General Formal Ontology (GFO)
A Foundational Ontology Integrating Objects and Processes

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Part I: Basic Principles

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Abstract This report is a living document of the Research Group Ontologies in Medicine (Onto-Med) which represents work in progress towards a proposal for an integrated system of foundational ontologies. It will be applied to several fields of medicine, biomedicine, and biology, and a number of applications are carried out in collaboration with the Center for Clinical Trials at the University of Leipzig, with the Max-Planck-Institute for Evolutionary Anthropology, and with the ICCAS at the University of Leipzig.
The General Formal Ontology (GFO) is a component of the Integrated System of Foundational Ontologies (ISFO), and ISFO is a part of the Integrated Framework for the Development and Application of Ontologies (IFDAO). The predecessor of IFDAO was the GOL project which was launched in 1999 as a collaborative research effort of the Institute of Medical Informatics, Statistics and Epidemiology (IMISE) and the Institute of Informatics (IfI) at the University of Leipzig.

Contents

1 Introduction

Research in ontology has in recent years become increasingly widespread in the field of information systems science. Ontologies provide formal specifications and computationally tractable standardized definitions of terms used to represent knowledge of specific domains in ways designed to maximize intercommunicability with other domains. The importance of ontologies has been recognized in fields as diverse as e-commerce, enterprise and information integration, qualitative modeling of physical systems, natural language processing, knowledge engineering, database design, medical information science, geographic information science, and intelligent information access. In each of these fields a common ontology is needed in order to provide a unifying framework for communication.

GFO (General Formal Ontology) is a component of ISFO (Integrated System of Foundational Ontologies), and ISFO is a part of an Integrated Framework for the Development and Application of Ontologies (IFDAO) whose predecessor was the GOL-project that was launched in 1999 as a collaborative research effort of the *Institute of Medical Informatics, Statistics and Epidemiology* (IMISE) and the *Institute of Informatics* (IfI) at the University of Leipzig. Besides ISFO the system IFDAO includes the subsequently developed modules: a *Library of Ontology Languages*, and a *System of Development Tools*. This system of tools supports the development of domain oriented and generic ontologies.

GFO exhibits a three-layered meta-ontological architecture consisting of an abstract top level, an abstract core level, and a basic level. Primarily, the foundational ontology GFO:

- includes objects (3D entities) as well as processes (4D entities) and both are integrated into one coherent framework,
- 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,
- is presented by a set of formal axioms which might be added by meta-logical links to domain specific ontologies,
- is intended to be the basis for a novel theory of ontological modelling which combines declarative specifications (theories) with algorithmic procedures,
- contains several novel ontological modules, in particular, a module for functions and a module for roles,
- 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, and adaptions that are triggered by the historical state of our knowledge, and the applications in nature and society.

The present report is the first one of a series of GFO-reports that are planned to cover all relevant topics related to GFO, from basic research to the applications in several areas. Part I (Basic Principles) sets forth the logical and philosophical basic assumptions and methods, and presents a conceptual account of the General Formal Ontology (GFO) in some detail. The forthcoming Part II (Axiomatics and Ontology Languages) presents a full axiomatization of GFO, as well as a library of ontology languages, and several tools for meta-logical analyses of formal axioms. In Part III (Applications) several applications of GFO are collected and presented. These include ontologically founded semantic wikis and tools for ontology development as well as applications in several domains as in biology, medicine, biomedicine, and economy. Finally, in Part IV (GFO Problem Book) a number of open problems is collected, and several topics for further research are presented and discussed.

1.1 Formal Ontology and Information Systems

Formal Ontology is the science that is concerned with the systematic development of axiomatic theories describing forms, modes, and views of being at different levels of abstraction and granularity. Formal ontology combines the methods of mathematical logic with the analyses and principles of philosophy, but also with the methods and principles of other sciences, in particular artificial intelligence, cognitive psychology, and linguistics. Hence, the term *Formal Ontology* is used here in a sense different from that in philosophy; it is intended to be a research area in computer science, artificial intelligence, and conceptual modelling that is aimed at the development of axiomatically founded theories that are represented by means of a formal language and describe parts of the world.[1]

At the most general level of abstraction, formal ontology is concerned with those categories that apply to every area of the world. We call this level of description *General Ontology, Top Level Ontology, or Foundational Ontology*, in contrast to the various *Generic*, *Domain Core* or *Domain Ontologies*, which are applicable to more restricted fields of interest. In the following, we adopt the term *foundational ontology* and assume that every domain-specific or generic ontology must use such an ontology as a framework and reference system.

Recently, formal ontology has been applied in various areas where the notion of an ontology is used in a very broad sense. A particular ontology is generally understood to be a description of a given domain that can be accepted and reused in all information systems referring to this domain. Sometimes even terminologies are considered as ontologies, but we take a more narrow position. Usually, the backbone of an application ontology is a taxonomy of concepts that is based on the subsumption link.

[1] Philosophy is a source for inspiration, but its contribution to the solution of conceptual modelling problems seems to be limited.

1.2 General Organization of ISFO

There is currently a debate regarding the organization of a foundational ontology. Some argue that it should be a single, consistent structure, while others argue that a foundational ontology should be a partial ordering of theories, some of which may be inconsistent with theories not situated on the same partial ordering path [42].

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.

We adopt a restricted version of the partial ordering approach. We want to use only few categorial systems (vocabularies), but we allow for a multitude of 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 exhibits an integrated and evolutionary system of foundational ontologies. These ontologies are compared and interrelated using methods of translation and interpretation. Furthermore, there should be sufficient flexibility to allow enough room for modifications and changes, by including new ontologies, and cancelling old (or parts of old) ontologies. ISFO is intended to be organized into three levels such that any of its foundational ontologies has an abstract top level (ATO), an abstract core level (ACO), and a basic level (BLO). We assume that every ACO contains the basic items of *categories* and *individuals*, and the relations *identity* and *instantiation*. Concerning the abstract top level, we see mainly two ontologies associated with it: *set theory* and *mathematical category theory*.

1.3 Applications

There is a wide range of intended applications for GFO/ISFO. One such application is to incorporate the ontological results into conceptual modeling. Current languages in use for conceptual modeling like the Unified Modeling Language (UML) [9, 48], entity relationship modeling in the database field, or the Object-Process Methodology [20] can be examined according to their ontological commitments. Moreover, extensions of these languages in terms of GFO categories could be useful.[2]

The next application leads from conceptual modelling to its utilization in software design. Against the background of the Research Group Ontologies in

[2] A UML-profile – based on the GFO-module for functions – has been developed in the context of [13].

Medicine, several software tools for the clinical domain are already in development.[3] In later stages of software development, ISFO/GFO exerts two levels of influence. On the one hand, modeling methodologies and languages can be used in the design of software applications, directing developers to their ontological assumptions and allowing them to make these more explicit. This should lead to a higher degree of correct reuse. On the other hand, the data processed by applications can be linked to or analysed in terms of the GFO.

The software application *Onto-Builder*[4] plays a central role in the latter part, particularly because one of its major purposes is to support the harmonisation of several definitional alternatives among experts within some limited domain (e.g. in the domain of clinical trials, many variants of definitions exist and have to be carefully collected and organized in order to allow for high-quality treatment within clinical trials and adequate reuse of results). A later version of the Onto-Builder may support the analysis of such definitions in terms of GFO.

A different method for using GFO involves the Semantic Web initiative[5]. One approach is to partially express GFO in a Semantic Web language, like the Web Ontology Language (OWL) [61], such that it can be used as a basis for domain-specific ontologies written in OWL. This allows for the reuse of reasoners and the collaboration with other groups adhering to the recommendations of the W3C.

Additional areas of applications for GFO include bioinformatics and biomedical domain ontologies[6], ontological modelling, medical information systems, and domain specific semantic wikis.

1.4 Related Work

Several groups are tackling the development of top-level ontologies or certain aspects of top-level ontologies. Here, we only mention a few important approaches. 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 [39, 40]. Further, two other ontologies are presented in [39], 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 [54] 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*.

[3] For more details of the applications, cf. the Onto-Med website: http://www.onto-med.de

[4] http://www.onto-builder.de

[5] Cf. the World Wide Web Consortium (W3C) website, http://www.w3.org/2001/sw/

[6] Cf. Open Biomedical Ontologies (OBO) at http://obo.sourceforge.net/ and the Gene Ontology (GO), http://www.geneontology.org/

The Standard Upper Merged Ontology (SUMO) is an effort of the P1600.1 Standard Upper Ontology Working Group at IEEE [57]. [43] provides the latest progress report. Thus far, there is no standard or draft standard for a Standard Upper Ontology (SUO) from this group. Instead, 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 supercategories, 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. [42]), including one of Russell and Norvig [49], one of John Sowa [54], as well as several others.

Similarly, Roberto Poli contributes an additional important account of ontology in the field of computer science [44]. In particular, Poli presents a theory of ontological levels (cf. [45, 46]) that is acknowledged and adopted in GFO.

Apart from recent approaches to top-level ontologies, other fields offer contributions as well. In particular, issues related to those raised herein have been discussed in knowledge representation, knowledge-based systems research as well as database and object-oriented modeling. The focus in these areas may be a different one, but often some ontological questions are touched as well.

2 Basic Assumptions and Logical Methods

This section reviews the main principles and methods from logic and philosophy that we assume when developing ontologies. The logical methods include the axiomatic method, the representation problem for categorial knowledge, and the principles of ontological reduction and mapping.

2.1 Philosophical Assumptions

First we present and discuss our philosophical position. We consider two topics: the notion and ontological status of categories, and the problem of existence. We support a realistic position in philosophy, but there is the need to clarify more precisely the term “realism”.

There is a close relation between categories and language, hence the analysis of the notion of category cannot be – in our opinion – separated from the investigation of language. Concerning the notion of existence we draw our inspiration partly from Ingarden [32], but mainly from our own ontological investigations and analyses. We use the term *entity* for everything that exists where existence is understood in the broadest sense.

2.1.1 Categories

The discussion in this section is inspired by Jorge Gracia’s ideas presented in [23], which proved to be useful for the purpose of conceptual modelling and computer-science ontologies. A general ontology is concerned with the most general categories, with their analysis and axiomatic foundation.

Categories are entities that are expressed by predicative terms of a (formal or natural) language and that can be predicated of other entities. Predicative terms are linguistic expressions which state conditions to be satisfied by an entity. Categories are what predicative terms express, their content and meaning, not the predicative terms themselves, understood as a string of letters in a language. Hence, we must distinguish: the category, the predicative term – as a linguistic entity – expressing the category, and the entities that satisfy the conditions stated by the predicative term.

The predicative term T, the expressed category C, and the satisfying entity e are mediated by two relations, $expr(T, C)$ and $sat(C, e)$. We stipulate that a category C is predicated of an entity e if and only if e satisfies the conditions that are associated to C. Equivalently we say that an entity e is an instance of a category C, or that e instantiates C. Hence, we hold that the following three conditions are equivalent: e instantiates C, C is predicated of e, and e satisfies the conditions of C.[7] Categories are designated and expressed by terms of a language. Terms of a language are words, sentences, texts, i.e., every expression that is well-formed according to the grammatical rules of the language.[8]

We assume that categories are conceived in such a way that we are not forced to commit ourselves to realism, conceptualism, or nominalism [23]. This assumption is compatible with our pluralistic approach discussed in the introduction above and it seems to be the most adequate for the purpose of computer-science ontologies and conceptual modelling. According to the approach of [23] we derive several kinds of categories from basic philosophical assumptions. We restrict these to the following basic kinds of categories: immanent categories (also called in the following universals), concepts (conceptual structures) , and symbolic structures. *Immanent categories* are not outside the world of human experience, but are constituents of this world. *Concepts* are categories that are expressed by linguistic signs and are present in someone's mind. *Symbolic structures* are signs or texts that may be instantiated by *tokens*. There are close relations between these three kinds of categories: an immanent category is captured (grasped) by a concept which is denoted (designated) by a symbolic structure. Texts and symbolic structures may be communicated by their instances that are physical tokens.

An important problem in conceptual modelling is to present (specify) categories in a formal modelling language, and to determine which conditions a formal language should satisfy to capture categories of several kinds adequately.

[7] We stipulate these equivalences for practical reasons, since more subtle distinctions seem to be irrelevant in modelling practice. A deeper investigation of the relations between satisfiability, instantiation, and predication is a project for future research.

[8] We do not assume that every well-formed expression of a language expresses a category. Hence, the categorial expressions of a language form – in general – a proper subset of all its expressions. The investigation and understanding of categorial expressions is related to logic, linguistics and cognitive science which play a dominant role in conceptual modelling and computer-science ontologies.

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.[9] For this reason we do not consider sets as categories. Sets serve as a formal modelling tool and are associated to the abstract top level of GFO.

