaning that *x* is a process, *t* is a time-entity (a chronoid or a time-point), and the entity *y* results from the restriction of *t* to *t*. Two cases may be distinguished. If *t* is a chronoid, then *y* has the temporal extension *t* and is itself a process; *y* is a processual (or temporal) part of *x*. If *t* is a time-point, then *y* has no temporal extension, and, hence, cannot be a process. If *e* is wholly present at *t* then *e* is presential.

4.3 Material Structures

A material structure is an individual that satisfies the following conditions: it is a presential, it occupies space, it is a bearer of qualities, but it cannot be a quality of other entities, and it consists of an amount of substrate. Every material structure *S* occupies a certain space-region that exhibits the basic relation of *S* to space. The relation *occ(x,y)* describes the condition that the material structure *x* occupies the space-region *y*. A material structure *S* is spatially contained in the space-region *y*, if the space-region *x* occupied by *S*, is a spatial part of *y*. In this case we say that *x* is the spatial location of *S* with respect to *y* or that y frames S . The relation *occ(x,y)* depends on granularity; a material structure *S*, for example, may occupy the mereological sum of the space-regions occupied by its atoms or the convex closure of this system. We assume that in our considerations the granularity is fixed, and – based on this dimension – that the space-region occupied by a material structure is uniquely determined.

Using the relations *occ*(*x,y*) and *spart*(*u,v*) we define the relation *matpart*(*a,b*) with the meaning

that the material structure *a* is a material part of the material structure *b*.

---

[15] A perpetuant has - similar as a primitive universal - an implicit relation to time. The persistence of this kind of individual derives from its cognitive character. Persistence seems to be reasonable only for items that are invariant through a time-interval and at the same time are related at time-points of its duration to individuals which are immediately related to time and which may have different properties at different time-

points. Such items are either special primitive universals or particular cognitive individuals. We do not apply the notion of persistance to abstract individuals, as to the number 100.

$$matpart(x,y) \leftrightarrow \forall u\ v\ (occ(x,u) \wedge occ(y,v) \rightarrow spart(u,v))$$

Material structures may be classified with respect to the mereotopological properties of their occupied space regions. A material structure is said to be *connected* if its occupied region is a topoid. Every material structure consists of an *amount of substrate*. An amount of substrate may is a special persistant whose instances are distinct amounts at certain time-points; we call these *presential amounts of substrate*. An amount of substrate at a certain time-boundary, i.e., a presential amount of substrate, is always a part of the substrate of a material structure. The basic relation consist(x,y) means the material structure *x* consists of the presential amount of substrate *y*.

Let x be a material structure which occupies a topoid T and let *b* be a spatial boundary of T. We postulate the existence of a material entity y which occupies the boundary *b*. These entities are called material boundaries, and they existentially depend on the material structure occupying the according topoid. Material boundaries are divided into *material surfaces*, *material lines* and *material points*. Every material surface is the boundary of a material structure, every material line is the boundary of a material surface, and every material point is a material boundary of a material line.

We introduce the basic relation *matbd*(x,y) with the meaning x is a material boundary of the material structure y. Two material structures (or their material boundaries) touch if their occupied space regions have spatial boundaries with coincident parts. One has to take into consideration here that the spatial boundary which is occupied by a material boundary depends on granularity and context. Our notion of material structure is very general; almost every space-region may be understood as the location of some material structure. We single out material objects as material structures with *natural material boundaries*. This notion can be precisely defined. Let us consider a material structure S with material boundary B. A part B(0) of B is a natural boundary if the two following conditions are satisfied:

1) There is a material structure T outside of S such that S and T touch at B(0).
2) A tangential part of S with boundary B(0) and a part of T touching S at B(0) can be distinguished by different properties.

Examples of such distinguishing properties are fluid, solid, and gaseous. As an example, let us consider a river. A river (at a time point of its existence, i.e., considered as a presential) is a material structure which consists of fluid substrate and has natural material boundaries at all places, with exception of the region of the river's mouth. The solid river bed may be distinguished from the river fluid and the river fluid may be distinguished from the air above the river. Within our framework certain puzzles can be easily solved. In Leonardo's notebooks there is mentioned: *What is it … that divides the atmosphere from the water? It is necessary that there should be a common boundary which is neither air nor water but is without substance, because a body interposed between two bodies prevents their contact, and this does not happen in water with air.* (cited in [Cas 1994]).

How can two things – the water and the air – be in contact and yet be separated? There are two material structures *W* and *A* (water and air), *W* consists of liquid substrate, *A* consists of gaseous substrate. *W* and *A* have natural boundaries because at the “touching area” we may distinguish *W* and *A* by the properties “fluid” and “gaseous”. These natural boundaries touch because their occupied space-boundaries coincide. The touching phenomenon is explained by the property described in the Brentano-space theory that pure space boundaries may coincide; they may be at the “same place” but, nevertheless, different. What is “interposed” between the two natural boundaries are two coinciding space-boundaries which do not occupy any space.[16]

4. 4 Processual Complexes, Processes, and Occurrents

Processual complexes are the most general kind of concrete individuals which have a temporal extension. The temporal extension of a processual complex is a mereological sum of a non-empty set of chronoids. Processes form the most important sub-class of processual complexes, and occurrents centers around the notion of process. Occurrents are dependent entities that are related to processes in various ways. Some examples of processes or ocurrents include: a rhinitis, seen as a sequence of different states of inflammation; writing a letter; sitting in front of a computer viewed as a state extended in time; the execution of a clinical trial; the treatment of a patient; the development of a cancer; a lecture in the sense of an actual event as well as a series of actual events, but opposed to the abstract notion of lecture; an examination.

4.4.1 Processual Complexes

A processual complex is a concrete individual whose temporal extension is a time region. The basic relation between temporal complexes and time is determined by the relation *prtime(tc,tr),* where *tr* is the time-region which is associated to the processual complex *pc*; we say that *pc* is projected onto the time-region *tr*. A processual complex is said to be connected if its projection to time is a chronoid. The relation *timerestr*(x,t,y) has the meaning that the processual complex x, restricted to the time-structure t yields the entity y. The time-structure *t* is a temporal part of the time-region of *x*, and may additionally include an arbitrary set of time-points, selected from the projection of *x*. Then *y* is the temporal restriction of *x* to the time-structure *t*. Processual complexes are classified into coherent and non-coherent complexes.

4.4.2 Processes

The set of processes is a proper subset of the set of connected temporal complexes. Not every connected processual complex is a process because the latter satisfies a number of further conditions. The projection of a process *p* to time - described by the relation *prtime(p,c)* - is a chronoid which is uniquely determined. Hence, the relation *prtime(p,c)* establishes a function from the set of all processes to the set of all chronoids.

Just as parts of chronoids can be chronoids themselves, we assume that parts of processes are always processes themselves. If *p* is a processual part of the process *q*,

---

[16] GFO presents a solution to a problem which arises in [Smi 2000]. GFO gives a new interpretation of bona-fide boundaries in terms of natural boundaries. The claim stated in [Smi 2000] that bona fide boundaries cannot touch is counter-intuitive and ontologically false. A similar critics is sated in [Rid 2003].

denoted by *procpart*(p,q) , then the temporal extension of *p* is a temporal part of the temporal extension of *q*. Two processes *p,q* meet, denoted by *procmeet*(p,q) , if their corresponding chronoids temporally meet. If there is a process *r* such that *p ,q* are processual parts of *r,* and the temporal projection of *r* is the mereological sum of the temporal projections of *p* and *q*, then *r* is said to be the processual sum of *p* and *q*. We stipulate that the processual sum of two processes - if it exists - is uniquely determined.

If a process *P* is restricted to a time-point of its temporal extension then the resulting entity cannot be a process, because it has no temporal extension. If this entity is a presential then it is called a boundary of the process. The relation *procbd*(p,t,e) has the meaning that p is a process, *t* a time-point of the temporal extension of *p*, and *e* a presential at time-points t being the restriction of P to t. We assume that *e* is uniquely determined. Processes may be classified with respect to their boundaries. *P* is a quality process if any boundary of *P* presents an aggregate of qualities. Material processes contain in any of its boundaries a material structure.

Every process is *coherent* and *coherence* of a connected temporal complex implies that its boundaries are ontically and causally connected by the relations *ontic(x,y)* and *caus(x,y).* Coherence is a basic notion that cannot be defined and reduced to other concepts; it must be characterized by axioms, and these axioms are based upon our intuitions and experience of the phenomenal world. The relation *ontic(x,y)* is considered and stipulated as a primitive basic relation, hence, we assume that it cannot be defined by other relations. This relation can be illustrated and elucidated by examples. Assume, we consider vase *V* at a certain time-point *t*, and suppose that *V* breaks down at a later time-point t_1 into three parts V_1, V_2, V_3. Then, these parts are ontically connected to V. One aspect behind the ontic-relation is a general ontological law of conservation of substrate and matter. Another example, demonstrating the ontic-relation, is related to the ship of Theseus S. Suppose, that after some time during which replacements of parts of S were carried out two ships S_1, S_2 came into beeing. Then only that ship is ontically conneted to S whose parts originate from the parts of S.

Another facet of coherence is causality. We assume that coinciding boundaries of a process are causally related. In particular, in a process any of its boundaries is determined by its past. Hence, in a coherent process a boundary cannot be replaced arbitrarily by another presential. Analogously, not every extension of a process is coherent. But, we assume that every process has a processual extension (which is, hence, coherent), and is at the same time an extension of a process. Hence, we postulate that every process can be prolonged to the future and to the past.[17]

Processes satisfy an ontological inertial principle that can be formulated as follows. A state (which is a particular process) prolongs to the same type of state unless there is a cause to change it. In summary: ontical connectedness, causality, and the ontological principle of inertia are satisfied for processes. Coherence is a very important principle for processes, without coherence the world would disaggregate in many isolated individuals.

A material process is a process whose boundaries are material structures. A structural

---

[17] We assume an eternal view on processes. If we are speaking about the future or the past then these are relative notions that are related to an observer.

layer *q* of some process *p* is a "portion" of *p* that may be explained by the following example. Let be *p* a 100 meter run with eight participants. Then the whole run is a process *P*, and every of its runners exhibits, as a process *Q* for itself, a layer of *P*. But even the process, associated to one of the runner's part, say his right hand, forms a layer of *P*.

The layer of a process can be understood as a particular part of it, captured by the relation with the meaning, that *x* is a layer of the process *y*. Further part-of relations of processes may be derived from them. We may consider, for example, those parts of a process *P* which are processual parts of a layer of *P*. Two layers of a process are said to be separated if there are no interlacements between then. We claim that every process can be decomposed into separated layers. Furthermore, we believe that any number of processes with the same temporal extension can be embedded into a process containing them as layers.

4.4.3 Occurrents

Occurrents are classified into *events, changes,* and *histories*. These entities depend on processes and are relatively defined with respect to universals. In contrast to a general understanding of "change" as an effect, a *change* - in the framework of GFO - refers to a pair of process boundaries. These pairs occur either at coinciding boundaries, like "instantaneous event" or "punctual", or at boundaries situated at opposite ends of a process of arbitrary extension. The enrollment of a student is an example for the first kind of changes, called *discrete*. It comprises two coinciding process boundaries, one terminating the process of the matriculation, one beginning the process of studying.

An example of *continuous* change is illustrated by the decline in the course of a rhinitis. If two boundaries of this process coincide, one may not be able to assign to them a difference to the severity of inflammation, but if one considers boundaries that belong to an extended part of the inflammation process, there will be a difference. Both notions of continuous and discrete change are relative to contradictory conditions between which a transition takes place. Frequently, these contradictions refer to pairs of categories that cannot be instantiated by the same individual.