2.1.2 Existence and Modes of Being

In [32] a classification of modes of existence is discussed that is useful for a deeper understanding of entities of several kinds. According to [32] 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 and to the levels of reality in the spirit of Nicolai Hartmann [29]. But, the theory of Roman Ingarden is not sufficiently elaborated compared with Hartmann's large ontological system. For Ingarden there is the (open) problem, whether material things are real spatio-temporal entities or intentional entities in the sense of the later Husserl. We hold that there is no real opposition between the realistic attitude of Ingarden and the position of the later Husserl, who considers the material things as intentional entities being constructed by a transcendental self. Both views provide valuable insights in the modes of being that can be useful for conceptual modelling purposes.

2.1.3 Epistemology and Ontology

2.2 The Axiomatic Method

A formal theory is a set of formalized propositions. 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, and is motivated by a number of considerations. On the one hand, a formal knowledge base contains primitive notions and axioms, on the other hand, it includes defined notions and definitions. Moreover, proofs show the logical validity of theorems. It would be ideal if one were able to explain explicitly the meaning of every notion, and then to justify each proposition using a proof. When trying to explain the meaning of a term, however, one necessarily uses other expressions, and in turn, must explain these expressions as well, and so on. The situation is quite analogous for the justification of a proposition asserted within a knowledge base, for in order to establish the validity of a statement, it is necessary to refer to other statements, which leads again to an infinite regress.

The axiomatic-deductive method contains the principles necessary to address this problem. If knowledge of a certain domain is to be assembled in a systematic way, one can distinguish, first of all, a certain small set of concepts in this

[9] The term *hereditary finite set*, for example, is an expression which denotes a category that can be predicated of sets. This category is an entity that is different from the set of all hereditarily finite sets.

field that seem to be understandable of themselves. We call the expressions in this set *primitive* or *basic*, and we employ them without formally explaining their meanings through explicit definitions. Examples for primitive concepts are *identity* and *part*.

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

How, then, can the basic notions be described; how can their meaning be characterized? Given the basic terms, we 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 and at the same time we define the given notions in a certain sense implicitly, i.e., the meaning of the basic terms is to some extent captured and constrained by the axioms. On the other hand, we agree to accept any other statement as true only if we have succeeded in establishing its validity from the chosen axioms via admissible deductions. Statements established in this way are called *proved statements* or *theorems*.

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. Other important meta-theoretical properties are completeness, and the classification of complete extensions. If several theories are considered, their interrelationships must be studied which will lead to questions regarding the interpretation of one theory in another, and identifying the more comprehensive or expressive theory.

2.3 Theory of Concepts

In this section some preliminary ideas on concepts are discussed and presented. Concepts have a complex structure that consists of interrelated particular parts, which are called *conceptual constituents* or *categorial parts*. We introduce a basic relation $catp(x, y)$ having the meaning that x is a categorial part of the concept y. In the following, we restrict to primitive concepts, i.e. concepts, whose instances are individuals. In the most simplest case a concept could be represented as a set or aggregate of predicates or attributes (as in [B.Ganter- R. Wille: Formal Concept Analysis]), and then every of these predicates would be a categorial part of the concept. Let us consider, say, the concept B of bird. B is presented by a linguistic expression designating the concept B. To B several other concepts are associated, for example those which describe the parts of individual birds. Then, there is the category of wings which is a categorial part of B. In general, a category D is a categorial part of C if for every instance e of C there exists an instance d of D such that the condition $r(d, e)$ holds, where $r(x, y)$ is some basic relation connecting the individuals x and y. Then, form, colour, weight, seize and many others are categorial parts of the concept B. The concept *liver*, denoted by L, is a categorial part of the concept of *human body* because for every instance h of the concept *human body* there is an instance l of the concept L such that l is a part of human body h. The categorial parts of a category C depend on the basic relations assumed. The following is, obviously, true. If the concept D is a categorial part of the concept C, and $E \preceq D$, then E is a categorial part C, too. The categorial parts of a concept C may be explicated by representing all categories being parts of C, and by fixing the connecting relations $r_1, \ldots, r_n$. Furthermore, if $D \preceq E$ then every instance of E is instance of D.

By using the relation $catp(x, y)$ we introduce a relation $C \preceq D$ between concepts C, D. $C \preceq D$ if and only if every categorial part of C is a categorial part of D. $\preceq$ is a partial ordering between concepts. Let ($\mathcal{CON}$ be denote the set of all concepts then the system $(\mathcal{CON}, \preceq)$ is called the *complete space of primitive concepts*, designated by $\mathcal{PCON}$. The space $\mathcal{PCON}$ can be relativized to a certain fixed extension. Let C be a (primitive) concept, and $ext(C)$ its extension. Then we introduce the set $\mathcal{CONC}(C)$ defined by the set of all concepts having the extension $ext(C)$. Obviously, $C \in \mathcal{CONC}(C)$. We postulate as an axiom that $(\mathcal{CONC}(C), \preceq)$ has a greatest element, denoted by $sup(C)$, the supremum of C. $sup(C)$ is a very large concept, that cannot be, usually, achieved, captured and presented. Capturing and representing the concept $sup(C)$ means to have absolute knowledge about the extension of C, which seems to be impossible. Nevertheless, we introduce such ideal concepts for technical reasons, to get a smooth formal theory for concepts.

The system $\mathcal{CONC}(C)$ has, in general, no least element, but we assume that there are always minimal concepts. Let us consider, for example, the set HB of human beings. There are many concepts having the same extension HB. Let us consider the concepts *genetically defined human being*, denoted *GHB*, and *socially defined human being*, denoted by *SHB*. There is no concept C such that $C \preceq GHB$, and $C \preceq SHB$ such that C has the same set of instances as GHB. Every category C being a categorial part of both GHB and SHB (for example the concept *entity*) properly extends the extension of GHB. Usually, there are more than one minimal concept in $\mathcal{CONC}(C)$, and this is an important reason why multi-inheritance cannot be avoided in conceptual modelling. This section expounds preliminary remarks about a theory of concepts, it exhibits the tip of an iceberg only. We are yet far from a more elaborated ontology of concepts, many aspects are at present not yet touched, among them the structure of concepts of higher order.

2.4 Representation of Ontologies

An ontology $\mathcal{O}$ – understood as a formal knowledge base – is given by an "explicit specification of a conceptualization" [24]. This specification – understood as a formal one – has to be expressed and presented in a formal language, and there are a variety of formal specification systems. A point to be clarified is what representation means. In the analysis of this notion we use the notion of denotation and symbolic structure. This indicates that in a representation one kind of category cannot be avoided, the category of symbolic structure. A main distinction may be drawn between logical languages with model-theoretical semantics and formalisms using graph-theoretical notations. We sketch some ideas about both types of formalisms.

2.4.1 Model-theoretical Languages

A model-theoretic language consists of a structured vocabulary $V(\mathcal{O})$ called *ontological signature*, and a set of axioms $Ax(\mathcal{O})$ about $V(\mathcal{O})$ which are formulated in a formal language $L(\mathcal{O})$. Hence, an ontology (understood as a formal object) is then a system $\mathcal{O} = (L, V, Ax)$; the symbols of V denote categories and relations between categories or between their instances. L can be understood as an operator which associates to a vocabulary V a set $L(V)$ of expressions which are usually declarative formulas. We assume the following conditions: $V \subseteq V'$ implies $L(V) \subseteq L(V')$, and $L(L(V)) = L(V)$. An ontology may be augmented by a derivability relation, denoted by $\vdash$, and by a semantic consequence relation, denoted by $\models$. Then, such an ontology takes the form of a knowledge system $(L, V, Ax, Mod, \vdash, \models)$ which includes a class $Mod(V)$ of interpretations which serves as a semantics for the language $L(V)$.

2.4.2 Graph-Based Systems

Graph-based formalisms for ontologies, as they are common for biological ontologies or at least related to medical terminologies, can be understood in the following way. Such an ontology $\mathcal{O}$ is a structure $\mathcal{O} = (Tm, C, Rel, Def, G)$. Terms Tm usually cover natural language aspects and are assigned to concepts C and relations Rel. Moreover, the relations connect concepts, which yields a labelled graph structure G over concepts, such that edges are labelled by relations. The definitions Def which are held in such systems, if any, are usually natural language definitions, sometimes in a semi-structured format. Particular systems of this kind can vary in several respects, e.g. focusing on the distinction between terms and concepts, the extent to which definitions are provided, the number of relations available, etc.; a corresponding overview and classification in the field of medical terminologies can be found in [19].

2.4.3 Frame-Based Systems

2.4.4 Hybrid Systems

2.5 Semantic Translations

The comparison of ontologies assumes a notion of semantic transformation and ontological mapping. Let $\mathcal{O} = (L, V, Ax)$ be an ontology and $V \subseteq V'$; we say that a sentence ϕ from $L(V')$ is ontologically compatible with $\mathcal{O}$ if ϕ is consistent with Ax. A *semantic mapping* (or *semantic transformation*) of an ontology $\mathcal{O}_1 = (L_1, V_1, Ax_1)$ into the ontology $\mathcal{O}_2 = (L_2, V_2, Ax_2)$ is a computable function $f : L_1 \rightarrow L_2$ such that $Ax_2 \models f(Ax_1)$. The most important semantic mappings are interpretations in the sense of logic and model theory [59].

We sketch the main ideas of the method of interpretability in the framework of theories in first-order logic (cf. [58]). A theory S is said to be interpretable in the theory T if it is obtainable from T by means of definitions. The question is which schemas of definitions are admitted, and what – in general – a definition is. The simplest case of definitions are explicit definitions which are assumed in the sequel. Let us assume that S and T are theories in the (first-order) languages $L(V)$, and $L(W)$, respectively. Translations from $L(V)$ into $L(W)$ are defined by means of codes. A code in the sense of [58] – in the simplest case – has the form $c = (1, U(x), F_1, \ldots, F_n)$, where U, $F_1, \ldots, F_n$ are formulas of the language $L(W)$ specified in the vocabulary W; here, a formula F_i is associated to every relation symbol $r_i \in V$, such that the arity of r_i equals the number of free variables of F_i. The formulas F_i serve as explicit definitions of the relational symbols r_i. A translation tr from $L(V)$ into $L(W)$ associates to every formula of $L(V)$ a formula of $L(W)$. Translations based on a code c are recursively defined (for details, see [58]).

A theory S is said to be (syntactically) c-interpretable in T if tr – which is based on the code c – satisfies the following condition:

(C) For every sentence $\phi \in L(V)$ holds: $S \models \phi$ if and only if $T \models tr(\phi)$.

Generally, a theory S is interpretable in T if a code c exists such that the translation tr which is based on c satisfies condition (C). Note that codes can be much more complicated than the simple version mentioned above.

2.6 Ontological Mappings and Reductions

In modelling a concrete domain D we start with a body of source information about D, denoted by $SI(D)$, which is usually presented in different languages (including natural language), often in a non-structured form. From $SI(D)$ a specification $Spec(SI)$ (which takes the form of a set of expressions) is constructed with the aim to capture the knowledge-content of $SI(D)$. Usually, $Spec(SI)$ is expressed in a (formal) modeling/representation language, but also in natural or semi-formal languages, here denoted by ML (modeling language). Examples of such languages are: KIF [22], Description Logics [4], Conceptual Graphs [53], and Semantic Networks, but also modeling languages like UML (Unified Modeling Language) [48] or OPM (Object Process Methodology) [20]. In general, the system $Spec(SI)$ is not sufficiently ontologically founded, and it remains the task to translate it into an ontologically founded and formal knowledge base which is formulated in some target language OL (Ontology Language). An ontological mapping translates the expressions of $Spec(SI)$ into the language OL resulting in the knowledge base $OKB(Spec(SI))$, which captures formally the ontological content of $Spec(SI)$. We say, in this case, that $OKB(Spec(SI))$ is an ontological foundation of $Spec(SI)$.

We explain the notion of ontological mapping for terminology systems. In general, a terminology system $\mathcal{T} = (L, Conc, Rel, Def)$ consists of a language L, a set $Conc$ of concepts, a set Rel of relations between these concepts, and a function which associates to every concept or relation $c \in Conc \cup Rel$ a definition $Def(c)$ which is an expression of the language L.

Let $\mathcal{T} = (L, Conc, Rel, Def)$ be a terminology system and $\mathcal{O} = (L', V, Ax)$ an (formalized) ontology called a reference ontology for $\mathcal{T}$. An ontological mapping from $\mathcal{T}$ into $\mathcal{O}$ is a (partial) function f from L into L' such that for every concept c in $Conc$ the expressions $Def(c)$ and $f(Def(c))$ are semantically equivalent with respect to Ax. In this case we may define a formal knowledge base $OntoBase(\mathcal{T}) = \{f(Def(c)) | c \in Conc\} \cup Ax$ which explicitly extracts the content in $\mathcal{T}$ and provides inference mechanisms. Note, that $\mathcal{O}$ is in general not a foundational ontology, but we assume that $\mathcal{O}$ is constructed from a foundational ontology, say GFO, by a number of well-defined steps. A detailed discussion of this method is presented in [31].