Locomotions are another representative of continuous change. Here, the contradictory conditions refer to some change of the distance of the moving entity to some entity or frame of reference. Changes are defined relatively with respect to a universal *U* whose instances are presentials.

Relying on those universals, we finally arrive at the following relations: Discrete changes are represented by dischange(p,e_1,e_2,u_1,u_2,u) [18] , where e_1 and e_2 capture the pair of coincident process boundaries[19]. This relation implies that p is a process, u_1 and u_2 are disjoint sub-universals of u, such that e_1 and e_2 instantiate u_1 and u_2, respectively. Note, that this implies instantiation of both

---

[18] The representation of a change could additionally mention also two sub-processes p(1), p(2), where both processes meet, and e(1) is the right boundary of p(1), and e(2) is the left boundary of p(2).

[19] Recall that "coincident process boundaries" refers to the fact that the respective time-boundaries coincide. It does not mean that the presentials themselves should coincide.

e_1 and e_2 of u , which prevents expressing artificial changes, e.g. a change of a weight of 20kg to a color of red. The conditions described about *dischange* are neccessary conditions a discrete change should satisfy. We may derive from *dischange* a relation *dischange*$_1$ defined as follows:

$$dischange_1(x,y,z,u) =_{df} \exists\ u_1\ u_2\ dischange(x,y,z,u_1,u_2)$$

Note, that if u has no proper disjoint subuniversals then discrete changes with respect to u cannot exist. Furthermore, if C is a change relative to the universal u and ext(u) $\subseteq$ext(v) then C is a change for v, too.

Any *continuous process* has no discrete changes. For the purpose of formalizing continuous changes, we consider a subprocess q of the process p. If q is a continuous change of p with respect to the universals u, denoted by *contchange*(p,q,u), then the following conditions are satisfied. q does not contain any discrete change with respect to subuniversals of u, but any two non-coinciding boundaries of q can be distinguished by subuniversals of u. The mentioned conditions are neccessary conditions that should be satisfied by any continuous change. But they are, we believe, not sufficient to adequately capture the notion of a continuous change. Continuous processes, and continuous changes in particular, must take into consideration some further conditions which are related to a measurement system that includes an ordering between certain universals. A complete theory of continuous processes and changes must be elaborated yet. A refinement and generalization of continuous changes takes into consideration the idea of observable or measurable differences between non-coinciding boundaries of a process. It might happen that not only coinciding boundaries cannot be distinguished, but also boundaries of sufficient small temporal distance. For this purpose we may introduce a universal $\Delta(\lambda)$ of chronoids of minimal duration λ that is employed in order to embody the idea of observable differences during chronoids of length $\rho \geq \lambda$, while the change does not allow the observation of a difference between boundaries whose temporal distance is smaller than λ. The predicate is intended to formalize this approach. Changes can only be realized in terms of ontical connectedness and persistants /perpetuants, in order to know which entities must be compared with each other to detect a change.

Events are entities that exhibit a certain behavior relative to a process; every event is a right boundary of a process. In describing events we introduce are relation *event*(p, e, u_1, u_2, u), where e is the right boundary of p, u_1, u_2 are different universals (with disjoint extension) of the “same”kind of instances, i.e. they are subsumed by a certain universal u. Furthermore, every boundary of p left from e, within a certain end-segment of p, is an instance of u_1, but e itself is an instance of u_2. We present the example of cell-division demonstrating an event. Let us assume the process p is called cell-division. This process starts with one cell, and ends with two cells. In the course of the process there is a continuous deformation of the cell, and at any time-point before the event we find one cell, i.e. to any boundary left from the event, the property of being one cell is verified. Hence the distinguishing properties to be considered are “to be one cell” (as a connected whole) or “to be two cells”. We may consider the same property for the left boundary of a process. The left boundary of a process p is a starting event of p, with respect to the universals u, u_1, u_2 , denoted by if every boundary right from e, within a certain initial segment of p is an instance of u_1, but e is an instance of u. We consider an example of a process that has a starting event and a (final) event. Let B be a pool and let us consider the universals $u_1 =_{df}$ *B is empty*, $u_2 =_{df}$ *B is completely filled* with water, u_3 the universal: *B is non-empty but not completely filled*. Then, the process of filling the pool B with water has a starting event e_1 (the empty B), and a final event e_2, B is completely filled.

Since every process is prolonged in the future there arises the question which types of coinciding boundaries may occur. Furthermore, not every universal is suitable to establish changes and events. We restrict in this section to the case that the boundaries of the process are material structures. Such a material structure p may undergo many changes during its existence. Which kinds of change for p are possible? We collect some types of changes without claiming that this classification is complete.

- P may change its qualities, say colour, weight, form, size; these are individuals that inhere in P, and are genuinely unary, i.e. it do not need any relation to other entities.
- P may change its relation to space, i.e. may move in space or may change its form, such that the relation occ(x,y) is changed.
- P may loose spatial parts or may unify with other material structures.
- P may change its relation to other entities, in particular, P may change its role.

In all these changes the type of the changed entity should be preserved. A colour, for example, should not change into a weight, a form should not change into a colour. Furthermore, different changes may be interrelated to each other, for example the change of form and morphology changes the occupied space. Some of these interrelations are causally founded, for example the relation between the temperature and the size of an iron poke.

Histories in GFO are related to processes. A history is a pair $(p, (a_i)_{i<k})$ whereas p is a process, and $(a_i)_{i<k}$ are presentials at certain time-points $(t_i)_{i<k}$ of the temporal extension of p such that these presentials are constituent parts of the associated boundaries of p. k is either a natural number or equals ω. As an example we consider a patient p. p can be considered as a process Proc(p), and let us assume that his temperature is measured every day four times and during on month. Then the measured values belong to presentials which are exhibited at the time-points of measurement.

4.4.4 Basic Classification of Processes

In this section we investigate the immanent structure of processes based upon the types of change occurring in it. Using the notions of discrete and continuous change, but also states, processes can be subdivided according to the nature of changes occurring within a process and according to their combinations. First, there are processes in which all (non-coinciding) internal boundaries determine sub-processes that exhibit continuous changes. These are continuous processes which are described, for example, in mechanics [Hrm 1959].

*States***.** A process p is a state with respect to the universal u, briefly a u-state , if every boundary of p instantiates u. p is said to be a strong u-state if, additionally, there are no disjoint sub-universals of u_1, u_2 of u and no boundaries e_1, e_2 which are separated by u_1, u_2, i.e. $e_1 :: u_1$, and $e_2 :: u_2$. Every strong u -state is a u -state, but not conversely. If p is a strong u-state, then there exists an extensionally minimal sub-universal v of u such that p is a strong v-state. This is not true for u-states. Furthermore, if the universal u does not contain any proper sub-universal then any u-state is a strong u-state. Strong u-states are already determined by certain minimal universals.

*Continuous Processes***.** A process p is said to be continuous if p has no discrete changes and p is the mereological sum of continuous changes and states. If a process p is continuous then the partition into continuous changes and states is not necessarily uniquely determined. An example is a circular motion of a body.

*Discrete and Discrete-Continuous Processes***.** But discrete changes may alternate with periods without changes (based on the same universals). Those parts of a process without changes may be called a *state*, which constitutes its own type of process. States, however, are a notion as relative as changes. A process is said to be discrete if it composed of states and discrete changes. Discrete-ontinuous processes are formed of discrete processes and continuous parts, hence such a process is e mereological sum of discrete and continuous processes. A process is said to be discreteless if it does not contain any discrete change. Continuous processes are always, by definition, discreteless. In summary, three standard types of processes can be identified: *continuous processes* based on intrinsic changes, *states,* and *discrete processes* made up of alternating sequences of extrinsic changes and states or continuous processes.

General Processes. We now consider the case that no restriction is proposed (fixed) for the distribution of universals over the boundaries of a process. Let *I* be a chronoid, and *Bd(I)* the set of all boundaries of *I*. Furthermore, let be $\{u_1,\ldots,u_k\}$ a set of universals whose instances are presentials, we assume that these universals are pair-wise extensional disjoint. Let f be a function Bd(I) $\text{--->}\{u_1,\ldots,u_k\}$. Does there exists a process P such that P has a temporal extension I and for every time-boundary t of Bd(I) holds that e(t) is an instance of f(t)? The classification of general processes is an open problem.

Another dissection of the category of processes is geared toward the complexity of the process boundaries in their nature as presentials. Consider a person walking compared to a clinical trial. In the first case, the process of walking focuses on the person only (and its position in space), whereas the clinical trial is a process with numerous participants and an enormous degree of complexity and interlacement. It is clear that every process is embedded in reality, so the walking is not separated from the world and could be considered with more complexity.[20] However, processes often refer to specific aspects of their participants, so that dividing simple and complex processes appears to be useful. A process is called *simple* if its process boundaries are simple presentials or even mere qualities of presentials. In contrast to simple processes, *complex processes* involve more than a single presential at their boundaries. A finer classification of simple processes (according to the nature of its presentials) could be *quality-process* and *material-structure-processes*. Processes are not directly related to space, but such a

---

[20] The categories of situations and situoids as discussed in this paper are a first attempt to account for this in a systematic manner.

relation can be derived from the process boundaries (which are presentials).[21] With material-structure processes, each boundary comprises exactly one material structure e(t), where t denotes the corresponding time-boundary. In this case, the convex frame f of the topoid occupied by e(t) can be defined, denoted by (e(t), f). In order to assign some topoid to the overall process we consider the convex closure of every frame f which is assigned to some e(t) for any time-boundary t in the duration of the process.

For complex processes, which involve a system of material structures and qualities, both approaches can be combined. First, the inherence closure of all qualities in each process boundary is derived. Then one can determine the convex closure for each of the material structures found. The final step integrates all topoids determined in this way within a single convex closure, which is then assigned to the complex process as its spatial location.

An material object is an artefact if it was designed and produced by a subject, a human being. Similarly, we introduce the notion of a artefactual process which is designed by human beings. Among them there a executions of software programs, or the realization of a plan to achievce certain goals.

4.5 Attributives

Attributives are dependent entities, they always need a bearer. Attributives include, among others, properties, relators, roles, functions, and dispositions. Examples of qualities are particular weights, forms and colors. A sentence like “This rose is red.” refers to a particular object, a rose, and to a particular quality, red. Objects and attributives are connected by the basic relation of inherence. Atomic attributives have no parts or sub-components, they include qualities and roles. Atomic attributives are classified into context-free and contextual. Contextual atomic attributives are always parts of complex attributives. Qualities are context-free atomic attributives, roles are contextual atomic attributives being parts of relators. Examples of roles are available through terms like parent, child or neighbor. Here, parent and child would be considered as a pair of interdependent roles. Apparently, these examples easily remind one of relations like “is-child-of”. Indeed, a composition of interdependent roles is a *relator*, i.e., an entity that connects several other entities.

4.5.1 Properties

Things can have certain characteristics, features. To express them, natural and artificial languages make use of syntactic elements like adjectives /adverbs, or attributes /slots, respectively. Examples are: the severity of a rhinitis (a severe or minor); the shape of a nose (bulbous, pointy, flattened); the size of a filing cabinet; the size of a clinical trial (the number of participating patients); the number of centers comprising mono- and multi-center trials; the age of a patient (which may affect the inclusion or the exclusion in a trial); the reputation of a university.

In the following, we present the GFO account on properties, which consists of two parts: First, the distinction between abstract *property universals* and their concrete

---

[21] This resembles the idea of “indirect qualities” in [Mas 2002].

instances, which are called *property individuals*.[22] Second, both property universals and property and individuals must be distinguished from their respective values. At the abstract (universal) level, we distinguish between property universals and their *values*, which include the difference between phrases like “the size of a cabinet” and “a big cabinet”. The first phrase refers to a certain aspect of the cabinet. The second phrase refers to a value of this property of the cabinet, which reflects a relationship between the property universal, x, and the same property as exhibited by another entity, y.