3 Meta-Ontological Architecture and Basic Principles of GFO

GFO has a three-layered meta-ontological architecture comprised of (1) a *basic level* consisting of all relevant GFO-categories, (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* (urelement) as the only meta-meta-categories.

3.1 Meta-Languages and Meta-Categories

There are two kinds of (interrelated) meta-levels, one which is based on the idea of meta-language and the other is founded on the notion of meta-category. Both kinds of abstraction are discussed in the following sections. The current document is mainly concerned with systems of categories, which arise from the principle of categorial abstraction. The architecture of meta-languages is elaborated upon and presented in Part II (Axiomatics and Ontology Languages) of this report series.

3.1.1 Meta-Languages

Let W be a world of objects. A formal language $\mathcal{L}$, whose expressions refer to the objects in W, is called an *object-level language* for W. In order to specify and communicate the meaning of these expressions, a *meta-language* $\mathcal{M}$ for the pair $(\mathcal{L}, W)$ is required. That means, $\mathcal{M}$ is a language whose expressions refer to the items included in $\mathcal{L}$ or in both, $\mathcal{L}$ and W, but which also refer to relations between $\mathcal{L}$ and W. A formal language $\mathcal{L}$ has a semantics if there is a class Sem of objects, and a relation $den(x, y)$ relating expressions of $\mathcal{L}$ to the objects of Sem. The denotation relation $den(x, y)$ stipulates a connection between a symbol x and a semantic object y.

Set theory is a convenient mathematical tool for describing and modelling arbitrary structures. Moreover, set theory is intimately tied to logical languages because the commonly accepted approach of Tarski-style model-theoretic semantics [60] is based on set-theoretical constructions. The relationship between such languages and their meta-theoretical treatment is well established. Hence, we adopt set theory as a general and an abstract modelling tool.

3.1.2 Categorial Abstraction

The other type of meta-level is related to the notion of a meta-category, which is a generalization of a meta-set or a meta-class in the set-theoretical sense. Is there a category C whose instances include all categories? In this case we say that C is a meta-category, and exclude that C is an instance of itself. C is then a meta-entity with respect to the next lower level of abstraction. This principle can be expanded to arbitrary sets of entities. 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. It is an open question whether sets of entities without any categorial abstraction exist. 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.

There are no well-established and complete principles of categorial abstraction. Furthermore, a classification of different types of categorial abstractions is needed. A *categorial similarity abstraction* tries to find 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 – perceptive 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 category. More complicated are categorial abstractions over categories, for example the category *species* in the field of biology. A specification of the category *species* captures more complex conditions that are common to all (concrete) species.

3.2 Abstract Top Ontology

The abstract top ontology (ATO) of GFO contains mainly 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 notion of existence.

The abstract top level 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:

$$\exists x(Set(x)) \wedge \neg\exists x(Set(x) \wedge Item(x))$$
$$Set(x) \wedge Set(y) \rightarrow (x = y \leftrightarrow \forall u(u \in x \leftrightarrow u \in y))$$
$$\forall xy(Item(x) \wedge Item(y) \rightarrow \exists z(Set(z) \wedge z = \{x, y\})$$
$$\exists x(Set(x) \wedge \forall u(u \in x \leftrightarrow Item(u))$$

We may constrain the expressive power of the abstract top level by stipulating that $\in$, $=$ are the only binary relations that are admitted in the formulas of the ontology.

3.3 Abstract Core Ontology

This section presents the meta-level in the architecture that is formed by abstract core ontologies. The abstract core level of GFO exhibits the upper part of GFO, in the same way as a domain core ontology is the upper part of a domain ontology.

Apart from pragmatic aspects, ACOs must first be determined by their main entity types and the relations among them, for which a certain vocabulary must be introduced. Secondly, logical interdependences of those entities and their relations need to be specified. The latter exemplify the formalization of several types of interdependence using axioms of first-order logic.

We start from the idea that the entities of the (real) world – being represented on the ATO-level by the items – are divided into *categories* and *individuals*, i.e., everything in an ontology is either a category or an individual, and individuals *instantiate* (::) categories. Moreover, among individuals we distinguish *objects*, *attributes*, *roles* and *relators*. Objects are entities that have attributes, and play certain roles with respect to other entities. Objects are to be understood in the same way as the notion of "object" in object-oriented analysis. In particular, objects comprise animate and inanimate things like humans, trees or cars, as well as processes, like this morning's sunrise.

Examples of attributes are particular weights, forms and colors. A sentence like "This rose is red." refers to a particular object, a rose, and to a particular attribute, red. Another basic relation is needed in order to connect objects and attributes. The phrases "having attributes" and "playing a role" used above are included in the basic relation of *inherence*, meaning that an attribute or a role inheres in some object. This relation illustrates the dependence of attributes and roles on entities in which they can inhere.

The difference between attributes and roles is that roles are interdependent [36]. 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. The formation of relators from roles further involves the basic relation, *role-of*.

By introducing a vocabulary for the considered entities we obtain the following signature:

$$\Sigma = (Cat, OCat, P, RCat, R; Ind, Obj, Att, Rol, Rel; =, ::, inh, roleof)$$

Cat denotes the meta-category of all categories, *OCat* represents the category of all object categories, *P* indicates the category of all properties, and *R* identifies the category of all relations. *Ind* is the category of all individuals, *Obj* designates the category of all objects, *Att* represents the category of all individual attributes, *Rol* identifies the category of all roles, and *Rel* 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. We present, as an example, a simple axiomatic fragment using the vocabulary that is related to a taxonomy of the unary predicates. [10]

$$\forall xy(inh(x,y) \rightarrow (Att(x) \wedge Obj(y)))$$
$$\forall x(Obj(x) \rightarrow \exists y(Att(y) \wedge inh(x,y)))$$
$$\forall x(Ind(x) \rightarrow \neg Cat(x))$$
$$\forall x(Obj(x) \leftrightarrow \exists y(OCat(y) \wedge x :: y))$$
$$\forall x(Att(x) \leftrightarrow \exists y(P(y) \wedge x :: y))$$
$$\forall x(PrimCat(x) \leftrightarrow Cat(x) \wedge \exists y(y :: x) \wedge \forall z(z :: x \rightarrow Ind(z)))$$

The core vocabulary Σ can be extended by categories that classify types, and by categories of individuals capturing its formal structure. The *type* is the most simple structural feature a category may possess. We start with the *primitive type* (the initial type), which is denoted by the symbol i (for individuals). Every primitive type is a type. If $t_1, \ldots, t_n$ are types, then $\langle\{t_1, ..., t_n\}\rangle$ is a type. Nothing is a type unless it follows the conditions mentioned. A category is said to be well-founded if it has a type. Two categories C_1 and C_2, are said to be extensional equivalent if they have the same instances. We may introduce a cross-level relation connecting categories with sets by postulating that for every category C, there is a set X such that $\forall u(u \in X \leftrightarrow u :: C)$. Such an axiom influences the structure of the ATO-level; if there are categories which are not well-founded, then the cross-level axiom implies the existence of hyper-sets.

The basic signature Σ of the ACO level may be extended by adding a number of meta-categories. One extension is created by adding for any finite type τ a meta-category $C\{\tau\}$ whose instances are just all categories of type τ. A special case are *primitive categories*, whose instances are individuals. Non-primitive categories can be found in every sufficiently complex field, for example, in the biological domain. Means of expressing categories of higher type have also found their way into UML, in the form of the UML elements "metaclass" and "powertype" [48].

3.4 Basic Ontology

The basic ontology of GFO contains all relevant top-level distinctions and categories. One should distinguish between primitive categories (whose instances are individuals), and higher order categories. In the present document we consider primitive categories and the category of persistants (which is a special category of second order). These categories will be be extended in the future using a number of non-primitive categories. Primitive categories and persistants of the basic level will be discussed further in the following sections and are the main content of the current report. All basic relations and categories are presented as set-theoretical relations and set-theoretical predicates. The ontology of the basic level is expressed in a formal language with restricted expressive power. We use a

[10] A full axiomatization is discussed further in Part II (Axiomatics and Ontology Language) of the report.

common (first-order) language througout all levels, but constrain the expressive power at every level, mainly by restricting the scope of the quantifiers. At the basic level, an unrestricted quantification over categories is not allowed. The basic predicates as $Proc(x)$, $Ind(x)$, $Pres(x)$, $Perst(x)$, and others, are considered (understood) to be meta-categories over the object level (domain) ontologies. $Perst(x)$ is a predicate whose elements contain those categories, which are persistants. The notion of a persistant is the result of an ontological analysis of notions as continuant, or endurant. One may extent the vocabulary of the basic level by adding further predicates, whose elements are categories. Examples of such predicates are stratum-predicates, $CatMat(x)$ is a predicate that contains all categories of the material stratum, $Cat_{tp}(x)$ is a predicate that contains all categories of a certain structural type *tp*.

Categories which are not contained within the basic level we call *domain categories*. Domain categories are related to a certain part D of the real 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. For the purpose of abbreviation we write sometimes $C[x]$ instead of $x :: C$.

Domain categories may be linked in a simple way to the basic level predicates of GFO, using domain-upper linking axioms. For example, if we want to say that a certain domain category C is a process category (i.e., all its instances are processes) we write the following linking axiom: $\forall x(x :: C \rightarrow Proc(x))$, or, by using the abbreviation $\forall x(C[x] \rightarrow Proc(x))$. Domain-Upper-Linking axioms exhibit an ontological embedding of a domain ontology into a foundational ontology.

We introduce particular notations for treating the persistants. If C is a persistant then $C[t]$ denotes the instance of C at the time-point t, and the relation $C[x, t]$ is defined by $x :: C \wedge at(x, t)$.

3.5 Numbers

Numbers are considered - in GFO - as abstract individuals. They could be placed also at the abstract top level since there is a reconstruction of numbers in the framework of set theory. We distinguish natural numbers and real numbers. Natural numbers are used to count the members of a set of entities, of objects.

3.6 Measurement

The notions of measurement combines concepts of the abstract top-level to other ontological levels. Quantitative measurement of entities, in particular, is based on the idea to associate values to entities. A value structure is given by a system $\mathcal{V} = (Val, \leq)$, where Val is a set of abstract indiviuals, called values, and a partial ordering $\leq$ on Val. Standard cases of value structures are the real and the natural numbers, and the linear ordering defined on them. A theory of measurement should include a classification of entities that may be measured. If $\mathcal{E}$ is a set of entities for which measuements can be reasonably defined then the measures for $\mathcal{E}$ are determined by a measurement function $\mu : \mathcal{E} \rightarrow Val$ which accociates the values of a value structure to the entities of $\mathcal{E}$. A theory of measurement, based on a value structure $\mathcal{V}$, includes an empirical determination of the value $\mu(e)$ of an entity e. Most of the value structures are based on numbers. The entities that can be reasonably measured include space and time, qualities of objects (form, weight, colour), size (that is related to the occupied space) and temporal extension of processes. There are many other entites to be measured, for example Moh's hardeness scale is an ordering of minerals from the softest (talc, 1) to the hardest (diamond 10).

4 Ontological Levels

We assume that the world is organized into *strata*, and these strata are classified and separated into *layers*. We use the term *level* to denote both strata and layers. According to Poli [45, 46] (based on the philosopher Hartmann), we distinguish 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 layers. We take the position that the levels are characterized by integrated systems of categories. Hence, a level can be understood as a meta-category whose instances are categories of certain kinds. 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.

4.1 Material Stratum

According to [45], we use the matter-form distinction to explain and understand specific relationships between certain kinds of entities. Thus, an atom may be understood as the matter of a molecule, the latter being already endowed with form, the molecules are the matter of the cell, and cells are the matter of multicellular entities. Each of these levels is captured by a system of categories. These categorial systems imply certain granularities; hence, granularity is a derived phenomenon. The passage from the material to the mental level cannot be understood as a matter-form dependency, here, new aspects occur with a new series of forms. The social stratum captures phenomena of communication, of economic and legal realities, language, science, technology, and morals etc.

4.2 Psychological Stratum

In accordance with Poli's work, we divide the psychological/mental stratum into a layer of awareness and a layer of personality. Awareness is comprised mostly of cognitive science subjects, such as perception, memory, and reasoning. Personality, on the other hand, is primarily concerned with the phenomenon of will, and an individual's reaction on her experiences. It is not clear where the borderline between the psychological stratum and the material stratum must be drawn. An individual subject has a relation to reality by perception, and perception is the basis for construction of phenomenal objects. Should these objects belong to the material stratum or are they included in the mental realm? We assume that a certain class of such phenomenal objects that include, among others, perpetuants, belong to the material stratum. In the more elaborated version of the report this borderline will be investigated in more detail.

4.3 Social Stratum

The social stratum is subdivided into Agents and Institutions. Agents are the bearers of the social roles that humans play. Institutions are defined as systems of interrelated social components. A social system can be considered as a network in which businesses, politics, art, language (and many other facets) both present their own features *and* influence each other.