Values of property universals usually appear in groups which are called *value structures* or *measurement systems*. Each of these structures corresponds to some property universal. More intuitively, one could say that the property may be measured with respect to some measurement system. For instance, sizes may be measured with the values “small”, “big”, or “very big”, which are the elements of one value structure. This structure and the particular values of the sizes of, e.g. a cabinet and a desk, respectively, allow for comparison of their sizes.

The notion of a value structure of a property is similar to a quality dimension in [Gar 2000][23]. Further, value structures are related to quality spaces in [Mas 2003][24]. Note, however, that various types of value structures can be found for the same property. Of course, one is tempted to include all these value structures within one comprehensive or “objective” structure. The latter would cover all values, such that any other structure appears as a selection of values of the objective structure. Instead of this, we currently consider it better to have distinct value structures (e.g. based on some measurement instrument), which may afterwards be aligned and composed into a broader structure, than to have a pre-defined “objective” structure. One reason for our approach is that the precise objective structure is unknown for most properties (choosing real numbers as isomorphic may often comprise too many values). In addition, all measurement instruments are restricted to a certain range of values, which can be measured using this instrument.

Within a value structure, several levels of generality may be distinguished, but, preliminarily, we understand value structures to be sets of values. Often it appears that a notion of distance can be defined, and that certain layers of value structures are isomorphic to some subset of real numbers, which allows for a mapping of values to pairs of a real number and a unit, as in the case of “10 kg”.

Coming to concrete entities, one can observe, that e.g. size (“the size of a filing cabinet”) can be a property of other entities apart from filing cabinets, as it is a universal. Hence the question arises whether the size of the particular cabinet and the size of some other particular entity is literally the same entity. To answer this question, we introduce the distinction between property universals and property individuals (regarding these two categories, note the terminological and conceptual affinity with [Mas 2003]).

In our example, we can differentiate between two entities: “the size” and “the size of that cabinet”. The size is a property universal (as introduced above). Because it is a

---

[22] In earlier texts these were referred to as “properties” and “qualities”.

[23] Note that the term “property value” here resembles Gärdenfors’ notion of “property”, our “property” his “quality dimension”

[24] A quality space consists of all “quales” (our property values) of some “quality” (our property).

universal, it is independent of the filing cabinet. But apart from the universal, we find the particular size of the particular cabinet, which exists only in the context of this cabinet and therefore existentially depends on it. We call individuals of this kind *property individuals*. To say that an individual entity has a property means that there is a quality individual which is an instance of the property universal and that this property individual *inheres* in its bearer. So the "size of that cabinet" is a property individual that inheres in the cabinet, while "size" is a property universal, of which the quality is an instance.

We introduce *values of property individuals*, which are analagous to values of property universals. For example, big and small may be the values of the size universal, whereas a particular big or small of some cabinet is the value of an individual quality, namely the size of that cabinet. Values of property individuals are individuals instantiating the corresponding property universals' values. Moreover, the particular value x is linked to a property individual y by the relationship .

It should be stated explicitly that values of property universals are not considered as specialisations of property universals. Properties themselves can be classified and subdivided in various ways. One natural way to classify perceptible properties is assigning them based on the way in which they are perceived. This leads to visible properties (like lengths and color), smells, tastes (e.g. sweetness, bitterness) and so on.

However, there are also more formal classification principles for properties, for instance, according to the categories of the characterized entities. The following subcategories of properties are preliminarily distinguished with respect to the categories their bearers belong to. Note that for each category a different subrelation of has-quality may be introduced, in order to integrate relationships that are fairly established.
Qualities of material structures, e.g. the color of a ball, Qualities of processes, e.g. the average speed of an object's movement, running for half an hour, and
Qualities of qualities, e.g. a color's hue or brightness.

4.5.2 Relations and Roles

Roles are common in modeling, yet they have lingered in the background and only in recent years have they attracted focused interest (cf. [Boe 2005]), although there are much earlier approaches dealing with roles as a central notion, as in [Bac 1977]. Initially, the term role calls to mind terms like student, patient, or customer – all refer to roles. In a comprehensive analysis, roles have been investigated for integration into GFO [Loe 2003], [Loe 2005]. Here we provide a compact introduction to the general understanding of roles as well as the current state of role classification.
General Approach

Starting with a *role r*, there are two directly related notions, namely *player* and *context.*[25] Each role q requires a player p and a context c. More precisely, r is one-sidedly existentially dependent on p, and mutually existentially dependent with c. Two basic relations connect entities of these types: *plays*, denoted as plays(x,y), connecting a player x with a role y,[26] and *role-of* (*role-of(x,y)*), which ties a role x to its context y. In terms of the "standard" role example of student, John plays the role of the student in the context of his relationship to his university. Other examples refer to John as an employee in the context of some company, or as a mover of some pen, in the context of that movement.

Moreover, apart from roles, players, and contexts, roles are often contrasted with *natural universals*[27], cf. [Gua 1992]. While "student" is a role, "human" is not a role, but a natural universal that provides players for roles. Intuitively, roles can be distinguished from natural universals by their dependence on a context, whereas for natural universals, the context of the considered role is irrelevant.

Each of these categories discussed thus far are self-contained, in the sense that they do not provide insights on how they are related to other GFO categories in this work. To establish these links, we first note that there are individuals as well as categories of roles (and all other notions). For more specific relations, different types of roles need to be distinguished. This classification is based on the contexts of roles, because the coupling of roles and contexts is more tight than between players and roles, cf. [Loe 2005].

Based on the literature, the following categories serve as contexts in various role approaches: relations, processes, and (social) objects. Accordingly, we distinguish three role types with the following informal definitions:

- A *relational role* corresponds to the way in which an argument participates in some relation;
- A *processual role* corresponds to the manner in which a single participant behaves in some process;
- A *social role* corresponds to the involvement of a social object within some society.

Here, we focus on the relationships to the general role notions identified above. Moreover, the given classification is not meant to be complete, i.e., other categories may be contexts, thus yielding further role types.

Relators are the contexts of relational roles, i.e., a relator can be decomposed into at least two relational roles which complement each other. Intuitively, the role-of relation seems like a part-of relation in this case. Because relational roles refer to exactly one player, the plays relation corresponds to has-property. Accordingly, relational roles are subsumed by the category of properties. Consider that the number two is a factor of four. This refers to a relator with two role individuals, one instantiating the role universal "factor", the other instantiating "multiple". The first of these role individuals is played by two, while four plays the second role individual.

---

[25] Note that "context" here is just an auxiliary notion for introducing roles, instead of being presented in a profound ontological analysis.

[26] The literature provides *fills* and *hasRole* as other common terms for the plays relation.

[27] Other terms in the literature are *natural type* [Gua 1992]], *natural kind* [Wil 1995], *phenomenon* [Sow 1984], *base classifier* in UML [Rum 1999], and *basic concept* in [Sun 2005].

The generality of relations regarding the entities they connect is reflected in the fact that players of relational roles cannot be restricted by any specific category; hence, the natural universal for relational roles in general is the category “entity”.

Processual roles have processes as their contexts. As such they are processes themselves, and one may identify them as special layers of a process, because role-of is understood as a part-of relationship (as in the case of relational roles). The plays relation is different from plays for relational roles, because here plays corresponds to participation in a process.

When John moves a pen, for example, the movement is a process in which John and the pen are involved, in different ways. Accordingly, the process can be broken into two roles, “the mover” and “the moved”. John plays the first role, the pen the second. Imagining John as a mime who pretends to move a pen should provide a natural illustration of the notion of processual roles.

The case of the mime further exemplifies an uncommon case of roles: a single processual role may itself form a context. Almost all role notions are relational in nature, in the sense that their contexts are composed of several roles. In contrast, processes that comprise only a single participant are understood as a processual role, and likewise, as a context. Considering the plays relation, the potential players of processual roles are restricted to persistants, because a persisting entity is required to carve out roles from processes.

Note that the similarities of relational and processual roles leads to a category of *abstract roles*. The latter is functionally defined as providing “a mechanism of viewing some entity — namely the player — in a defined context” [Loe 2005]. Given this abstraction, we can now introduce a final type.

Social roles differ from abstract roles in that their understanding depends much less on their context. Instead, social roles come with their own properties and behavior, which is a common requirement in many role approaches in computer science, cf. [Stei 2000]. For example, if John is a student, he is issued a registration number and gains new rights and responsibilities. From a philosophical perspective, this view is further inspired by Searle [Sea 1995] and the ontological levels of Poli [Pol 2001], see sect. 4. Social roles are considered to be social structures in GFO, which is an analogous category to material structures, but in the social stratum. However, social roles also need a foundation on the material level, which in general role terms corresponds to the plays relation. For instance, the human John plays a social role that is characterized by specific rights and responsibilites. Note that so far we do not exclude that social roles themselves may play other social roles; hence, there may be chains of the plays relationship that must ultimately terminate by a role played by a material structure.

The contexts of social roles are also social structures, which may be called societies or institutions, cf. [Sea 1995]. Accordingly, a rough similarity between role-of and part-of is present for social roles as well. However, there are complex interrelations among entities of the social stratum, and the ontology of this stratum requires much more work.

Given that the general approach to roles is initially independent of other GFO categories, as well as the diversity of individuals introduced as roles, leads us to question why all roles should fall within the same category. Stated differently, what should the intrinsic commonalities between processual and relational roles be? We must admit that there are none – a fact that lies in the nature of category "role" itself, because, under a meta-level perspective, all general role characteristics apply to "role" itself.

These meta-level aspects further relate to the account of roles given by Guarino (and colleagues), who characterizes "role" as a meta-category of relationally dependent and anti-rigid categories [Gua 2001], [Mas 2004]. The latter means that for each instance of a role category, it is not essential to instantiate that category. These criteria can be reconstructed in GFO, where relational dependence corresponds to our contexts and anti-rigidity must be re-interpreted in terms of player universals. Roles in GFO differ from this approach in the sense that (1) there are role individuals, and (2) it may be essential to play a role. For instance, it is essential that the natural number two is a factor of four, and it is likewise essential that each human is a child. Anti-rigidity thus does not hold for *every* player universal. Nevertheless, in most cases it is a useful indicator for detecting player universals, and thus roles.

4.5.3 Functions

We understand a function to be an intentional entity, defined in purely teleological terms by the specification of a goal, requirements and a functional item. Functions are commonly ascribed by means of the has-function relation to entities that, in some context, are the realizations of the goal, execute such realizations or are intended by a reliable agent to do so. Functions are considered to be intentional entities and, hence, they are not objective entities of the world, but agent-dependent entities that primarily belong to the mental and social strata.

Structure of Functions

The pattern of the specification of a function *F*, called a function structure, is defined as a quadruple, *Label(F), Req(F), Goal(F), Fitem(F)*, where:

- *Label(F)* denotes a set of labels of function F;
- *Req(F)* denotes the requirements of function F;
- *Goal(F)* denotes a goal of F;

Fitem(F) denotes a functional item of F.

Except for the label, these are called the function determinants, and they determine a function. Labels are natural language expressions naming the function. Most commonly, they are phrases in the form "to do something", e.g. "to transport goods". The requirements of the function set forth all the necessary preconditions that must be met whenever the function will be realized. For example, in the case of the function "to transport goods from A to B ", goods must be present at location A. Functions are goal oriented entities – specifying a function requires providing the goal it serves. However, goals are not identified with functions, as in [Cha 1997]]. The goal of the function is an arbitrary entity of GFO — referred to also as a chunk of the reality — that is intended to be achieved by each realization of the function. In the case of transporting goods, the location of the goods at B is the goal. The goal specifies only the part of the world directly affected (or intended to be affected) by the function realization. In our case, it is the relator of goods being located at B . Often a goal is embedded in a wider context, being a complex whole, e.g. a fact, configuration, or situation, called final state. A final state of a function includes the goal plus an environment of the goal, therefore making the goal more comprehensible. Here, it is the relator together with its relata, i.e., goods located in B.

Functions are dependent entities, in the sense that a function is always the function of some other entity, executing it. The functional item of the function F indicates the role of entities executing a realization of F , such that all restrictions on realizations imposed by the functional item are also stipulated by some goal of F . In the case of “to transport goods”, the functional item would be the role universal “goods transporter”. Entities are often evaluated against functions. This is reflected in GFO by the relations of realization and realizer. Intuitively, an individual realization of a function F is an individual entity, in which (and by means of which) the goal of F is achieved in circumstances satisfying the requirements of F . Take the example of function F “to transport goods G from Leipzig to Berlin”, and the individual process of transportation of goods G by plane from Leipzig to Berlin. In brief, we can say that the process starts when the requirements of F are satisfied, and ends by achieving the goal of F, which, therefore, is the realization of function F.

Realization of Functions

It is important to understand the difference between a function and a realization, in particular with regard to their specification. To specify a function and its structure one must state what will be achieved; representing a realization usually means specifying how something is achieved. Note that not all functions must be realized by a process, as in the above example. In fact, in GFO we do not interpret functions in terms of processes or behaviors as described in [Sas 1995]. Apart from functions that are typically realized by processes or behaviors, we also consider functions realized by presentials. Consider, for instance, a pepper moth with a dark covering sitting on a dark bark. This situation is the realization of the function of camouflaging a moth.

In every realization we find entities that execute this realization. They may be identified by references to functional items. For example, for the function “to transport oxygen”, the role “oxygen transporter” is the functional item. Now consider an individual transport process, i.e., a realization, involving a single red blood cell. That cell has the role “oxygen transporter” within this realization. This fact gives rise to a new entity that mediates between the realization and the cell itself, namely the cell as an “oxygen transporter” (cell-qua-oxygen transporter). Such an entity is called the realizer of the function and is considered to be a qua-individual, i.e., an instance of a role universal.

Ascription of Functions

Functions are often ascribed to entities, e.g. the function of oxygen transport is assigned to a process of blood circulation. We assign functions to entities by the has-function relation, whose second argument is a function, and the first is one of the following:

- an entity that is a realization of the function, e.g., for the function of transporting oxygen, the process of blood circulation;
- an entity that plays the role of the realizer in a realization of a function, e.g. the red blood cell in the process of blood circulation;
- an entity intended to be a realization or a realizer of a function.

The third case especially refers to artifacts that often inherit their functions from the designer, who intends for them to realize particular functions. The function ascription of that kind is called intended-has-functions. Note that artifacts are not only understood to be entities playing the role of realizers, as, e.g., a hammer that plays a realizer of the function "to hammer nails". Additionally, artifacts may play the role of realizations, e.g. the process of transporting goods, which is a realization of the transport function, may be an artifact as well. This holds true especially with regard to services.

The intended-has-functions have a normative character, which allows for assigning such functions to entities that possess them as malfunctions. In short, the entity that has an intended function F , but is neither a realization nor a realizer of F , is said to be malfunctioning. The flavors and more detailed specification of malfunctions and of other notions outlined above can be found in [Bur 2006].

4.6 Facts, Propositions, and Situations

With relations, relators and roles, all components of facts are available, such that a more formal approach can be established. Since relations are entities connecting others, it is useful to consider collections of entities and their relators. 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. Note that the existence of facts is not uncontroversial in the philosophical literature. Approaches span from the denial of facts on the one hand, to their acknowledgement as the most primitive kind of entity on the other, cf. [Arm 1997], [Wit 1922].

Further, facts are frequently discussed in connection with other abstract notions like propositions (cf. [Lou 1998]), which are not covered in depth here. However, what can be said about propositions is that they make claims about the existence or non-existence of facts. Therefore, truth-values are assigned to propositions and they can be logically combined. In contrast, facts do not have a truth value.

There are additional notions that are frequently mentioned in connection with facts, for example *states of affairs*, which have yet to be included properly in GFO. With respect to representations of facts and propositions, we intend to study and integrate results from *situation theory* as initiated by Barwise and Perry [Bar 1983]. This study will consider notions like infons and situation types, and will comprise the integration of these notions with those mentioned herein, like propositions and facts.

Another aspect to be stressed refers to the kinds of entities which facts are about, as these are not necessarily individuals. For example, the fact "Mary is speaking about humanity" refers to a relator of type "speaking", which connects Mary with the universal humanity. On the basis of the relator and the types of the arguments, several kinds of facts can be distinguished. Here, one immediate option is to look at the appearance of individuals (e.g. none, at least one, all) and categories. Facts that contain at least one individual are called *individual facts*, while non-individual facts are called *abstract*.

Individual and abstract facts may be further classified. We outline a refined classification that pertains to individual facts and is important for the category of situations and situoids. The basis of this classification is the temporal interrelationships of the individual constituents of facts. An individual fact is called a *presential fact* if all of its individual constituents are presentials, which exist at the same time-boundary. Facts that are not presential facts can still be classified in many different sub-types based on similar temporal criteria. Another dimension for classification is to refer to a finer classification of the constituents, like facts about presentials, facts about processes, mixtures of these, and so forth. The development of a practically relevant classification remains to be completed.

As yet, facts themselves have only been considered as individuals. However, it appears reasonable to speak of factual universals. For instance, sentences in the form "A man kisses a woman", can be interpreted in a universal sense. Each relation R , gives rise to a factual universal F(R), whose instances are composed of a relator of R and its arguments. Altogether, every relator of R has a corresponding fact instantiating F(R). In this section we survey some basic notions about the most complex entities in reality, namely situations and situoids.

Material structures, properties, and relators presuppose one another, and constitute complex units or wholes. The simplest units of this kind are facts. A *configuration* is an aggregate of facts. We restrict the discussion in this section to a special type of facts, and ask whether an aggregate of facts can be integrated into a whole. Put differently, we ask whether a collection of facts constitutes a whole. We consider a collection of presential facts which exist at the same time-boundary. Such collections may be considered to be presentials, and we call them *configurations*.

It is further required that configurations contain at least one material object. Material objects are entities having a natural boundary, and on this basis, configurations may be classified as either *simple* or *non-simple*. A simple configuration is a configuration that is composed of exactly one material object and has only properties inhering in that material object. A configuration is said to be non-simple if it is made up of more than one material object, and these are connected by relators.

A *situation* is a special configuration which can be comprehended as a whole and satisfies certain conditions of unity, which are imposed by relations and categories associated with the situation. We consider situations to be the most complex kind of presentials.

Configurations have a counterpart in the realm of processes, which we call *configuroids*. They are, in the simplest case, integrated wholes made up of material structure processes and property processes. Furthermore, there is a category of processes whose boundaries are situations, and that satisfy certain principles of coherence, comprehensibility and continuity. We call these entities *situoids*; they are regarded as the most complex integrated wholes of the world. As it turns out, each of the entities we have considered thus far, including processes, can be embedded in a 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. An example of a situoid is "John's kissing of Mary", conceived as a process of kissing in a certain environment which contains individuals of the persistants John and Mary.

Every situoid is framed by a chronoid and a topoid. We use here two relations *tframe*(s,y), and *tframe*(s,y). Note that the relation *tframe*(s,x) is equivalent to *prt*(s,x), since a situoid is a process. The relations *prs*(s,x) and *sframe*(s,x) are different.

Every temporal part of a situoid is a process aggregate. 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 prt(a,c,b), where *a* is a situoid, *c* is a part of the framing chronoid of *a*, and *b* is the process that results from this projection. Boundaries (including inner boundaries) of situoids are projections to time-boundaries. We assume that projections of situoids to time-boundaries, which are denoted by prt(a,t,b), are situations. In every situation, a material structure is contained, and we say that a presential *e* is a constituent of a situoid *s*, cpart(e,s) , iff there is a time-boundary t of s such that the projection of s onto t is a situation containing e .

Situoids can be extended in two ways. Let s, t be two situoids; we say that t is a *temporal extension* of s, if there is an initial segment c of the chronoid t such that the projection of t onto c equals s . We say that t is a *structural extension* of s if s is a structural layer of t (cf. section 2). Both kinds of extensions can be combined to form the more general notion of a *structural-temporal extension*. Reality can – in a sense – be understood as a web of situoids that are connected by structural-temporal extensions. The notion of an extension can be relativized to situations. Since there cannot be temporal extensions of situations, an extension t of the situation s is always a structural extension. As an example, consider a fixed single material structure p, which occurs in situation s. Every extension of s is determined by adding further qualities or relators to s to the intrinsic properties of p. A quality-bundle that is unified by the material structure p is called *saturated* if no extension of s adds new qualities. It is an open question whether there is an extension t of s, such that every material structure p in t unites with a saturated bundle of qualities.

A *configuroid c* in the situoid s is defined as the projection of a structural layer of s onto a chronoid, which is a part of the time-frame of s. In particular, every structural layer of s is itself a configuroid of s. Obviously every configuroid is a process. But not every process is a configuroid of a situoid, 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 within the framework of situoids. Also, situoids may be used as ontological entities representing contexts. Developing a rigorous typology of processes within the framework of situoids is an important future project. Occurrents may be classified with respect to different dimensions, among them we mention the *temporal structure* and the *granularity* of an occurrent.

As a final note regarding situoids, configurations, and their relatives, there are a number of useful, derivable categories. For instance, one can now define situational histories as histories that have only situations as their boundaries. In general, the theory of these entities is considered a promising field for future research.

5. Basic Relations of GFO

In this section we summarize the basic relations of GFO.

5.1 Existential Dependency. *Entity* is the category of everything that exists. We consider the entity level as a philosophical level at which the most general distinctions are considered. These are distinctions of modes of existence and of existential dependency. For many types of entities, their instances existentially depend on other entities. For instance, a time-boundary depends on the chronoid it is a boundary of, or the quality that inheres in a material structure depends on that structure. Various types of dependency relations are discussed in the philosophical literature, see e.g. chapter 9 in [Jha 1989]. It turns out that the notion of existential dependency is rather vague and needs further investigation. The classical definition of *existential dependence* or *ontological dependence* is given by the following informal definition which is preliminarily adopted:

Definition: An entity x is ontologically dependent on y when x cannot exist unless the y exists.

5.2 Set and Set-theoretical Relations. The membership relation is the basic relation of set theory. Set(x) denotes the category of all sets, represented as a unary predicate. $x \in y$ implies that either x and y are both sets, or x is a so-called class-urelement and y is a set. The subset relationship $\subseteq$ is defined in terms of membership. We include in the ontology of sets an axiomatic fragment of formal set theory, say of ZF, in particular, the axiom of extensionality: As sets can be nested, we can consider all set-urelements that occur in a set. First, there is the least flattened set y = trans(x), which extends the nested set on the first level of nesting with all class-urelements contained in any depth of nesting. That means, y satisfies the conditions $x \subseteq y$, and for every $z \in y$ holds that $z \subseteq y$. Then the class supp(x) = $\{a \mid a$ is a class-urelement and $a \in$ trans(y)$\}$, called the support of x, contains all class-urelements of x and only them. A class x is said to be pure if supp(x) = $\varnothing$.

We defend the idea by D. Lewis [Lew 1991] that the ontological status of sets can be reduced to the singletons, i.e. to the understanding of the transformation providing the singleton $\{a\}$ from an entity a. In [He 2007 b] some ideas about this topic are discussed.