5 Space and Time

Beginning with space and time, this section opens a discussion of GFO categories that extends over several sections. There are several basic ontologies concerning space and time. In the top-level ontology of GFO presented herein, the basic entities of space and time are chronoids and topoids; these are considered as individuals. Chronoids can be understood as temporal intervals with boundaries, and topoids as connected spatial regions having boundaries as well as a certain mereotopological structure.

5.1 Time

The GFO approach of time is inspired by Brentano's ideas [11] on continuum, space and time. Following this approach, *chronoids* are not defined as sets of points, but as entities *sui generis*.[11] 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 $tcoinc(x, y)$.

[11] The GFO approach to time is related to what P. Hayes calls the *glass continuum* [30]. Furthermore, we advance and refine the theory of [1]

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 our opinion, there are at least three conditions that a correct model must fulfill:

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

If, as is common practice, intervals of real numbers are used for modeling time intervals (with real numbers as time points), there are four possibilities for modeling the meeting-point:

1. The first interval is right-closed and the second is left-closed. This allows for two options with regard to the overlap of both intervals:
   (i) The intervals do not overlap. This conflicts with conditon (a), because a new interval can be placed between the final point of the first and the starting-point of the second interval.
   (ii) The intervals overlap at the meeting-point. This raises, however, the possibility of contradictions between properties of the first, and properties of the second process (cf. the examples below).
2. The first interval is right-open and the second one is left-closed. However, this conflicts with condition (b).
3. The first interval is right-closed and the second one left-open. This conflicts with condition (c).
4. The first interval is right-open and the second left-open. This variant fails on both conditions (b) and (c).

In contrast, the approach via the glass continuum 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. Let us consider additional examples below.

> "She drew a line with her fountain pen until there was no more ink left."
> What do the conditions (a) – (c) mean in this example?
> (a) There is no gap where there is no ink in the pen or ink in the pen.
> (b) There is a final point where the pen is not empty.
> (c) There is an initial point where the ink pen is empty.
>
> "Student X changed his course of study from physics to computer sciences by filling out the appropriate form." What do (a) – (c) mean in this example?
> (a) There is no gap where X studies nothing.
> (b) There is a final point where X is a student of physics.
> (c) There is a first point where X is a student of computer sciences.

5.2 Representation of Temporal concepts

Many temporal concepts are based on a measurement function for chronoids. We assume such a measurement function $\mu : Chron \rightarrow Real$. 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.

5.3 Space

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.[12] 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 $spart(x,y)$ if 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.

Similar to the problem of meeting processes, our approach with coinciding boundaries of topoids is useful in modeling two objects that are "right next to" each other ("touching"), i.e., with (a) no gap between them, (b) a true ending-point of the first object and (c) a true starting-point of the second. Again, a model using real numbers as representation of spatial entities must use either two closed, one open and one closed, or two open intervals of real numbers. And just as in the temporal case, this violates at least one of the conditions (a), (b) and (c).

5.4 Representation of Spatial Concepts

Similar as for time, many spatial concepts are based on measurements. Others can be defined (derived) from the basis relations introduced for space.

6 Basic Categories of Individuals

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 the first infinite cardinal number ω_0.

[12] Again, we use ideas of Brentano [11] and Chisholm [18] for our theory.

6.1 Endurants and Perdurants

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 [**?**], [**?**], and [**?**] 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 [**?**] - 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, $Caesar(t)$, while Caesar at age of 50 at s, $Caesar(s)$. Then, persistence of x implies that $x(t)$ and $x(s)$ are identical.

6.2 Presentials, Perpetuants, Persistants, and Processes

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 motiviated 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.

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 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.[13]

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 $timerestr(x, t, y)$. The relation $timerestr(x, t, y)$ 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 x 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.

6.3 Space-Time Templates of Individuals

Individuals exist in time or space in different ways. To obtain a more detailed overview of these possibilities we introduce the notion of the template of an individual. A template of an individual e is a pair $(s(e), t(e))$ of numbers that are determined using two functions s, t being defined for arbitrary individuals e. $s(e)$ is the space dimension of e, and $t(e)$ the time structure which is associated with e. The values of s may be $-1,\ 0,\ 1,\ 2,\ 3$, while those of t can be $-1,\ 0,\ 1$. $s(e) = -1$ has the meaning that e is independent from space, analogously, e is independent from time if $t(e) = -1$. We consider time entities (chronoid, boundaries) or space entities (topoids, surfaces, lines, points) as individuals. Therefore, there are 15 combinations (m, n), $m = -1, 0, 1, 2, 3$; $n = -1, 0, 1$. $(-1, -1)$ means that the individual is independent from space and time. A material structure e has the template $(3, 0)$, because e occupies a three-dimensional space region and exists at a particular time-point. A material boundary of a material structure e has the template $(2, 0)$ because any material surface occupies a spatial entity of

[13] 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.

dimension 2, which is a spatial boundary. It is not clear which of these combinations can be realized by individuals. For instance, a process p always satisfies the condition $t(p) = 1$; however, the determination of the possible values of $s(p)$ seems to be an open question. Therefore, a complete analysis of all combinations should be completed in order to determine which can actually be realized by individuals. The perpetuants play a special role since they persists through time; hence they have an indirect relation to time only. We stipulate that for a perpetuant p the value of $t(p)$ is a pair $(0, 1)$ indicating in the second argument is a chronoid, and in the first a time-point. The time-structure associated to a perpetuant p is the set of all time-points of a chronoid. The value of $s(p)$ can be 0,1,2,3, depending on the spatial dimension of the presentials which are related to p by the relation $exhib(x, y, t)$.

7 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 entites, and it consists of an amount of substrate. One may assume that every space region is occupied by some material structure which is composed of solid bodies, fluids and gases.

7.1 Material Structures, Space, and Time

A material structure S is a presential; hence, it exists at a time-point t, denoted by $at(S, t)$. Furthermore, a material structure S exhibits the ability to occupy space. This ability is based on an intrinsic quality of S, which is called its *extension space* or *inner space*. The relation $extsp(e, S)$ defines the condition that e is the extension space of S, and the extension space is regarded a quality similar to its weight or size.

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. 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.

For $occ(x, y)$, we may ask whether for every spatial part of y there exists a uniquely determined material structure z that occupies y. In this case z is called a *material part* of x; this relation is denoted as $matpart(z, x)$. Such a strong condition is debatable because it might be that the substrate that a material structure comprises has non-divisable atoms. For this reason we introduce the relation $matpart(z, x)$ as a new basic relation, and stipulate the axiom that $matpart(z, x)$ implies that the region occupied by z is a spatial part of the region occupied by x. Because granularity plays a role here, we separately stipulate to this condition for every fixed occupation-relation separately.

A spatial region T *frames* a material structure S if the location that S occupies is a spatial part of T. 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.

7.2 Material Structures and Substrates

Every material structure consists of an *amount of substrate*. An amount of substrate may be understood as 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. We introduce the predicates $Substr(x)$ and $PSubstr(x)$, where x is an amount of substrate, and x is a presential amount of substrate, respectively. The basic relation $consist(x, y)$ means the material structure x consists of the (presential amount of) substrate y. There are several kinds of substrates, they may be classified as solid, fluid, and gaseous substrates. Let x be an amount of substrate; in which way can one say that an amount of substrate persists, i.e., there is a persistant whose instances are amounts of substrate? Consider, for example, an amount G of gold. G may undergo several changes; many different forms may inhere in G at different time-boundaries. There may be rings, teeths, broochs, lumps etc., whose substrates contain the "same" G as parts. Furthermore, there is an ontological connectedness between this G at different time-boundaries. There are several properties that can be attributed to x (solidity, fluidity, gaseity). Hence, material structures are constituted by (presential) amounts of substrates, boundaries, forms, and other presential qualities (color, weight). Basic relations then bring these constituents together to form the whole of a material structure.

7.3 Boundaries of Material Structures

Let x be a material structure which occupies a topoid T and let b be the spatial boundary of T. Does a material structure y exist which occupies the boundary b? This seems to be impossible because material structures occupy three-dimensional space regions, while b is two-dimensional. Nevertheless, we assume that such material entities exist, and we call them material boundaries. These are dependent entities that 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 the boundary of a material line. We introduce the basic relation $matb(x, y)$ with the meaning x is a material boundary of the material structure y. One may ask whether a material boundary of a body B is a kind of "skin", a very thin layer that is a part of B. We do not assume this and consider material boundaries as particular dependent entities.

In contrast to spatial and temporal boundaries, material boundaries cannot coincide. Instead, in order to explain the notion of two material boundaries touching each other, their spatial locations must be considered. 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. Cognitive aspects may refine this dependency. For example, the spatial boundary occupied by a material boundary may depend on an observer's distance from the considered objects.

Our notion of material structure is very general; almost every space-region may be understood as the location of a material structure. Without an elaborated account of unity, we single out material objects as material structures with *natural material boundaries.* A body is a connected material object that consists of an amount of solid substrate. An organism is an example of a body. The notion of a natural material boundary depends on granularity, context and view. This notion can be precisely as defined. Let us consider a material structure S, which occupies a topoid t and let B the material boundary of S which occupies the boundary b of t. A part A of the boundary B is considered to be natural if two conditions are met (1) there is a material structure $P(A)$ outside of S such that $P(A)$ and S touch at A (the spatial boundary occupied by A) and (2) $P(A)$ and S (or a tangential part of S with boundary A) can be distinguished by a property. Examples of such properties are fluid, solid, 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.* [15]

How can two things – the water and the air – be in contact and yet be separated? Leonardo's problem can be analysed as follows. 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.

7.4 Universals of Material Structures

There are several criteria that could be used for a classification of material structures. For simplicitiy, we assume that the material strcutures considered have a maximal natural boundary. The most basic distinctions of material structures refer to topological properties and morphological properties. We summarize some distinctions. A material structure is boundary-connected if its maximal (natural) boundary is itself connected. We may count the the number of maximal connected components of the structure's greatest boundary. Furthermore, we may classify the topological types of the occupied topoids (these are related - to some extent - to the classifixcation of three-dimensional manifolds which are embedded into the R^3).

Unlike the approach of Casati-Varzi, the notion of a hole should be understood as property of the topology and the morphology of the natural boundary of a material structure.

8 Temporal Complexes, Processes, and Occurrents

Temporal complexes are the most general kind of concrete individuals which have a temporal extension. The temporal extension of a temporal complex is a mereological sum of a non-empty set of chronoids. Processes form the most important sub-class of temporal 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.

8.1 Temporal Complexes

A temporal 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 temporal complex tc; we say that tc is projected onto the time-region tr. A temporal complex is said to be connected if its projection to time is a chronoid.

We generalize the relation $timerestr(x, t, y)$, introduced in section 6, to arbitrary temporal complexes x. 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.

8.2 Processes

The set of processes is a proper subset of the set of connected temporal complexes. Not every connected temporal 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. Hence, we postulates the following axiom:

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

We assume, furthermore, that every chronoid is a temporal projection of a process. Accordingly, there does not exist empty time in the world.

$$\forall x(Chron(x) \rightarrow \exists y(Proc(y) \wedge prtime(x, y))$$

This axiom says that the function $Prtime(x) = y \leftrightarrow prtime(x, y)$ is surjective for the set of chronoids. What can be said about the structure of the set $PR(c) = \{p \mid Prtime(p) = c\}$, whereas c is a chronoid? We assume that this set is infinite for every chronoid. Does there exists a process P in $PR(c)$ such that every proccess of $PR(c)$ is a layer of P?

8.2.1 Processual Parts and Extensions of Processes

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, denoted by $procpart(p, q)$, then the temporal extension of p is a temporal part of the temporal extension of q. We may ask whether for every temporal part d of the temporal extension of q there exists a processual part p of q whose temporal projection is d. We leave this open and introduce the following weaker axioms:

$$procpart(x, y) \wedge prtime(x, u) \wedge prtime(y, v) \rightarrow tpart(u, v)$$

$$procpart(x, y) \wedge prtime(x, t) \rightarrow timerestr(y, t, x)$$

Another temporally derived notion is the idea of *meeting* processes. 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.

8.2.2 Processual Boundaries

If a process p is restricted to a time-point of its temporal extension c 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. We do not assume that for every p and t such a presential e exists, satisfying $timerestr(p, t, e)$. Instead we formulate a weaker condition:

$$procbd(p, t, e) \rightarrow Pres(e)$$

$$procbd(p, t, e) \rightarrow timerestr(p, t, e)$$

The boundaries of processes are not considered to be processual parts of processes, because parts of processes are themselves processes and cannot exist at a single time-point. Furthermore, processes cannot be considered as mere aggregates or sets of their boundaries. Hence, our theory of boundaries differs significantly from the theory of stages in a 4-dimensional setting [Theodor Sider: Four Dimensionalism]. In a general sense, a presential identified as a process boundary will be classified as a *configuration*, i.e., a conglomeration of material structures, qualities and relators (see sect. 12). Every constituent s of that configuration e is said to *participate* in p, a relation that is expressed as $partic(s, p)$. 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.

8.2.3 Coherence

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_1, and suppose that V breaks down at a later time-point t_2 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 in 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.[14]

[14] 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.

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 conncetedness, 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.

8.2.4 Layers of Processes

Apart from participation based on time-boundaries, a notion of participation of persistants is required. Consider John drinking some water, p. This corresponds to a participation relation between the persistant j_{pers} and p, because every presential instance of j_{pers} is constrained to a single time boundary. On the other hand, the persistant gives rise to a part or a "layer" of the process, not cut along the temporal dimension, but regarding persistant participants. Such parts of a process are called *processual roles*, because they essentially capture the role of the participant in a process. In the given example, John plays the role of the drinker, while the water has the role of the "drunken". To a large extent, processual roles exhibit the character of processes, i.e., they are temporally extended entities. However, the processual roles of a process are mutually dependent, i.e., they cannot exist independently.

The notion of processual roles can be generalized as a *structural layer* of a material process, i.e. a process whose boundaries are material structures. A structural layer q of some process p is a "portion" of p satisfying the following conditions:

1. q is a process, such that every boundary contains a material structure,
2. p and q are projected onto the same chronoid, and
3. Let t_1, t_2 be arbitrary time-boundaries of the framing chronoid of p, such that t_1 occurs before t_2, and let $procbd(q, t_1, e)$ and $procbd(p, t_2, f)$. Then: if m is a material structure that is contained in the q-boundary e, and n is a material structure that is contained in the p-boundary f, and m, n are ontically connected, $ontic(m, n)$, then n is contained in the corresponding q-boundary g, where $procbd(q, t_2, g)$.

Layers of a process 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.

8.2.5 Mereological Structure of Processes

The layer of a process can be understood as a particular part of it, captured by the relation $layerpart(x, y)$, with the meaning, that x is a layer of the process y. Until now, we introduced the part-of relations $procpart(x, y)$ and $layerpart(x, y)$. 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. One may ask whether for any chronoid c there exists a process P such that every process with temporal extension c is a layer-part of P.

8.3 Occurrents

Occurrents are classified into events, changes, and histories. These entities depend on processes and are relatively defined with respect to universals.

8.3.1 Changes

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 a good 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.

Discrete Changes

Relying on those universals, we finally arrive at the following relations: Discrete changes are represented by $dischange(p, e_1, e_2, u_1, u_2, u)$ [15] , where e_1 and e_2 capture the pair of coincident process boundaries[16]. 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

[15] 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.

[16] 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:

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

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.

Continuous change

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 $contchange1(p, q, u, \Delta c)$ is intended to formalize this approach.

Changes can only be realized in terms of ontical connectedness and persistants (cf. sect. 6.2), in order to know which entities must be compared with each other to detect a change.

8.3.2 Events and Coinciding Boundaries

In this section we discuss the notion of an event and investigate the propoerties of coinciding boundaries of processes.

Events and Extremal Boundaries

Events are entities that exhibit a certain behaviour 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 continuos 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 resepct to the universals u, u_1, u_2, denoted by $stevent(p, e, u_1, u_2, u)$ if every boundary right from e, within a certain initial segment of p is an instance of u_2, 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 $u_1 : B$ is empty, $u_2 : B$ 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.

Properties of Coinciding Boundaries

Since every process is prolonged in the future there arises the question which types of coinciding boundaries may occur. Let e_1, e_2 two coinciding boundaries of the processes p_1, p_2 whereas e_1 is the right boundary of p_1 and e_2 is the left boundary of p_2. In classifying the possible situations we consider four universals u_1, u_2, u_3, u_4 being pairwise extensional disjoint such that all of them are subsumed by a suitable universal u. [17] The quadruple $(u_{i_1}, u_{i_2}, u_{i_3}, u_{i_4})$ expresses the condition that e_1 instantiates u_{i_2}, e_1 instantiates u_{i_3}, there is an endsegment of p_1 whose boundaries instantiate u_{i_1}, there is an initial segment of p_2 whose boundaries instantiate the universal u_{i_4}.

We select some special cases. If $u_{i_2} \neq u_{i_3}$, and $u_{i_1} \neq u_{i_2}$, $u_{i_3} \neq u_{i_4}$, then the pair (e_1, e_2) forms a discrete change, and, furthermore, e_1 is an event of p_1, and e_2 is a starting event of p_2. It is an open question whether this situation may be realized by processes p_1, p_2. The following situation may be simply realized. Let be $u_{i_2} = u_{i_3}$, $u_{i_1} \neq u_{i_2}$, $u_{i_3} \neq u_{i_4}$. Then, this situation is realized by the above example of the processes p_1 of filling a pool and the process p_2 of emptying the pool. The universals $u_{i_2} = u_{i_3}$ describe the filled pool, and u_1, u_4 describe the non-filled pool.

8.3.3 Universals Determining Changes and Events

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

[17] The suitability of such a universal u must be made precise, yet.

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. Relative to which universals changes should be considered? We consider - for simplicity - the case that all categorical parts of the universal u are property universals. Let us assume that $v_1, ..., v_n$ are all property universals occurring as categorial parts of u. If e_1, e_2 presents a discrete change with respect to u, then there a sub-universals u_1, u_2 of u whose categorical parts are sub-universals of the property universals $v_1, ..., v_n$ such that $u_1 \cap u_2 = \emptyset$. In this case the material structure e_1 changes its individual properties, and we have to consider whole bundles of properties. In cases that we consider purely quality processes, the boundaries are individual properties (qualities), and we must take into consideration that the type of the quality preserves.

8.3.4 Histories

Histories 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.

8.4 Immanent Structure 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 sccording to their combinations. First, there are processes in which all (non-coinciding) internal boundaries determine subprocesses that exhibit continuous changes. These are continuous processes, described e.g. in mechanics (vergl Hermes: Axiomatic Method).

8.4.1 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 subuniversals 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 mimimal subuniversal 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 subuniversal then any u-state is a strong u-state. Strong u-states are already determined by certain minimal universals.

8.4.2 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.

8.4.3 Discrete and Discrete-Continuous Processes

Discrete 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-Continuous Processes

These processes are formed of discrete processes and continuous parts, hence such a process is e mereological sum of discrete and continuous processes.

8.4.4 Discreteless and General Processes

Disreteless Processes

A process is said to be discreteless if it does not contain any discrete change. Continuous processes are always, by definition, discreteless. Is every dsicreteless process continuous?

General Processes

In this section we 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 ares pairwise extensional disjoint. Let f be a function $Bd(I) \longrightarrow \{u_1, \ldots, u_k\}$. Does there exists a process p such that p has temporal extension I and for every time-boundary t of $Bd(I)$ holds that $e(t)$ is an instance of $f(t)$?

In summary, three common kinds 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.

8.5 Simple and Complex Processes

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 focusses 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[18] 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*.

8.6 Processes and Space-Time-Regions

Processes are not directly related to space, but such a relation can be derived from the process boundaries (which are presentials).[19]

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 $\mathit{convf}(e(t), f)$. 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.

With respect to quality processes, an additional step has to be taken, because qualities do not exhibit a direct relation to space. Therefore, for each boundary of the quality process, one must determine the material structure the quality inheres in. The construction for material-structure processes can then be applied to these material structures.

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.

8.7 Artefactual Processes

An material object is an artefact if it was designed and produced by a subejct, a human being. Similarly, we introduce the notion of a artefactual process. which is

[18] The categories of situations and situoids as discussed in sect. 12 are a first attempt to account for this in a systematic manner.

[19] This resembles the idea of "indirect qualities" in [40].

desinged by human beings. Among them there a executions of software programs, or the realization of a plan to achievce certain goals.

8.8 Categories and Patterns of Processes

Above we have presented two ways of classifying processes, first into as either discrete or continuous, and second as either simple or complex processes. However, neither is well suited as a general process classification, because the first case is a relative notion, whereas the second one is very structural in nature and appears useful from a technical point of view. Philosophical literature offers some other classifications which we analyze below.

Casati and Varzi [16] draw a classical distinction of what they call events ("things that happen") between *activities*, *achievements*, *accomplishments*, and *states*[20]. This classification is summarized in table 1. The classification criteria are homogeneity, culmination, and instanteity. An event is homogeneous if the same description applies to its sub-events. Culmination is understood as having a natural finishing point. Instantaneity refers to the duration of the event.

Type of Event	**Homogeneity**	**Culmination**	**Instantaneity**	**Example**
Activity	homogeneous	never culminates	extended in time	John is walking uphill.
Accomplishment	not homogeneous	may culminate	extended in time	John is climbing a mountain.
Achievement	not applicable	is a culmination	instantaneous	John reaches to top of the mountain.
State	homogeneous	not applicable	not applicable	John knows the mountain.

Table 1. Types of events compiled according to [16]

Obviously, these types involve more kinds of occurrents than only processes. First, achievements appear to be extrinsic changes, as they are assumed to happen instantaneously. The choice of extrinsic changes, as opposed to intrinsic, is based on the notion of culmination which seems to refer to a realizable difference. States, as defined by Casati and Varzi [16] seem to refer to the realm of relations and facts, since there are no changes (in an intuitive sense) involved.

What remains are achievements and accomplishments, which are at least extended in time like processes. However, we doubt that these are an adequate classification of processes due to relying on the notion of homogeneity. Homogeneity is not a property of a process individual, but it is a property of some

[20] Note here that this is a different notion of state. A substantiation of this is given below.

process universal, like walking. Neglecting granularity aspects, one can agree that all temporal parts of an individual walking are also instances of walking. However, this is not a property of the individual. For instance, we may extend the description to "John walks from A to B.", which still refers to a walking, but more precisely to a walking from A to B. The latter is no longer homogeneous, but it has the same instance.

Culmination allows for a similar argument. It seems to be based on identifying what can be derived at the end of the process. A culminating event is associated with an end point. This does not mean, however, that a non-culminating event does not have an end point. Each walking of John finds an end, and could thus also be classified as an accomplishment in the form, John walked to X.

For the above reasons, we refrain from accepting the distinction between achievements and accomplishments as a classification for process individuals, although we acknowledge that these terms refer to process universals. Note that difficult questions of the identity of processes touch the issues just discussed. Nevertheless, we will not address such issues, as they are not in the focus of this work.

9 Properties

Things can have certain characteristics. 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 instances, which are called *property individuals*.[21] Second, both property universals and property and individuals must be distinguished from their respective values.

9.1 Property Universals and Their 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

[21] In earlier texts these were referred to as "properties" and "qualities".

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 [21][22]. Further, value structures are related to quality spaces in [39][23]. 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".

9.2 Property Individuals and Their Values

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 [39]).

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 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

[22] Note that the term "property value" here resembles Gärdenfors' notion of "property", our "property" his "quality dimension"

[23] A quality space consists of all "quales" (our property values) of some "quality" (our property)

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 $value(x, y)$.

9.3 Classification of Property Universals

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.

9.4 Properties of Processes

10 Object-Process Integration

In this section we study the inter-relations between processes and other entities. In GFO, processes are the most fundamental category of individuals. Presentials may be derived from processes; on the other hand, persistants and perpetuants play a special role, that cannot be reduced to processes.

10.1 Processes and Presentials

Presentials are dependent entities, they depend on processes, they may derived from processes. Every presential is a part of the boundary of process. hence we may formulate the following axiom:

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

Presentials may participate in processes, denoted by the relation $prespartic(x, y)$: the presential x participates in the process y. This is the case if a boundary of y contains x as a constituent part. We believe also in the following axiom:

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

A process is not equal to the set of its boundaries, neither it is the mereological sum of its boundaries.

10.2 Processes, Persistants, and Perpetuants

Material persistants are particular universals whose instances are material structures; they are related to those entities that are sometimes called continuants or objects, as apples, cars or houses. Material persistants represent the phenomenon of persistance through time of a material object. A material persistant P satisfies a number of neccessary conditions. For every material persistant P, there exists a process $Proc(P)$ such that the set of instances of P coincides with the set of process-boundaries of $Proc(P)$. This implies the existence of a chronoid $Chron(C)$, such that for every time-point t of $Chron(C)$, there exists exactly one instance of P at time point t. Persistants exhibit a particular kind of categorial abstraction over a collection of presentials that are boundaries of processes. The construction of persistants seems to be connected to the cognitive abilities of agents, human beings or animals. [24] [25]

10.3 Integrated Individuals

The complete specfication of a material structure, say an ordinary object, integrates three aspects into one system: the object as a presential, as a process, and as a persistant. We explain and demonstrate this interrelation and integration using an ontological analysis. Consider an everyday name like "John". What does John refer to in an ontologically precise sense? There are, obviously, three possibilities, i.e., three entities of different categories:

– John denotes a presential $Pres(John, t)$ at some point t in time,
– John refers to a persistant $Perst(John)$, or
– the name is given to a process $Proc(John)$.

[24] The ability of recognizing a human face, for example, seems to be based on the existence of a persistant which is represented in our memory as a system of features. This persistant enables us to identify a face at a time-point by verifying this face as an instance of the persistant.