5.3 Instantiation and Categories. Cat(x) is a predicate that represents the (meta)-

category of all categories. We do not consider Cat to be an instance of itself. The symbol :: denotes instantiation. Its second argument is always a category, the first argument can be (almost) any entity. If the second argument is a primitive category, then the first must be an individual. Individuals – in general – can be understood as urelements with respect to instantiation. Since we assume categories of arbitrary (finite) type, there can be arbitrarily long (finite) chains of iteration of the instantiation relation. Since sets have no instances (they have elements) they can be understood as another kind of urlements w.r.t. instantiation. On the other hand, categories do not have elements, but instances, hence categories are urlements with respect to the membership relation.

The definable extension relation, ext(x,y), is a cross-categorial relation, because it connects categories with sets and is explicitly defined in the following way: $ext(x,y) = Set(y) \wedge \forall u\ (u \in y \leftrightarrow u :: x)$. We may stipulate the existence of the set of all instances of a category by the following axiom (existence axiom): $\forall x\ (Cat(x) \rightarrow \exists y\ (ext(x,y)))$. If we assume this axiom then we may define the extensionality operator for categories: $Ext(x) = \{y \mid y :: x\}$. Note, that the existence axiom contradicts the foundation axiom for sets, in case of existence of non-wellfounded categories. For this reason, we do not assume the foundation axiom for sets.

5.4 Property Relations and Relators. Further, several relations connect properties (or individual property instances), their values and their bearers. If – for reasons of brevity – individual properties are called "qualities", there are the general relations has-property hprop(x,y), and has- quality, hqual(x,y), which relate a property bearer x to one of its properties/qualities y. However, there are specializations for certain types of arguments. The best known of such specializations is the relation of inherence, inh(x,y), to be a sub-relation of has-quality. 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". Sometimes inherence is called ontic predication. The second kind of relations connects a property with some value of a measurement system. In the denotation value(x,y) x refers to the property/quality y to the value. Relators are instances of relations. The role-of relationship was introduced as a close relative of part-of. It relates roles x and their contexts y, denoted by roleof(x,y). Thus far we have introduced role-of between processual roles and processes and between relational roles and relators.

5.5 Parthood Relation. Part-of is a basic relation between certain kinds of entities, and several relations have a similar character.

Abstract and Domain-specific Part-of Relations. The abstract part-of relation is denoted by p(x,y), while the argument-types of this relation are not specified, i.e., we allow arbitrary entities to be arguments. We assume that p(x,y) satisfies the condition of a partial ordering. Domain-specific part-of-relations are related to a particular domain D, which might be the set of instances of a category. We denote these relations as $part_D(x,y)$. We assume that for a domain D, the entities of D and its parts are determined. There is a large family of domain-specific part-of relations, the most general of these are related to basic categories as Chron(x), TReg(x), Top(x), SReg(x), MatS(x), Proc(x). In the following sections we provide an overview of the most important category-specific part-of relations.

Part-of Relation for Sets. We hold that the part-of-relation of sets is defined by the set inclusion, hence *part-set*(x,y) := $\mathrm{Set}(x) \wedge \mathrm{Set}(y) \wedge x \subseteq y$. If we assume the power-set axiom for sets, then the mereology of sets corresponds to the theory of Boolean algebras.

Part-of-Relations for Time and Space The part-of relations of time and space are related to chronoids, time-regions, topoids, and space regions. We introduce the unary predicates Chron(x), TReg(x), Top(x), SReg(x), and the binary relations tpart(x,y), spart(x,y). Every notion of part-of allows for a non-reflexive version of the relationship, which expresses proper parthood. These are denoted by adding a "p" to the above predicates, e.g. *pp*(x,y) or *tppart*(x,y). In particular, *spart* applies to spatial regions, *tpart* refers to time regions and chronoids, while *cpart* represents a relationship between situoids (or situations) and their constituents. The constituents of a situoid s include, among other entities, the pertinent material structures (that participate in s) and the qualities that inhere in them. Further, facts and configurations are constituents of situoids. Not every part of a constituent of a situoid, however, is contained in it.

Part-of Relation for Material Structures The basic relations pertaining to material structures are MatS(x), for "x is a material structure", and matpat(x,y), which means that the material structure x is a part of the material structure y. We assume among the basic axioms:

$$\forall x\, y\, u\, v\, (\mathrm{MatS}(x) \wedge \mathrm{matpart}(x,y) \wedge \mathrm{occ}(x,u) \wedge \mathrm{occ}(y,v) \rightarrow \mathrm{spart}(v,u))$$

We stipulate that the relation matpart(x,y) is a partial ordering, but additional axioms depend strongly on the domain under consideration.

Part-of-Relation for Processes.

The part-of relation between processes is denoted by procpart(x,y), meaning that the process x is a processual part of the process y. We assume the basic axiom:

$$\forall x\, y\, (\mathrm{Proc}(x) \wedge \mathrm{procpart}(y,x) \wedge \mathrm{prt}(x,u) \wedge \mathrm{prt}(y,v) \rightarrow \mathrm{tpart}(v,u)).$$

prt(x,u) states that the process x has the temporal extension u, or that the process x is temporally projected onto u. Again, we stipulate that the relation *procpart*(x,y) is a partial ordering, but additional properties of this relation depend on a concrete domain. For example, in the processes of surgery, only certain processual parts are relevant.

5.6 Boundaries, Coincidence, and Adjacence. We do not consider boundaries as being parts of entities. The boundary-of relationship connects entities of various categories, namely (a) time-boundaries and chronoids, (b) spatial boundaries and space regions, (c) presentials and processes, and (d) material boundaries and material structures.

We have not introduced a general relationship, but particular boundary-relations for each of these cases. Case (a) relies on the notions of left and right boundary-of, lb(x,y) and rb(x,y), respectively. In case (b), bd(x,y) denotes the fact that x is a spatial boundary of y. Case (c) is discussed in the section on time and space, whereas the fourth case is not yet formalized.

Coincidence is a relationship between space boundaries or time boundaries, respectively. Intuitively, two such boundaries are coincident if and only if they occupy "the same" space, or point in time, but they are still different entities. Obviously, congruence of extended boundaries like surfaces is entailed by their coincidence.

Further, the notion of coincidence allows for the definition of *adjacency*. In the case of space-time-entities, these are adjacent as soon as there are coincident parts of their boundaries. In contrast, material structures and processes cannot have coincident boundaries. Nevertheless, they are adjacent if the projections of their boundaries are adjacent.

5.7 Relations of Concrete Individuals to Space and Time

Concrete individuals have a relation to time or space.

Material Structures. Material structures are presentials, hence they exists at a time-point, and the relations *at(m,t)* captures this relation. The relation *at(m,t)* is functional, hence a presential m cannot exist at two different time-points. The binary relation of *occupation*, occ(x,y), describes a fundamental relation between material structures and space regions. Occupation is a functional relation because it relates an individual to the minimal topoid in which a material structure is located. *Location* is a less detailed notion, which can be derived in terms of occupation and spatial part-of. An x is located in a region y, loc(x,y), iff the topoid z, occupied by x, is a spatial part of y. Every process has a temporal extension. This temporal extension is called the projection of the process to time, and is denoted by prt(x,y). We distinguish several cases: prt(x,c), at(y,t), prb(x,t,y), where x is a process, y is a presential, c is a chronoid, and t is a time-boundary. The binary relations assign a temporal entity to presentials and processes, while prb(x,t,y) is the projection of a process x to its boundary y, which is determined by the time-boundary t. Note that *prb* can be used to define the relations at(x,y) and partic(x,y).

Every situoid, for example the fall of a book from a desk, occurs over time and occupies a certain space. The binary relations of *framing*, such as tframe(s,c), sframe(s,x) binds chronoids c or topoids x to situoids s. We presume that every situoid is framed by exactly one chronoid and one topoid. The relation tframe(s,z) / sframe(s,z) is to be read: "the chronoid / topoid z frames the situoid s".

5.8 Participation. Participation relates individuals to processes. There are several forms of participation of an individual in a process. *particpres*(x,p) means that the presential x participates in the process p. This is the case if the restrictopn of p to a certain time-point contains x. The relation *particperp*(x,y) states that the perpetuant x participates in the process y. This is the case if every presential z which x exhibits stand in the relation *particpres*(z,y). The participance of a persistant x in a process y is defined analogously. A process x participates in the process, denoted by *particproc*(x,y) if x is a layer-part of x.

5.9 Association.

The relation assoc(s,u) means "the universal u is associated with the situoid s". These universals determine which material relations and individuals occur as constituents within a given situoid. Thus, the association provides information about the granularities and viewpoints that a situoid presupposes. For example, a situoid *s* may be a certain part of the world encompassing 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 viewpoint of a biologist, and the associated granularity of included types of individuals (branches are included, electrons are not). The association relation is related to a cognitive procedure that transforms the mere material structures into situations and situoids. Situations and situoids are parts of the world that can be "comprehended as a whole". At the purely material level, these parts can be understood – we believe – as superimposing fields (gravitational, electromagnetic, etc.), which constitute a certain distribution of energy and matter. At the mental or psychological level, this distribution is perceived as a material structure. A material structure – as we have introduced it – is a pre-version of a situation. At this level of perception, certain structures may already be perceived: material boundaries, colors and the like. The level of comprehension, of understanding this part of the world as a situation, needs more than only the elementary perceptual structures. Comprehension presupposes the availability of concepts, and the formation and the use of concepts seems to be a component of the mind's cognitive process. The association relation is related to this ability of the mind to understand material structures of the world as situations.

5.10 Ontical Connectedness and Causality

Presentials are connected by spatio-temporal and causal relationhips, which give rise to persistants and perpetuants. The relation ontic(x,y) connects x and y by an integrated system of such relationships. It is assumed that x and y are processes or presentials. We believe that there are different relations of this kind. One interesting case of ontical connectedness is substrate-connectedness. Two material structures x and y are substrate-connected if they consist of the same amount of substrate. For example, a statue s made of clay, considered at a certain time-boundary, is substrate-connected with the material structure that results from a crash, which destroys s. In the present stage of investigation of *causality*, the relation between *causes* and their *effects* is seen as a special relation between presentials (contrary to the DOLCE account as given in [Leh 2004]). This basic relation shall support the traditional intuitions of regularity, counterfactual dependency and manipulability. In a second step, the basic causal relation is then extended to cover processes as causal relata as well.

6. Object-Process Integration

In this section we study the inter-relations between processes and other entities. In particular, we propose a framework for integrating several aspects of objects and processes into one system.

6.1 Processual Unification and Cognition

In GFO, spatio-temporal processes are independent individuals of reality; they exhibit the most fundamental of its categories.[28] All other categories of individuals are built upon them. Hence, processes unify the world of spatio-temporal individuals. Processes establish the coherence of the world; without processes the world would disintegrate into numerous separate and isolated entities. Presentials existentially depend on processes; we hold that every presential is a part of a boundary of a process. Hence, we stipulate the following axiom:

$$\forall x\, (Pres(x) \rightarrow \exists yz(Proc(y) \wedge procbd(z,y) \wedge cpart(x,y))$$

A presential x participates in the process y, denoted by *particpres*(x,y), if a boundary of y contains x as a constituent part. We postulate that for every time-boundary *t* of the temporal extension of a process *p* there exists a presential which is the boundary of *p* at *t*. From this follows the condition

$$\forall xy\, (Proc(x) \wedge procbd(y,x) \rightarrow Pres(y)).$$

Let Bd(p) be the set of boundaries of the process p. Every categorical abstraction over Bd(p) is called a persistant of p. Hence, a persistant is a concept whose instances equals the set of boundaries of a process. A persistant U of a process p is called maximal if there is no persistant V of p containing U as a proper intensional sub-concept. We hold that for every process there exists a greatest persistant which is uniquely determined. Persistants present the phenomenon of persistence through time with respect to the boundaries of a process; they capture those features of the boundaries of a process which do not change through time.