[25] We emphasize that the construction of universals by cognition does not contradict philosophical realism. The idea that "objective" universals can be immediately mirrored without any intermediate step of conceptualization, i.e., without introducing concepts, would certainly be a kind of non-serious vulgar-realism.

The following connections between these three entities can be stated. Starting with an act of perception of John, we assume that a presential is recognized, 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 persistant, say $Perst(John)$. Now one may consider the extension of this persistant (which is a universal), i.e., the class $Ext(Perst(John) = \{J|J :: Perst(John)\}$. 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 third 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 projections to its time-boundaries equals the class of instances of $Perst(John)$. Such processes are called persistant-processes, and they exhibit an integration of an object (a continuant, a persistant) with a process. Furthermore, we see that the presentials associated to John can be derived from a process by taking the projections of this process to time-boundaries. On the other hand, the persistant $Perst(John)$ cannot be directly derived from a process because a categorial abstraction must be taken into consideration. Hence, the system $(Perst(John), Proc(John))$ represents the complete information about the entity whose name is "John". The categorial abstraction over the presentialist Johns captures an important aspect of John's personal identity.[26]

Finally, we show that a complete understanding and decription of concrete individuals needs all three 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 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 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.

10.4 Integrated Information Schemata

How the information about integrated individuals can be represented? Let us consider a person P, say a patient. First, we summarize relevant medical information about P, and then we show that all these informations may be extracted from the integrated individual and the environment in which this individual takes place. Hence, we have to consider a system $(\mathcal{I}(P), \mathcal{E}(P))$. This system is the basis for representing medidal information in electronic health care records.

[26] 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.

11 Relations, Facts, and Propositions

To put it in simple terms, *relations* are entities that bind things of the real world together whereas *facts* are constituted by several related entities considered together with their relation. Every relation has a finite number of *relata* or *arguments* that are connected or related. The number of a relation's arguments is called its *arity*. We admit the possibility of *anadic* relations, i.e., relations with an indefinite number of arguments. Further, the relata of a relation can play the same or different *roles* in the context of the relation. Examples are: a nose being part-of a head, an inflammation being more severe than another, a file being to the left of another, being a patient of a physician, being a participant of a clinical trial, being a student of a university, being related by attending the same lecture.

11.1 Relations, Relators and Relational Roles

Let us first consider the connection between a relation and its arguments (referring to facts on an intuitive basis). At this point, a particular fact seems to involve a relation and particular arguments. John's being a patient of hospital A is one fact, while the same John's being a patient of hospital B amounts to a different fact. Different particular arguments are involved in these facts, but the same relationship appears, namely "being a patient of". For this reason we assume that relations exhibit a categorial character.[27]

As a consequence, we must identify the instances of a relation. In contrast to the extensional definition of relations in a mathematical reading, we do not consider the mere collection of the arguments with respect to a single fact, as an instance of a relation. For example, the pair $(John, hospitalA)$ is not an instance of the relation "being a patient of". Instead, we assume that there are individual entities with the power of connecting other entities (of any kind). These connecting entities are called *relators* or relation individuals, and they are the instances of a relation. Relators themselves offer an "internal" structure that allows one to distinguish the differences between the way in which the arguments of a relation participate in a fact. Returning to the example, John is involved differently in the fact of being a patient of hospital A, as is the hospital. Exchanging John and the hospital would result in a strange sentence like "the hospital A is a patient of John". We say that John and the hospital play different roles in that relationship. Formally, this leads us to the introduction of an additional type of entity: *relational roles*[28]. A relator can be decomposed into relational roles, such that each role is a mediator between exactly one argument and the relator.

Now, the link between an argument and a relator can be completed. The relationship between relators and roles is called *role-of*. As indicated in [37, 36],

[27] Identifying the subcategories of the category to which relations belong, i.e. whether relations can exist as universals, concepts and the like, remains to be analyzed.

[28] For convenience, "role" is used as an abbreviation for relational role this section.

role-of might be understood as a subtype of an abstract part-of relationship (namely between roles and relators), but we will not adopt this definition until a sound standing comparison of the role-of and part-of relations is available. Further, roles must be connected with the relata of the relator. This purpose is served by the basic relation *plays*. It is then subsumed by the basic relation *dependent-on*, because roles are a specific kind of dependent entity: they are dependent on their player (which is the relatum) and on complementary roles (such that the totality of involved roles constitutes the relator).

11.2 Facts and Propositions

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. [2, 64].

Further, facts are frequently discussed in connection with other abstract notions like propositions (cf. [38, chapter 4]), 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 [7]. 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 (discussed in sect. 12). 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 $F(R)$.

11.3 Propositions

12 Situoids, Situations, and Configurations

In this section we survey some basic notions about the most complex entities in reality, namely situations and situoids.

12.1 Situations and Configurations

Material structures, properties, and relators (see sect. 11.1) presuppose one another, and constitute complex units or wholes. The simplest units of this kind are facts (cf. sect. 11.2). 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.

12.2 Situoids and Configuroids

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 $\mathit{tframe}(s, x)$, and $\mathit{sframe}(s, y)$. Note that the relation $\mathit{tframe}(s, x)$ is equivalent to $\mathit{prt}(s, x)$, since a situoid is a process. The relations $\mathit{prs}(s, x)$ and $\mathit{sframe}(s, x)$ are different, though, such that the following relation is satisfied: $\mathit{prs}(s, x) \wedge \mathit{sframe}(s, y) \rightarrow \mathit{spart}(x, y)$.

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 $\mathit{prt}(a, c, b)$, 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 $\mathit{prb}(a, t, b)$, are situations. In every situation, a material structure is contained, and we say that a presential e is a constituent of a situoid s, $\mathit{cpart}(e, s)$, 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 8.2). 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.

12.3 Situoids and Tuthmakers

12.4 Ontology of Contexts

13 Roles

Roles are common in modeling, yet they have lingered in the background and only in recent years have they attracted focused interest (cf. [8]), although there are much earlier approaches dealing with roles as a central notion, as in [5]. 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 [37, 36]. Here we provide a compact introduction to the general understanding of roles as well as the current state of role classification.

13.1 General Approach

Starting with a *role* r, there are two directly related notions, namely *player* and *context*.[29] 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,[30] and *role-of* ($roleof(x, y)$), which ties a role x to its context y. In terms of the "standard" role example of

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

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

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*[31], cf. [27]. 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. [37].

13.2 Classification of Roles

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.

Note that relational and processual roles have been discussed earlier, in the sections on their corresponding context categories (see sect. 8 and 11, respectively). 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.

13.2.1 Relational Roles

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

[31] Other terms in the literature are *natural type* [25], *natural kind* [63], *phenomenon* [54, p. 80], *base classifier* in UML [48, p. 194 ff.], and *basic concept* in [56].

instantiating “multiple”. The first of these role individuals is played by two, while four plays the second role individual.

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”.

13.2.2 Processual Roles

Processual roles have processes as their contexts. As such they are processes themselves, and sect. 8.2.4 identifies 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” [37]. Given this abstraction, we can now introduce a final type.

13.2.3 Social Roles

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. [55]. 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 [51] and the ontological levels of Poli [45], 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. [51]. 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.

13.3 Meta-level Status of Roles

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 [28, 41]. 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.

14 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.

14.1 Structure of Functions

The pattern of the specification of a function F, called a function structure, is defined as a quadruple $STR(F) = (Label(F), Req(F), Goal(F), Fitem(F))$, 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 [17]. 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.

14.2 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 [50]. 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.

14.3 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 [13].

14.4 Ontological Status of Functions

15 Social Ontology

16 Ontology of the Psychological Stratum

The psychological stratum has its own structure, it is associated to subjects, sometimes called (particularly in the field of artificial intelligence) agents. We assume that psychological/mental entities have no independent existence, but they are founded on/in material objects. Mental entities emerge out of biological entities and it is an open problem where the borderline should be drawn between material and mental entities. We assume that every human agent has a mental level that divides into two basic components, one is called awareness, the other personality. Awareness is comprised mostly of cognitive science subjects, such as perception, memory, and reasoning. Personality, on the other hand, is primarily concerned with the phenomenon of will, and an individuals's reaction on her experience. The mental level of a human agent is not isolated from the material world, there is a direct interaction between a human agent and the outside world; this interaction is mediated mainly by perception and the phenomenal objects constructed out of them. We call these phenomenal objects intermediate entities, they may be put to/on the side of the material stratum. Phenomenal objects can be understood as dispositions of physical objects that come to appearence in the mental level of an individual subject.

These phenomenal entities are the individuals of the medioscopic material stratum that was described and investigated in the preceding sections of the report. Phenomenal individuals constitute the basic for every higher order activities of the mind, for memory, reasoning, language, and communication.

17 Ontologically Basic Relations and Basic Categories

Sections 5 to 14 presented several categories of entities, reticently accompanied by formal relations among entities of these categories. We consider some of these formal relations as basic relations that will not be defined explicitly, but which must be characterized axiomatically. We briefly summarize important representatives of formal relations in the GFO in the following subsections.

17.1 Entity and 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 [33]. It turns out that the notion of existential dependency is very vague. In this section we present our own approach to this relation. The classical definition of existential dependence (or ontological dependence) is given by the following doubtful definition.

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

This definition uses modalities in can be translated into a formal definition which introduces a problematic predicate $Ex(x)$. The predicate $Ex(a)$ has the meaning that the entity a exists. If we assume that we consider only entities that by definition exist then the predicate $Ex(x)$ is equivalentt to $x = x$. The formalization of the above definition takes the following form.

$depends(x, y) =_{df} \Box(Ex(x) \rightarrow Ex(y))$.

Now, we may postulate that $Ex(x) \leftrightarrow x = x$. If we replace $Ex(x)$ by $x = x$ then we get the new formula $\Box(x = x \rightarrow y = y)$, which is a trivial tautology. One may doubt whether the replacement of formulas by other - equivalent formulas - is allowed in modal contexts (in the scopus of a modal functor).

17.2 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. Usually, the notation $\in$ is used for type-free systems (e.g. ZF), but it may be adapted for typed languages. $x \in y$ 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: $x \subseteq y =_{df} \forall z(z \in x \rightarrow z \in y)$. We include in the ontology of sets an axiomatic fragment of formal set theory, say of ZF, in particular, the axiom of extensionality:

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

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 $supp(x) = \emptyset$.

17.3 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: $ext(x, y) =_{df} Set(y) \wedge \forall u(u \in y \leftrightarrow u :: x)$. 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.

17.4 Property Relations

Further, several relations connect properties (or individual property instances), their values and their bearers as introduced in sect. 9. 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 and y to the value.

17.5 Parthood Relation

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

17.5.1 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, i.e., the following axioms:

$$p(x, x),\ p(x, y) \wedge p(y, x) \rightarrow x = y, \text{ and } p(x, y) \wedge p(y, z) \rightarrow p(x, z).$$

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.

17.5.2 Part-of Relation for Sets

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

17.5.3 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.

17.5.4 Part-of Relation for Material Structures

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

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

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

17.5.5 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:

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

$prt(x, u)$ 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.

17.5.6 Role-of

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.

17.6 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.

Space and time entities with an extension allow for the notion of *congruence*, e.g. two topoids are congruent if they share exactly the same size and shape. The relation of congruence is mentioned in section 5.3.

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 (cf. sect. 5). 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.

17.7 Relation of Concrete Individuals to Space and Time

Concrete individuals have a relation to time or space.

17.7.1 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.

17.7.2 Processes

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 and $partic$.

17.7.3 Framing

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".

17.8 Participation

Participation, denoted as $partic(x, y)$, relates presentials and persistants to processes. Participants in a process form an orthogonal axis of division for processes, compared to the more common division into temporal parts. Splitting processes based on participants results in *processual roles*. The relationship of participation is introduced in section 8.2.2. It can be defined in terms of the projection relation, prb.

17.9 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 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.

17.10 Ontical Connectedness

Presentials are connected by spatio-temporal and causal relationhips, which give rise to persistants. 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.

17.11 Causality

In the present state, *causality*, the relation between causes and their effects, is seen as a special relation between presentials (contrary to the DOLCE account as given in [34]). 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.

18 Applications of GFO

We will now show a few exemplary applications of GFO, from specific analyses to more general considerations.

18.1 Examples

18.1.1 Example for Comparison: The Statue

The following example is discussed in [39], for the DOLCE and other approaches therein. We refer to the formalization in the framework of DOLCE only. A formalization in GFO is expounded and then compared to the DOLCE formalization.

Source Material

The example is stated as follows in [39]:

> "A statue of clay exists for a period of time going from t_1 to t_2. Between t_2 and t_3, the statue is crashed and so ceases to exist although the clay is still there."