A process is said to be material if every boundary of it is a material structure; the associated presistants are called material. Perpetuants are individuals that exhibit a cognitive construction built upon particular material persistants; the existence of such cognitive individuals is supported by results and methods of Gestalt theory [Wer 1912], [Wer 1922][29]. Perpetuants are related to those entities that are sometimes called continuants or objects, as apples, cars or houses. Unlike persistants, being concepts, perpetuants are individuals which have an indirect relation to space and time.

6.2 Completed Categories and Integrated Individuals

The spatio-temporal individuals of the world are classified into processes, presentials and perpetuants. Persistants are universals which present categorial abstractions of the set of boundaries of a process. The complete specification of a material structure with closed boundary, say, of an ordinary object, integrates four aspects into one system: the object as a presential, as a process, as a perpetuant, and as a persistant. We explain and demonstrate this interrelation and integration by an ontological analysis. Consider an everyday name like “John”. What does John refer to in an ontologically precise sense?

---

[28] Processes, as other individuals, are not completely free of cognition. To clarify this situation we introduced in section 2.4 layers between the subject and reality. The layer of perception connects the subject with reality and we stipulate that the phenomenal world, though cognitively biased, belongs to the reality outside the subject.

[29] Persistants apply to every process, whereas the construction of perpetuants is restricted to a particular class of material processes.

There are, obviously, four possibilities, i.e., four entities of different categories:

- John denotes a presential *Pres(John,t)* at some point *t* in time,
- John refers to a perpetuant *Perp(John)*,
- the name is given to a process *Proc(John,)*
- John refers to a persistant *Perst(John)*.

Starting with an act of perception of John, we assume that a presential is recognized at a time-point t, call it *Pres(John,t).* If one has seen John several times, with probably varying properties, but still being able to identify him, this forms the basis for a perpetuant and a persistant, say *Perp*(John), and *Perst*(John). Now, one may consider the extension of this persistant (which is a universal), i.e., the set Ext(Perst(John)) = {J| J :: Perst(John)}, and analogously, the set Exhib(*Perp*(John)) = {J | exhib(Perp(John),t,J)}. Obviously, the entity Pres(John,t) referred to above is a member of this class. Also, one can say that any two members of that class represent "the same John".

In the fourth interpretation, the name John denotes a process *Proc(John)* of a special kind. We postulate the existence of a process *Proc*(John) whose set of restrictions to its time-boundaries equals the set of instances of *Perst*(John) and the set *Exhib*(Perp(John)). Furthermore, we see that the presentials associated to John can be derived from a process by taking the restrictions of this process to time-boundaries. On the other hand, the persistant Perst(John) or the perpetuant *Perp*(John) cannot be directly derived from a process because a categorial abstraction and a cognitive construction must be taken into consideration. The entities Perp(John) and Perst(John) capture important aspects of John's personal identity.[30] We call Int(John) = (Proc(John), Perp(John)) an integrated individual.

A complete understanding and description of concrete individuals needs all four aspects specified in our integrative system. If one of these aspects is missing we will face problems. If, for example, we consider John as a persistant or perpetuant only, then this John cannot engage in any temporal action, for example, the activity of eating. John's actions and activities are realized on the process level. If we consider John as the set of all presentialist Johns, then we have the same problem; since any action takes time, but a presentialist John cannot carry out any action. If John is a process only, then the problem becomes identifying the boundaries of the process because any natural process may be prolonged both into the future and into the past. Furthermore, we perceive John as a presential, which is missing in a pure processual understanding. We face similar problems pertaining to a full understanding of concrete entities, if we combine only two of the above aspects.

The notion of an integrated individual can be generalized to categories. Let us consider, for example, the category E of elephants. We may associate to E three basic categories: Proc(E), the category of all processes spanned by all individual elephants, Pres(E) the class of all presentialist elephants, Perp(E) the class of all perpetuant elephants. The completed category of elephants, denoted by Compl(E), has the three

---

[30] A full elaboration of our approach to personal identity is much more complicated. It must consider the underlying process, the place of consciousness and will, and the dynamic interrelations between the persistant, the perpetuant, the presentials, and the process.

instances Proc(E), Perp(E), Pres(E); hence Compl(E) is a higher order category. Compl(E) can be extended by adding a class of persistants associated to the elephants. Hence, the system (Compl(E), Perst(E)) exhibits the complete informations about the category of elephants.

6.3 Comparison to other 4D-Ontologies

GFO is basically a 4D-ontology, in the sense, that the processes form the most fundamental category of individuals. Furthermore, processes cannot be considered as mere aggregates or sets or mereological sums of their boundaries. Hence, our theory of boundaries differs from the theory of stages in a 4-dimensional setting in the spirit of Sider [Sid 2001]. Further, GFO adds to the pure 4D-view a cognitive level at which perpetuants and persistants are introduced; these correspond to entities called continuants. Persistants can be introduced for every process p by a categorial abstraction over the set Bd(p) of boundaries of p.

7. Principles of Ontology Development and Ontological Modelling

The application of GFO as a framework for conceptual modelling needs an exposition of principles for ontology development. In this section some basic ideas are outlined.

7.1 Domains and Conceptualizations

The starting point of ontology development is a domain. The formation and emergence of domains is a result of the evolution of scientific knowledge about the world, but also the outcome of common sense reasoning and social knowledge as well as the result of philosophical contemplations and reflections. Ontological levels and strata, for example, as elaborated and exposed by the philosopher N. Hartmann [Har 1964], [Har 1965] and further developed by R. Poli in [Pol 2001], exhibit very comprehensive domains of the world. Another group of domains is related to the evolution of empirical sciences including, for example, the physical domain, the biological domain, the domain of medicine and many others. The domain of mathematics has a special nature and differs significantly from the domains of the empirical sciences. The realm of mathematics is the world of sets that are understood and conceived by the majority of mathematicians as platonic ideal entities which exhibit a subject-independent and atemporal existence.

A domain D = (Obj(D), V(D), CP(D)) is determined by a set Obj(D) of objects associated to it, by a set V of views at Obj(D), and by a set CP of classification principles for Obj(D). The notion of view is used in an informal, intuitive sense, whereas the classification principle CP can be made usually more precise. In understanding, acquiring and representing the knowledge about a domain D we use categories and relations between them, and must specify the domain's objects and their fine-structure. Hence, we associate to a domain D two further constituents: the categories of D, denoted by Cat(D), the relations of D, denoted by Rel(D). These additional constituents are influenced by the view V at Obj(D) and the classification principle CP of D. The system Concept(D) = (Obj(D), Cat(D), Rel(D)) can be conceived as a detailed form of a conceptualization of the domain D in the sense of [Gru 1993]. This approach to conceptualizations supports the ideas expounded in [Cra 2006], since we assume that the categorial system Cat(D) as well as the relations in Rel(D), and also the classification principles CP(D), depend on the deeper rooted world view of its designer including the purpose for which the categorical system is generated. An ontology of a domain D is based on a conceptualization Concept(D); it is determined by adding axioms describing inter-relations between the categories and properties of relations. We present an ontology Ont by a system Ont = (Concept(D), Ax(Concept(D)), where Ax(Concept(D)) denotes the set of axioms about the conceptualization Concept(D). The most simple axioms are presented by relational links between categories.

The categories of Cat(D) are divided into the set of principal categories of D, denoted by PrincCat(D) of D, into the set of elementary categories of D, designated by ElemCat(D), into the set of aspectual categories of D, symbolized by AspCat(D), and into the linguistically defined categories, denoted by LingCat(D). These sets of categories form an increasing chain, i.e. we suppose that PrincCat(D) $\subseteq$ ElemCat(D) $\subseteq$ AspCat(D) $\subseteq$ LingCat(D). The principal categories are the most fundamental ones of a domain. For the domain of biology the category of organism is accepted as being principal. The linguistically defined categories are introduced by formulas of a language, usually a formal language L. The system (PrincCat(D), ElemCat(D), AspCat(D)) is called a graduated conceptualization of D.

The elementary categories of a domain are introduced and determined by a classification based on the domain's classification principles; they usually present a taxonomy. There is a great variety of combinations of the classification principles being applied to specify elementary categories. A domain D is called simple if it has only one view and one classification principle, and if the taxonomy based on (Ind,V,CP) exhibits a tree-like structure. If the domain has multiple views then the taxonomic ordering of elementary concepts cannot be assumed to be tree-like. Multiple views can be the reason for the occurrence of multiple inheritance. Aspectual categories are derived from elementary categories by aspectual composition and deployment.

7.2 Steps of Ontology Development

We summarize the basic steps for the development of an ontology. An ontology usually is associated to a domain, hence, we must gain an understanding of the domain which is under consideration. The constituents of a domain D include the objects of D, the assumed views V, and the classification principles to be used for the construction of concepts. These constituents can be analysed in the framework of a top level ontology. We sketch a top-level centred approach to ontology development and use as a basis the ontology GFO.

1.Step: Domain Specification and Proto-Ontology

A domain is determined by classification principles and a set of views. The first step is the construction of a domain specification. In particular, a description of the objects of the domain A must be established. The considered objects are determined by the assumed views, whereas the classification principles provide the means for structuring the set Obj(D) of objects. Usually, there is source information which is associated to the domain, in particular a set *Terms*(D) of terms denoting concepts in the domain. The system ProtoOnt(D) =(Spec(D), Terms(D)) consisting of the domain specification Spec(D) and a set of terms Terms(D) is called a *proto-ontology*. A proto-ontology of a domain contains the relevant information needed to make the further steps in developing a *axiomatized ontology* about D.

2.Step: Conceptualisation. A conceptualisation is based on a proto-ontology; the result of this step is a *graduated conceptualization*. Hence, the principal and elementary concepts of the domain must be identified or introduced. The resulting concepts belong either to the concepts denoted by the terms of Terms(D) or they are constructed by means of the classification principles. A further sub-step is pertained to the desired aspectual concepts which are derived from the elementary concepts. Finally, we must identify relations which are relevant to capture content about the individuals and concepts. It would be helpful if a meta-classification of relations is available. GFO provides already a basic classification of relations which must be extended and adapted to the particular domain D.

3.Step: Axiomatisation. During this step axioms are developed. This needs a formalism, which can be a graph-structure or a formal language. We expound in more detail the construction of a formal knowledge bases assisted and supported by a top-level ontology TO. Generally, a axiomatized ontology $Ont = (L, V, Ax(V))$ consists of a structured vocabulary V, called ontological signature, which contains symbols denoting categories, individuals, and relations between categories or between their instances, and a set of axioms $Ax(V)$ which are expressions of the formal language L. The set $Ax(V)$ of axioms captures the meaning of the symbols of V implicitly. A definitional extension $Ont^d = (L, V \cup C(DF), Ax(V) \cup DF)$ of Ont is given by a set DF of explicit definitions over the signature V and a new set $C(DF)$ symbols introduced by the definitions. Every explicit definition has the form $t := e(V)$, where $e(V)$ is an expression of L using only symbols from V (hence the symbol t does not occur in e(V)).
An *ontological mapping M* of a conceptualization Conc(D) into an axiomatized ontology *Ont* is given by a pair $M = (tr, DF)$ consisting of a definitional extension Ont^d of Ont by (the set of definitions) DF and by function tr which satisfies the following condition:
For every term $t \in Tm$ denoting a concept C of Conc(D) which is defined by the (natural language) expression $Def(t)$ the function tr determines an expression $tr(Def(t))$ of the extended language $L(V \cup C(DF))$ such that $Def(t)$ and $tr(Def(t))$ are semantically equivalent with respect to the knowledge base $Ax(Ont) \cup DF$.
Then the set $OntMap(Conc(D)) = Ax(V) \cup DF \cup \{tr(Def(t)) : t \in Conc(D)\}$ is a formal knowledge base which formally captures the semantics of the conceptualization of D. The notion of *semantical equivalence with respect to a knowledge base* is used here informally because a strict formal semantics for natural language sentences does not yet exist; the notion has to be read "the meaning of the natural language (or semi-formal) sentence $Def(t)$ is equivalent to the meaning of the expression $tr(Def(t))$. An expression e is considered as ontologically founded on an ontology *Ont* if it is expressed in some definitional extension Ont^d of *Ont*. Hence, an ontological mapping of a conceptualisation Conc(D) associates to every term of Conc(D) an equivalent formal description which is based on a formally ax-

iomatized ontology *Ont*. A final axiomatization for Conc(D) can be achieved by starting with a top-level ontology, say GFO, and then constructing by iterated steps an ontological mapping from Conc(D) into a suitable extension of GFO. An advanced elaboration of this theory, which is being investigated by the Onto-Med group, is presented in [He 2006a]. The construction of an ontological mapping, which yields an axiomatization of the conceptualization includes, according to [He 2006a], three main tasks:

1. Construction of a set *PCR* of primitive concepts and relations out from the set $\{Def(t) : t \in Conc\}$ (*problem of primitive basis*)
2. Construction of an extension TO_1 of *TO* by adding new categories *Cat* and relations *Rel* and a set of new axioms. $Ax(Cat \cup Rel)$ (*axiomatizability problem*)
3. Construction of equivalent expressions for $Def(t) \cup PCR$ on the base of TO_1 (*definability problem*).

7.3 Ontological Modelling

In this section we set forth some ideas on a new area of research which aims at the use of ontologies for modelling of processes and their simulations. The basic idea of ontological modelling is expounded in [Her 2006a]. Subsequently, we add further ideas on this field of research. The starting point is a class P of (natural) processes which can be considered to be included in a class of situoids. A strict ontological model of P is a category C := OntMod(P) whose extension equals P, i.e. for all processes p holds: $p \in P$ if and only if p :: C. Usually, the condition of a strict ontological model for a class P of processes can hardly be achieved. For this reason we say that C is an ontological model of P if the extension of P sufficiently approximates the class P. [31] A process $p \in P$ is said to be computable if there is an execution of an algorithm α which approximates p.[32] The class P of processes is said to be computable if there is an algorithm α such that every $p \in P$ is approximated by an execution of α. We assume that any reasonable class P of natural processes is computable.[33]

The paper [Roe 2002] expounds a conceptual analysis of the notion of a stem cell. The authors argue that stemness of a cell cannot be considered as a specific property that can be determined at one time-point without putting the cell to functional tests. Hence, stem cells exhibit stemness by participating in certain interacting processes which are embedded in a larger process which we call stem-cell process. Let *SCP* be the class of all stem-cell processes. An expressive ontological model for *SCP* should be specified in a formal language which includes among others the conditions presented in the model description in [Roe 2002]. But, more properties must be taken into consideration, among them those which pertain to different granularity levels of the stem cell processes, but also to properties which are related to the snapshots of the process and its sub-processes. Hence, the acquisition of relevant presentialist and processual properties of stem cell

---

[31] This vagueness cannot be avoided because we assume that the specification of OntMod(P) exhibits a decidable set of conditions. By Gödel's incompleteness theorems a complete specification of P cannot be, in general, achieved.

[32] The term „an execution of α approximates p" needs further explanation. This can be made precise by using the approaches of computable and constructive analysis [Wei 2000], [Geu 2007]. The development of an ontological theory of computational simulation of natural processes is in progress and will be published elsewhere.

[33] It is an open problem whether every reasonable natural process is computable [Kre 1974].

processes is important. Using this idea of ontological models a number of notions can be clarified and refined, among them computer simulation, prediction, practical experiment, etc.

Acknowledgement.

Many thanks to P. Burek, R. Hoehndorf, F. Loebe, H.Michalek who contributed significantly to the development of GFO. I am grateful to R. Poli and anonymous reviewers for their critical remarks that contribute to the quality of the paper. Thanks to M. West for fruitful discussions which lead to deeper insight into 4-dimensionalism. Finally, thanks to J. Gracia for inspiring discussions on the relations between different kinds of categories, and the proper interpretation of the notion of realism.

References

[All 1990] James F. Allen and Patrick J. Hayes. Moments and points in an interval-based temporal logic. *Computational Intelligence*, 5(4):225–238, 1990.

[Arm 1997] D. M. Armstrong. *A World of States of Affairs*. Cambridge University Press, 1997.

[Ash 2000] M. Ashburner, C. A. Ball, J. A. Blake, D. Botstein, H. Butler, J. M. Cherry, A. P. Davis,K. Dolinski, S. S. Dwight, J. T. Eppig, M. A. Harris, D. P. Hill, L. Issel-Tarver, A. Kasarskis, S. Lewis, J. C. Matese, J. E. Richardson, M. Ringwald, G. M. Rubin, and G. Sherlock. Gene Ontology: tool for the unification of biology. *Nature Genetics*, 25(1):25–29, 2000.

[Baa 2003] Franz Baader, Diego Calvanese, Deborah McGuinness, Daniele Nardi, and Peter Patel-Schneider, editors. *The Description Logic Handbook: Theory, Implementation and Applications. Cambridge University Press, Cambridge (UK), 2003.*

[Bac 1977] Charles W. Bachman and Manilal Daya. The role concept in data models. In *Proceedings of the Third International Conference on Very Large Databases*, pages 464–476. IEEE Computer Society, 1977.

[Bar 2005] Jonathan Bard, Seung Y. Rhee, and Michael Ashburner. An ontology for cell types. *Genome Biology*, 6(2):R21, 2005.

[Bar 1983] Jon Barwise and John Perry. *Situations and Attitudes*. Bradford Book. MIT Press, Cambridge (Massachusetts), 1983.

[Blo 1987] Bloch, E. Subject-Objekt. Suhrkamp, 1985

[Boe 2005] Guido Boella, James Odell, Leendert van der Torre, and Harko Verhagen, editors. *Proceedings of the 2005 AAAI Fall Symposium 'Roles, an Interdisciplinary*

Perspective: Ontologies, Languages, and Multiagent Systems', Nov 3-6, Arlington, Virginia, number FS-05-08 in Fall Symposium Series Technical Reports, Menlo Park (California), 2005. AAAI Press.

[Boo 1999] Grady Booch, James Rumbaugh, and Ivar Jacobson. *The Unified Modeling Language User Guide*. Object Technology Series. Addison Wesley, Reading (Massachusetts),1999.

[Bra 1987] Eugene Braunwald, Kurt J. Isselbacher, Robert G. Petersdorf, Jean D. Wilson, Joseph B. Martin, and Antony S. Fauci, editors. *Harrison's Principles of Internal Medicine*. McGraw-Hill, New York, 11 edition, 1987.

[Bre 1976] Franz Brentano. *Philosophische Untersuchungen zu Raum, Zeit und Kontinuum*. Felix- Meiner Verlag, Hamburg, 1976. Edited by S. Körner and R. M. Chisholm.

[Bro 2005] Catherine Brooksbank, Graham Cameron, and Janet Thornton. The European Bioinformatics Institute's data resources: towards systems biology. *Nucleic Acids Res*, 33(Database issue):D46–D53, 2005.

[Bur 2007] Patryk Burek. *Ontology of Functions: A Domain-independent Framework for Modeling Functions. PhD thesis, University of Leipzig, Institute of Informatics (IfI), 2007*

[Bur 2006] Patryk Burek, Robert Hoehndorf, Frank Loebe, Johann Visagie, Heinrich Herre, and Janet Kelso. A top-level ontology of functions and its application in the Open Biomedical Ontologies. *Bioinformatics*, 22(14):e66–e73, 2006.

[Cas 1994] R. Casati and A. Varzi. *Holes and other Superficialities*. MIT Press, Cambridge (Massachusetts), 1994.

[Cha 1997] B. Chandrasekaran and J. R. Josephson. Representing functions as effect. In *Proceedings of the Functional Modeling Workshop, Paris, France*, 1997.

[Chi 1983] R. M. Chisholm. Boundaries as dependent particulars. *Grazer Philosophische Studien*, 20:87–96, 1983.

[Chn 1971] Chang, J., Keisler: Model Theory, North-Holland Publishing Company, Amsterdam 1977

[Kei 2000] N. F. de Keizer, A. Abu-Hanna, and J. H. M. Zwetsloot-Schonk.

Understanding terminological systems I: Terminology and typology. *Methods of Information in Medicine*, 39(1):16–21, 2000.

[Dor 2002] Dov Dori. *Object-Process Methodology: A Holistic Systems Paradigm*. Springer, Berlin, 2002.

[Gar 2000] Peter Gärdenfors. *Conceptual Spaces: The Geometry of Thought*. A Bradford Book. MIT Press, Cambridge (Massachusetts), 2000.

[Gen 1992] Michael R. Genesereth and Richard E. Fikes. Knowledge Interchange Format Technical Report Logic-92-1, Stanford Logic Group, Stanford, 1992.

[Geu 2007] Geuvers, H., M. Nigqui, B. Spitters, F. Wiedijk. Constructive analysis, Types and Exact Real Numbers. Math. Struct. in Computer Science, vol. 17, vol. 17, pp. 3-36

[Gra 1999] Jorge J. E. Gracia. *Metaphysics and Its Tasks: The Search for the Categorial Foundation of Knowledge*. SUNY series in Philosophy. State University of New York Press, Albany, 1999.

[Gru 1993] Thomas R. Gruber. A translation approach to portable ontology specifications. *Knowledge Acquisition*, 5(2):199–220, 1993.

[Gua 1992] Nicola Guarino. Concepts, attributes and arbitrary relations: Some linguistic and ontological criteria for structuring knowledge bases. *Data & Knowledge Engineering*, 8(3):249–261, 1992.

[Gua 2004] Nicola Guarino and Christopher Welty. An overview of OntoClean. In Steffen Staab and Rudi Studer, editors, *Handbook on Ontologies*, International Handbooks on Information Systems, chapter 8, pages 151–159. Springer, Berlin, 2004.

[Gua 2000] Nicola Guarino and Christopher A. Welty. A formal ontology of properties. In Rose Dieng and Oliver Corby, editors, *Knowledge Engineering and Knowledge Management: Methods, Models, and Tools: Proceedings of the 12th International Conference on Knowledge Engineering and Knowledge Management (EKAW2000), Juan-les-Pins, France, Oct 2-6*, volume 1937 of *Lecture Notes in Computer Science*, pages 97–112, Berlin, 2000. Springer.

[Gua 2001] Nicola Guarino and Christopher A. Welty. Supporting ontological analysis of taxonomic relationships. *Data & Knowledge Engineering*, 39(1):51–74, October 2001.

[Gui 2004a] Guizzardi, Giancarlo and Gerd Wagner: Towards Ontological Foundations for Agent Modelling Concepts Using the Unified Foundational Ontology (UFO), Lecture Notes for Computer Science, vol. 3508, June 2004, pp. 110-124 doi: http://dx.doi.org/10.1007/1147248

[Gui 2004b] Guizzardi, Giancarlo and Gerd Wagner: A Unified Foundational Ontology and some Applications of it in Business Modelling. Proceedings of the CAiSE'04 Workshops. Faculty of Computer Science ands Information Technology, Riga Technical University, Riga, June 2004, volume 3. pp. 129-143. Riga, Latvia.