Ontological Analysis

Many entities can be identified on the basis of the statement. The term "statue" may have different meanings; we assume that "statue" denotes a persistant *st* of material objects, with a certain lifetime *c*, which we assume to be a chronoid. "clay" is an amount of substrate *cl*. The statue *st* consists of the amount of clay *cl*. More precisely, at each time-boundary at which a presential instantiates the persistant *st*, there is a presential amount of substrate of which the instance of *st* consists:

$$\forall x, t(persist(st, x, t) \wedge substrate(cl, y, t) \rightarrow consist(x, y))$$

The demolition is a process *cr*, in which many different (sub-)processes and material structures may be involved. The demolition is projected onto a framing chronoid, say *d*, with starting time-boundary *s*, and ending time-boundary *t*:

$$prt(cr, d) \wedge lb(s, d) \wedge rb(t, d)$$

The original statement refers to three time-boundaries, t_1, t_2, and t_3, and the following ordering holds among them: $t_1 \leq t_2 \leq s \leq t \leq t_3$[32]. The statue exists from t_1 to t_2, thus one can assume that *c* starts with t_1, therefore $lb(t_1, c)$. We may further expect that at *s*, the statue is present, but at *t*, the statue ceased to exist. Further, *st* participates in the beginning of the demolition, *cl* in the whole event.

$$\forall x, y(persist(st, x, s) \wedge procb(cr, s, y) \rightarrow cpart(x, y))$$

$$perstpartic(st, cr) \wedge perstpartic(cl, cr)$$

The lifetime of *st* and the framing chronoid *d* overlap, more exactly there is a chronoid *f*, such that *f* is an end-segment of *c* and at the same time an initial segment of *d*[33]:

$$\exists f(procstarts(f, d) \wedge procends(f, c))$$

The process-boundary at *t* does not contain a constituent part that is an instance of the persistant *st*, but there is a material structure which is the "successor" of *st*, in the sense that its instances are ontically connected with those of *st*:

$$\exists st', z(MatPerst(st') \wedge persist(st', z, t) \wedge procb(cr, t, y) \wedge$$
$$cpart(z, y) \wedge \forall x(persist(st, x, s) \rightarrow ontic(z, x)) \wedge$$
$$\forall u(substrate(cl, u, t) \rightarrow consist(z, u)) \wedge$$
$$\neg \exists rvw(persist(st, v, r) \wedge persist(st', w, r)))$$

[32] Depending on the reading of "between", one may identify t_2 with *s* and t_3 with *t*, respectively. For generality, we allow for a distinction of these time-boundaries.

[33] In general, there can be a special case that the end-point of *c* and the starting point of *d* coincide. In this case, the demolition would have no temporal extension, and is considered as a change instead of a process. It could be that – from the point of view of a certain granularity – this assumption is realistic.

Finally, let us consider the point in time when the statue ceases to exist. This can be understood as an extrinsic change, such that before the change, *st* still persists, whereas after the change, it does not:

$$\exists u, v(s \leq u \leq t \wedge tcoinc(u, v) \wedge rb(c, u) \wedge \exists x(persist(st, x, u)) \wedge \neg\exists y(persist(st, y, v)))$$

Figure 2 provides a graphical overview of some connections between the aforementioned entities.

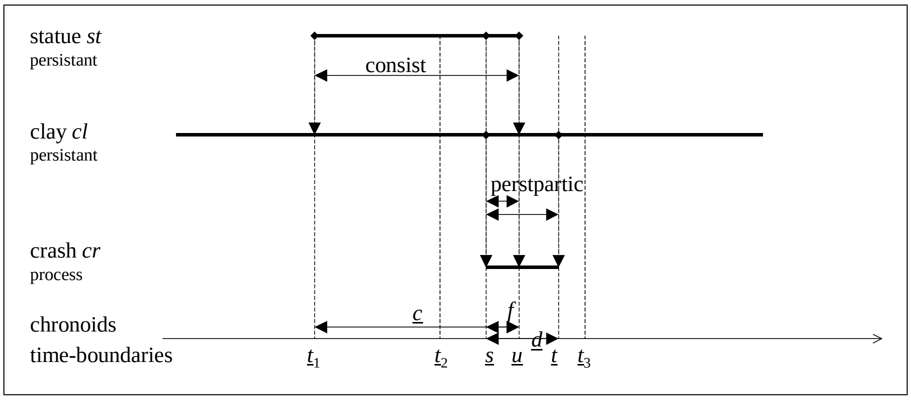

Figure 2. Visualization of some aspects of the formalization

Comparison with the DOLCE Formalization

We consider t_i to refer to time-boundaries, which is not possible in DOLCE, because it does not have this notion of a boundary. However, we consider time-boundaries more adequate, based on the expressions "going from t_1 to t_2" and "between t_2 and t_3". Altogether, relating the entities to time (and space) is different in DOLCE as compared with GFO, because there is no direct projection (e.g. *prt*), but DOLCE establishes the link to time and space as a relation to qualities.

Similarly, on the basis of time-boundaries, GFO can formalize the extrinsic change covering the particular moment when the statue is no longer considered as existent. Note that this depends on the granularity of the model, while the granularity is not yet explicitly expressible in GFO.

The remainder of the formalization appears rather similar to that of DOLCE. The relationship between the statue and the clay is covered (*DK* in DOLCE, *consist* in GFO), but note that this relation will be extended and revised in terms of the theory of levels, cf. sect. 4. The participation of the statue and the clay in the demolition are expressed in DOLCE (by *PC*) and GFO as well (*perstpartic* and *procb*).

18.1.2 Race Example

This example will provide a rough overview of the GFO ontology in a single, coherent, (but rather simple) modeling case. It employs many, yet not all applicable GFO categories.

Source Material

Let us consider a 100-metre sprint, in which two runners take part: $runner_1$ and $runner_2$. The race starts with the signal at time t_1 and lasts until t_4, when the last runner crosses the finishing line.

$runner_1$ quickly reaches a high speed and takes the first position, while $runner_2$ does not accelerate that rapidly but manages to pass $runner_1$ at t_2. At t_3, $runner_2$ crosses the finishing line, winning the race. The victory of $runner_2$ is a big surprise for the audience, so the race is broadly discussed and is announced to be the most surprising and interesting race of the decade.

Ontological Analysis

For brevity, let $m \in \{1, 2\}$ and $1 \leq n \leq 4$ in all formulae.

Situoids: The whole race can be interpreted as one complex entity extended in time, namely a situoid *race*, spatially delimited by a topoid *tp*: $sframe(race, tp)$, and temporally framed by a chronoid *c*: $tframe(race, c)$. *race* is associated with certain universals, which select the point of view and granularity. Here we assume that these universals are *runner*, *track* and *audience*, which delimit the context in which we analyze the race. So, we have $assoc(runner, race)$, $assoc(track, race)$ and $assoc(audience, race)$.

Chronoids and Time Boundaries: We have identified the chronoid *c*, framing the race. It has a left boundary t_1 as the race starts, $lb(t_1, c)$, and a right boundary t_4, where $runner_1$ crosses the finish line, $rb(t_4, c)$. Moreover, we identify two inner boundaries, $innerb(t_2, c)$ and $innerb(t_3, c)$, that are of special interest: t_2, where $runner_2$ takes the lead and t_3 where he wins the race.

Persistants: The persistence of the runners throughout the entire race is provided by viewing them as two persistants, $runner_m$, which are instantiated by ontically connected presentials $runner_{m,t}$ present at each time boundary t of the race. Each persistant persists through time, or more precisely, through the time boundaries on which its instances exist. Moreover, each persistant $runner_m$ participates in the process of the race. Analogous considerations apply to the persistence of the audience and the track.

Space Regions and Topoids: The location of the race is determined by the topoid *tp* framing the situoid *race*. The topoid *tp* is assumed to be a convex closure of the mereological sum of all space regions occupied by the material structures constituting the situations of *race*. In our case, *tp* is the sum of space regions of the presential runners, the track and the audience, across the overall period of the race.

Situations: At each time boundary t in the course of the race, one can project the race to its boundaries $race_t$, which are situations. In particular, one may consider the situations at t_n which are referred to in the example. Each of these situations is a compound of several constituents, of which those are of particular interest. They are determined by the universals associated with the situoid race. Therefore, we focus on $runner_{m,t_n}$, $track_{ind,t_n}$, and $audience_{ind,t_n}$.

Constituents / Material Structures: All constituents of the situations of the race considered here are material structures, and as such occupy some spatial region (cf. the remarks on space regions and topoids above), and consist of some presential amount of substrate. For example, we could say that *body* is a solid substrate of the runner: $consist(runner_{m,t_n}, body_{m,t_n})$.

Properties: Moreover, each material structure comes together with its individual properties. The runners or the track, for example, inhere qualities like speed, blood pressure or hardness (here: of the track). In the case of the property universal *speed*, for example, at each time boundary of the race we find an individual speed for each runner, as well as individual values of those property individuals: let the speeds of the runners at t_2 be 25 km/h and 30 mph, respectively. We observe that the individual property values are instances of the categorial property values belonging to two different measurement systems. The first measurement system is a set of values in the form of pairs of a number and the unit "km/h", while the second is a set of values with unit "mph". Nevertheless, the individual quality values 25 km/h and 30 mph are comparable, since the individual qualities they refer to, say $speed\text{-}runner_{m,t_n}$, are instances of the same property speed.

Further, one can find properties of the whole race, which seem to be indicated by the expression: "it was the most surprising and interesting race of the decade". Here we identify being-the-most-interesting-race-of-decade as the quality value of the individual quality, level-of-entertainment-of-the-race. It is clear, however, that this quality does not belong to the material, but rather to the social level. Here we do not say it inheres in *race*.

Processes: The race as a process is a combination of several processes, among them $run\text{-}runner_m$ processes. Here we can observe that either of these processes is a coherent process, the boundaries of which contain material structures, namely instances of the persistants referred to above, $runner_{m,t}$. Hence, we have $procb(runner_{m,t_n}, run\text{-}runner_m)$, and all of those instances are ontically connected (for the same m).

Changes: Moreover, we observe certain dynamics between those processes, which can be modelled using intrinsic and extrinsic changes. First, the changes in the speed of the runners can be interpreted as intrinsic changes. Second, we may identify an extrinsic change at t_2, when $runner_2$ takes the lead. To represent this change we identify two parts of the process *race*, namely $leading\text{-}runner_1$ and $leading\text{-}runner_2$.

These processes meet at t_2 which means that t_2 and a coincident time-boundary are the pair of the right boundary of the projection of $leading\text{-}runner_1$ and the left boundary of the $leading\text{-}runner_2$. The extrinsic change of taking the lead – or switching from the position of losing the race to the position of winning – by $runner_2$ is represented as change($b_1, b_2, loosing, winning, position\text{-}in\text{-}race$), with b_1 and b_2 representing the process boundaries at the end and at the beginning of $leading\text{-}runner_1$ and $leading\text{-}runner_2$, respectively. Analogously, the crossing of the finish line by the $runner_2$ could be represented, which is a change from winning to being the actual winner.

Levels: So far we have concentrated on the material aspects of the race, where runners are identified as material objects with inherent material qualities. But we should keep in mind that the runners and the race cannot be reduced to the movement of two material objects along the line of the track. Rather we identify runners as the social roles of some individuals, just as the track is the role of some solid object of a certain shape with certain properties. We see that the situoid *race*, in part, does not belong to the material level, but to the social and conceptuals level as well. At the social level, we do not consider bodies with material qualities, but rather social objects, their roles, e.g. being runners or the audience, and their social qualities, together with their corresponding values, like those of winning or losing.

18.1.3 Staging Example

This example is taken from the domain of clinical trials, one of the major fields for application of the research group Onto-Med. The example is a first attempt to define the term “staging” using GFO, and illustrates the method for ontological mappings, cf. sect. 2.5.

Source Material

There are various sources for defining staging, including discussions with medical experts. Therefore, we provide our own definition, based on discussions with our medical experts, respective literature, e.g. “Pschyrembel” [47] and “Harrison” [10], and several websites[34].

The definition is divided into three parts of overall validity, some background facts of frequent validity and general background knowledge.

Definition: Staging is a process composed of the detection of the anatomic extent of $tumor_1$[35] and the classification of the result with respect to a staging system.

Background knowledge: Anatomic extent refers to the size of the $tumor_1$, in both its primary location and in metastatic sites. The most common staging system is the TNM classification, but there are others, e.g. those used for cancers of children and those used for cancers of female reproductive organs. Staging is applied to malignant $tumors_2$. The result of staging, i.e., the classification in

[34] Each of these pages were available on 01.05.2006:
http://imaginis.com/breasthealth/staging.asp#what
http://www.cancer.org/docroot/ETO/content/ETO_1_2X_Staging.asp

[35] Note that two different notions (here: $tumor_1$, $tumor_2$) are commonly named tumor; this will be clear from below.

a staging system, is used for treatment planning, prognosis evaluation and the comparison of treatments.

There are four types of staging. *Clinical-diagnostic staging* involves what a doctor can see, feel and determine through x-rays and other tests. *Surgical-evaluative staging* involves exploratory surgery, biopsy or both. After surgery, the $tumor_1$ can be directly examined and its cells microscopically analysed, which is called *post-surgical-treatment pathologic staging*. If additional or new treatments are applied to the same disease, *re-treatment staging* uncovers the extent of the $tumor_1$.