[Har 1964] Nicolai Hartmann. *Der Aufbau der realen Welt*. Walter de Gruyter and Co, 1964.

[Hay 1995] Patrick J. Hayes. A catalogue of temporal theories. Technical Report UIUC-BI-AI-96-01, University of Illinois, 1995.

[Hel 2004] Heller, B., Herre, H., Lippoldt, K., Löffler, M. 2004. Standardized Terminology for Clinical Trial Protocols Based on Ontological Top-Level Categories. In: Kaiser, K.,Miksch, S.,Tu, S.W. (eds.) *Computer-based Support for Clinical Guidelines and Protocols. Proceedings of the Symposium on Computerized Guidelines and Protocols.* (CGP2004), 2004 April 13-14. Prague. p. 46-60. Studies in Health Technology and Informatics, Vol.101. Amsterdam: IOS-Press

[Her 2006a] Heinrich Herre and Barbara Heller. Semantic foundations of medical information systems based on top-level ontologies. *Journal of Knowledge-Based Systems*, 19(2):107–115, 2006.

[Her 2006b] Herre, H., Heller[†], B. Burek, P., F Loebe, R. Hoehndorf,.H. Michalek. General Formal Ontology (GFO)- A Foundational Ontology Integrating Objects and Processes, Report Nr. 8 , (2006), Onto-Med, IMISE

[Her 2008a] Herre, H.. The Ontology of Medical Terminological Systems: Towards the next Generation of Medical Ontologies, this volume.

[He 2008b] Herre, H. Ontology of Mereological Systems - A Logical Approach, this volume.

[Hrm 1959] Hermes, H. Zur Axiomatisierung der Mechanik. In: The Axiomatic Method, L. Henkin, P. Suppes, A. Tarski (eds). North-Holland Publishing Company, Amsterdam, p 282-290

[Ing 1964] Roman Ingarden. *Der Streit um die Existenz der Welt I (Existentialontologie)*. Max Niemeyer Verlag, Tübingen, 1964.

[Jha 1989] Ingvar Johansson. *Ontological Investigations: An Inquiry into the Categories of Nature, Man and Society*. Routledge, New York, 1989.

[Joh 1987] Johnston, M., Forbes, G. Is there a Problem About Persistence? *Aristotelian Society* vol. 61, p. 107-135, 1987

[Kre 1974] Kreisel, G. A Notion of Mechanistic Theory. Synthese 29 (1974), pp. 16-26

[Leh 2004] Jos Lehmann, Stefan Borgo, Aldo Gangemi, and Claudio Masolo. Causality and causation in DOLCE. In Achille C. Varzi and Laure Vieu, editors, *Formal Ontology in Information Systems: Proceedings of the International Conference FOIS 2004*, volume 114 of *Frontiers in Artificial Intelligence and Applications*, pages 273–284, Amsterdam, 2004. IOS Press

.

[Len 1990] Douglas B. Lenat and Rahmanathan V. Guha. *Building Large Knowledge-Based Systems: Representation and Inference in the Cyc Project*. Addison-Wesley, Reading (Massachusetts), 1990.

[Lew 1986] Lewis, D. On the Plurality of Worlds. Basil Blackwell, 1986

[Loe 2003] Frank Loebe. An analysis of roles: Towards ontology-based modelling. Onto-Med Report 6, Onto-Med Research Group, University of Leipzig, 2003.

[Loe 2005] Frank Loebe. Abstract vs. social roles: A refined top-level ontological analysis. In Boella et al. [8], pages 93–100.

[Loe 2007] Loebe, F. Abstract vs social roles_ Towards a general theoretical account or roles. Applied Ontology, vol. 2, n.2., p. 127-158, 2007

[Lou 1998] M. Loux. *Metaphysics: A Contemporary Introduction*. Routledge, 1998.

[Mas 2003] Claudio Masolo, Stefano Borgo, Aldo Gangemi, Nicola Guarino, and Alessandro Oltramari. Wonderweb Deliverable D18: Ontology Library (final). Technical report, Laboratory for Applied Ontology – ISTC-CNR, Trento, 2003.

[Mas 2002] Claudio Masolo, Stefano Borgo, Aldo Gangemi, Nicola Guarino, Alessandro Oltramari,and Luc Schneider. Wonderweb Deliverable D17. Preliminary Report Version 2.0, Laboratory for Applied Ontology – ISTC-CNR, Padova (IT), 2002.

[Mas 2004] Claudio Masolo, Laure Vieu, Emanuele Bottazzi, Carola Catenacci, Roberta Ferrario, Aldo Gangemi, and Nicola Guarino. Social roles and their descriptions. In Didier Dubois, Christopher Welty, and Mary-Anne Williams, editors, *Principles of Knowledge Representation and Reasoning: Proceedings of the Ninth International*

Conference (KR2004), Whistler, Canada, June 2-5, pages 267–277, Menlo Park, 2004 AAAI Press.

[Nil 2001] Ian Niles and Adam Pease. Towards a standard upper ontology. In Christopher Welty and Barry Smith, editors, *Formal Ontology in Information Systems: Collected Papers from the Second International Conference*, pages 2–9, New York, October 2001. ACM Press.

[Pea 2002] Adam Pease and Ian Niles. IEEE Standard Upper Ontology: A progress report. *Knowledge Engineering Review*, 17(1):65–70, 2002.

[Pol 2001] Roberto Poli. The basic problem of the theory of levels of reality. *Axiomathes*, 12(3–4):261–283, 2001.

[Pol 2002] Roberto Poli. Ontological methodology. *International Journal of Human-Computer Studies*, 56(6):639–664, 2002.

[Psc 2002] Willibald Pschyrembel and Otto Dornblüth, editors. *Pschyrembel Klinisches Wörterbuch*. Walter de Gruyter, Berlin, 259. edition, 2002.

[Rid 2002] Ridder, L. Mereologie. Vittorio Klostermann. Frankfurt a. Main, 2002

[Roe 2002] Roeder, I., M. Loeffler. Anoval dynamic model of hematopoietic stem cell organizations based on the concept of within-tissue plasticity. Experimental Hematology 30 (2002), 853-861

[Ros 2003] Rosse, C., Mejno, J.L. A Reference Ontology for Biomedical Informatics. The foundational Model of anatomy. *J. Biomed Inform* 2003. 36: 478-500

[Rum 1999] James Rumbaugh, Ivar Jacobson, and Grady Booch. *The Unified Modeling Language Reference Manual. Object Technology Series. Addison Wesley, Reading* (Massachusetts), 1999.

[Rus 1995] Stuart Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*. Prentice Hall Series in Artificial Intelligence. Prentice Hall, Upper Saddle River (New Jersey), 1995.

[Sas 1995] Munehiko Sasajima, Yoshinobu Kitamura, Mitsuru Ikeda, and Riichiro Mizoguchi. FBRL: A function and behavior representation language. In *Proceedings of the 14th International Joint Conference on Artificial Intelligence, IJCAI 95, Montreal, Quebec, Canada, Aug 20-25*, pages 1830–1836. Morgan Kaufmann, 1995.

[Sea 1995] John R. Searle. *The Construction of Social Reality*. Free Press, New York, 1995.

[Sei 2003] Johanna Seibt. Free Process Theory: Towards a typology of processes. *Axiomathes*,
14(1):23–55, 2003.

[Sha 1994] Shahar, Y. A Knowledge-Based Method for Temporal Abstraction of Clinical Data. PhD Thesis, Stanford University, 1994

[Sid 2001] Sider, T. Four-dimensionalism: an Ontology of Persistences and Time. Clarendon Press. Oxford, 2001

[Smi 2000] Smith, B., A. Varzi. Fiat and Bona Fide Boundaries. Philosophy and Phenomenological Research 60 : 2 (2000), 401-420.

[Smi 2004] Smith, B. Beyond Concepts: Ontology as Reality Representation. In: FOIS, International Conference on Formal Ontology and Information Systems. Turin, 2004

[Smi 2005] Smith, B., Ceusters, W., Temmermann, R. Wüsteria. In: Proceedings Medical Informatics Europe 2005, Geneva; Stud. Health Technol Inform. 2005: 116: 647-652

[Smi 2006a] B. Smith: From Concepts to Clinical Reality: An Essay on the Benchmarking of Biomedical Terminologies; *Journal of Biomedical Informatics* 2006; 39: 288-298

[Smi 2006b] Smith, B., W. Ceusters. Ontology as the Core Discipline of Biomedical Informatics. In Computing, Philosophy, and Cognitive Science. C. D. Crnkovic, S. Stuart (eds.). Cambridge, Scholars Press, 2006

[Smi 2007] Smith, B. et. al. The OBO Foundry: coordinated evolution of ontologies to support biomedical data integration. Nature Biotechnology, vol. 25, Number 11, November 2007, 1251-1255

[Sow 1984] John F. Sowa. *Conceptual Structures: Information Processing in Mind and Machine*. Addison-Wesley, Reading (Massachusetts), 1984.

[Sow 2000] John F. Sowa. *Knowledge Representation: Logical, Philosophical and Computational Foundations*. Brooks/Cole, Pacific Grove, 2000.

[Ste 2000] Friedrich Steimann. On the representation of roles in object-oriented and conceptual modelling. *Data & Knowledge Engineering*, 35(1):83–106, 2000.

[Sun 2005] Eiichi Sunagawa, Kouji Kozaki, Yoshinobu Kitamura, and Riichiro Mizoguchi. A framework for organizing role concepts in ontology development tool: Hozo. In Boella et al. [8], pages 136–143.

[Suo 2004] SUO. IEEE P1600.1 Standard Upper Ontology Working Group (SUO WG) [homepage]. http://suo.ieee.org, 2004.

[Szc 1977] L. W. Szczerba. Interpretability of elementary theories. In Robert E. Butts and Jaako Hintikka, editors, *Logic, Foundations of Mathematics and Computability Theory*, volume 9 of *The Western Ontario Series in Philosophy of Science*, pages 129–145. D. Reidel, Dordrecht, 1977.

[Tar 1944] Alfred Tarski. The semantic conception of truth and the foundation of semantics. *Philosophy and Phenomenological Research*, 4:341–375, 1944.

[Tar 1983] Alfred Tarski. *Logic, Semantics, Metamathematics: Papers from 1923 to 1938*. Hackett, Indianapolis, 2. edition, 1983. ed. by Corcoran, John.

[W3c 2004] W3C. Web Ontology Language (OWL) Specifications. W3C Recommendations, World WideWebConsortium (W3C), Cambridge (Massachusetts), 2004. http://www.w3.org/2004/OWL/.

[Wei 2000] Weihrauch, K. Computable Analysis. Springer Verlag, 2000

[Wer 1912] Wertheimer, M. Experimentelle Studien über das Sehen von Bewegung. *Zeitschrift für Psychologie* (1912) , 161-265

[Wer 1922] Wertheimer,M. Untersuchungen zur Lehre von der Gestalt. I. Prinizpielle Bemerkungen.

[Wes 2993] Matthew West, Jan Sullivan, and Hans Teijgeler. ISO/FDIS 15926-2: Lifecycle integration of process plant data including oil and gas production facilities. ISO TC184/SC4/WG3N1328, July 2003. http://www.tc184-sc4.org/wg3ndocs/wg3n1328/lifecycle_integration_schema.html.

[Wil 1995] T. E. Wilkerson. *Natural Kinds*. Avebury Series in Philosophy. Avebury, Aldershot (UK), 1995.

[Wit 1922] Ludwig Wittgenstein. *Tractatus logico-philosophicus*. Routledge & Kegan Paul, London, 1922. transl. by Ogden, C. K.