General background knowledge: A $tumor_2$ is a disease that causes the growth of $tumor_1$ (often tumor tissue).

Ontological Embedding into GFO

Following the axiomatic method, we begin by collecting important terms from their definitions. There are: staging, process, detection, anatomic extent, $tumor_1$, classification, staging system, disease, $tumor_2$, primary location, metastatic site, size and malignant.

Now these terms can be analyzed and ontologically embedded into GFO. Each term is subsumed by a GFO category or linked to GFO categories by means of basic relations, as specifically as possible. We analyze and group terms with respect to the basic category to which they refer.

Processes: Staging is a process that is composed of two steps, a process of detection and a process of classification. Thus, staging is a discrete process. Detection and classification are processes as well, but they are not analyzed in detail here, since they will be used as domain primitives below. Further, each disease is a process, and thus a $tumor_2$, as well.

Topoids: Topoids are only indirectly involved, through the notions of "location" and "site". These refer to topoids determined relative to the body of the patient and the $tumor_1$, respectively. A $tumor_1$ may spread throughout the body. The topoid occupied by that part of the $tumor_1$ first occurring or discovered is called the primary location. Topoids of other $tumor_1$ parts (metastases) are called metastatic sites.

Configurations: Consider the anatomic extent of the $tumor_1$, which is determined and classified during staging. This should be understood as a situation rather than a single quality, although the latter may appear appropriate at first glance. This situation refers to (a) the size of the parts of the $tumor_1$ at the primary location and metastatic sites, (b) the relationship between the $tumor_1$, the involved anatomic entity and adjacent anatomic entities, and (c) possibly more relations between the $tumor_{1,2}$ and the body (cf. the TNM staging system).

Properties: First, the sizes of connected parts of the $tumor_1$ are qualities that are measured in centimeters or inches. Second, there is an evaluative quality of a $tumor_2$, which is the degree of malignity. The simplest measurement system contains just the values "malignant" and "benign", which are mutually exclusive. Usually, malignant $tumors_2$ are staged.

Material structures: A $tumor_1$ (often tumor tissue) is a material structure, which is created and (usually) growing throughout the course of the disease, i.e., $tumor_2$.

Symbolic structures: In order to fully describe the notion of a staging system, the category of symbolic structures is required. A staging system is, in the simplest case, a set of symbolic structures that denote universals of anatomic extents (viewing the extent of a $tumor_1$ as a multi-dimensional or -faceted configuration, as introduced above). However, this cannot be further analyzed without a deeper understanding of symbolic structures and the denotation relation.

Domain-specific Extension

The above descriptions provide an ontological embedding of several domain-specific terms into GFO. However, this is obviously rather weak, e.g. for staging only, a structural decomposition into two processes could be stated. In order to add domain-specific dependencies, a domain extension is necessary. That means, new primitives must be added and ontologically embedded, which can then be used to express more domain-specific interdependences.

18.2 Application of GFO to Biomedical Ontologies

Various domain-specific ontologies have been developed within the biomedical domain over the last years. For example, Open Biomedical Ontologies[36] (OBO) is an umbrella organization for various ontologies covering domains such as the anatomy of individual species, celltypes [6], or molecular functions of genes and gene products [3].

The rapid growth of biomedical ontologies in size and number leads to the problem of ontology and data integration. How is it possible for different ontologies to interoperate? How can the content of different ontologies be retrieved in a single query?

In contrast to GFO, most biomedical ontologies are represented using a weak formalism. They can be represented as a directed acyclic graph (DAG). In a DAG, the categories are represented as nodes, and the relations between the categories are represented as edges. For example, the relation that "nucleus" is part of a "cell" is represented by two nodes, "nucleus" and "cell", which are linked by a directed edge, which is labeled "part-of". These graphs are commonly used in conjunction with a minimal set of axioms, such as transitivity or symmetry.

Many of the relationships used in these biomedical ontologies can be defined in GFO. For example, the mereological relations, like part-of, are already present in GFO. It is often the case that the semantics of relations using the same name differ between different biomedical ontologies. Aligning two ontologies that use a relation with the same name in different ways requires a formalism that will allow for a representation of the differences in the two ontologies used. These

[36] http://obo.sf.net

differences are beyond the expressiveness of DAGs, but can be made precise within first order logic using the conceptualization that is provided by the GFO.

In [14], GFO has already been used to represent knowledge about biological functions in the Gene Ontology[3], the Celltype Ontology [6] and the Chemical Entities of Biological Interest (ChEBI) Ontology [12]. As shown in [14, 13], the GFO's method for describing functions using requirements, goals and a role universal leads to greater expressiveness, and the possibility for more fine-grained analyses of biological phenomena. In addition, it is possible to use this analysis to re-analyze the so-called *annotation* relation[37].

Furthermore, GFO plays a role in a curation framework for biomedical ontologies, which is currently under development[38]. This framework is based on a semantic wiki, and it allows for the formal representation of relations between concepts within the wiki. These relations are typed, in the sense that their arguments are restricted to categories, and these are based on GFO. In a sense, a core ontology is derived from the content upon which the semantic wiki is based.

GFO, however, provides the possibility for further uses in biomedical ontologies. In [14], the construction of a domain ontology based on GFO's treatment of functions is proposed. GFO can provide the conceptual means to ease the construction of additional domain-specific ontologies, and provide a common framework that will be compatible with a majority of the biomedical ontologies, in order to assist in the integration of different ontologies, and to make them amenable for automated reasoning.

18.3 Applications of GFO to Medical Terminologies

19 Comparisons With Other Foundational Ontologies

Apart from GFO, a number of top-level ontologies are proposed by different groups or persons, among them DOLCE[39] [39, 40], SUMO[40] [42], CYC[41] [35], Matthew West's 4D-ontology[42] [62], John Sowa's ontology [54], Johanna Seibt's process ontology (cf. [52]) and others. Moreover, the continuous coexistence of different top-level approaches was acknowledged at the March 2006 Upper Ontology Summit, a meeting of several representatives from some of these groups.[43] Hence, the comparison and alignment of different top-level ontologies remains

[37] The annotation relation is primarily a database relation in biomedical ontologies. In particular, it relates genes or gene products to the categories of a biomedical ontology, meaning that a gene is somehow related to a category.

[38] For progress, see http://onto.eva.mpg.de.

[39] "Descriptive Ontology for Linguistic and Cognitive Engineering"

[40] "Suggested Upper Merged Ontology", see homepage at http://www.ontologyportal.org/

[41] see http://www.cyc.com/cyc (commercial version) and http://research.cyc.com/ (research version)

[42] http://www.tc184-sc4.org/wg3ndocs/wg3n1328/lifecycle_integration_schema.html

[43] http://ontolog.cim3.net/cgi-bin/wiki.pl?UpperOntologySummit

an important task in general. Here, we compare GFO with two of the above ontologies, namely DOLCE and that of John Sowa, while further comparisons remain to be completed. The next ontologies to be included are SUMO and the ontologies of M. West and J. Seibt.

The following comparison is based on textual specifications, and is neither intended to be complete, nor to provide a formal mapping between the ontologies. Tables 2 and 3 (p. 71 and 72) present coarse mappings between GFO and DOLCE. Tables 4 and 5 (p. 77 and 78) offer analogous mappings between GFO and Sowa's ontology. Two mappings are specified for each ontology because only very few categories correspond to one another exactly, but several categories may describe one category in the other ontology. Parentheses in the right columns indicate a lower level of adequacy for a particular mapping.

19.1 Comparison to DOLCE

In this section we briefly discuss some similarities and differences between GFO and DOLCE. Figure 3 presents a tree of the DOLCE categories as shown in [39]. In reference to that report, we omit a comprehensive introduction of DOLCE herein and discuss the basic distinctions in combination with the comparison, roughly following the order of the GFO elements presented in sections 4 to 14 . For an overview of DOLCE categories, refer to figure 3.

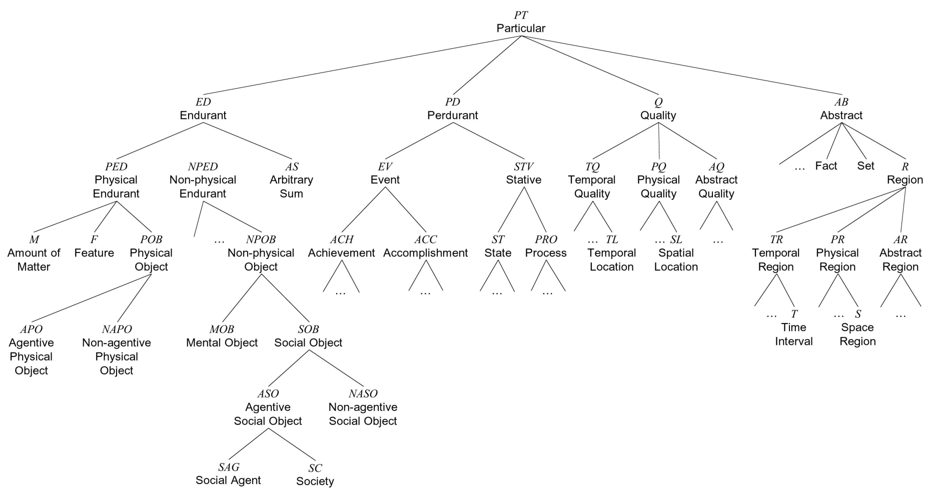

Figure 3. Taxonomy of Basic Categories in DOLCE [39, p. 14].

19.1.1 Ontological Levels

In DOLCE, levels of reality are not introduced explicitly. It seems that the levels are reflected in the DOLCE taxonomy of endurants, since physical, mental and social objects are distinguished therein. Here the question arises why the distinction between physical, mental and social entities is only embodied in the taxonomy of endurants, and is not present with respect to DOLCE perdurants and qualities. In GFO we explicitly distinguish three levels of reality, but we have not yet elaborated on levels for specific categories (cf. sect. 4).

19.1.2 Classes, Universals, and Individuals

DOLCE is an ontology of particulars. The root element of the DOLCE hierarchy is "Particular", understood to be an entity having no instances. This corresponds to our notion of an individual. Universals are mentioned in [39], but excluded from the ontology itself. Hence, we observe that DOLCE supports neither the distinctions provided in GFO concerning sets and items, nor concerning the typology of categories. However, it seems that our notion of set is similar to the DOLCE category "Set", which in DOLCE is only indicative. In the case of unary universals, DOLCE refers to the meta-ontology presented in [27].

19.1.3 Time and Space

A time or a space model is not built directly into DOLCE. Instead, the representation of various models of space and time is permitted, which can be introduced by means of qualities and their associated qualia (the latter are similar to our quality values, cf. sect. 19.1.5). The temporal and spatial locations of entities are understood as individual qualities, with temporal and spatial regions regarded as qualia, while regions are "abstract particulars" (this term indicates a similarity with GFO abstract individuals). In the GFO, spatial location is modelled in terms of spatial regions and relations, like occupation and location; temporal location is based on time regions and projection relations. In addition, presently the GFO provides a model for time and space, adopting ideas from Brentano. However, we admit that there is the possibility of differences between the time and space models of distinct ontological levels.

GFO chronoids and space regions, respectively, can be reconstructed in the context of DOLCE as time intervals and space regions. However, time and space boundaries are not yet contained in DOLCE. Perhaps they can be integrated, but this should be examined carefully, because of the inclusion of time and space under qualities and qualia in DOLCE. It should also be stressed that the GFO approach to time is not equivalent to the common view of intervals composed of points. Rather, a novel solution has been presented in terms of the coincidence relationship (cf. sect. 5.1).

Moreover, in the case of material structures, we have introduced the notion of an individual quality called extension-space, related to a material structure by a specialized inherence relation. This may appear similar to the category of spatial location of DOLCE, but note that extension-space and the space occupied are completely distinct entities.

19.1.4 Presentials, Persistants, and Endurants

The DOLCE distinction between endurant and perdurant is based on the behavior of entities in time. Endurants are entities that can change in time, are wholly present at any time of their existence, and have no temporal parts but their parts are time-indexed. They also participate in perdurants. GFO distinguishes two aspects of these phenomena of endurants introduced as in DOLCE: persistence through time and being wholly present at a time-boundary. This has produced two categories instead of endurant alone: persistants and presentials (cf. sect. 6.2).

The notion of persistant refers to the idea of persistence through time as attributed to DOLCE's endurant. However, persistants are not considered in GFO as individuals but as universals. Accordingly, we assume that they do not change (directly), but rather that several of their instances, all of which belong to the category of presentials, can have different properties.

Presentials, on the other hand, can be generally interpreted as DOLCE endurants, but without temporal extension. They reflect the aspects of being wholly present at a time of their existence and being involved in processes (in GFO by being the projection of a process to a time-boundary). Hence we can interpret GFO material structures and material objects, respectively, as DOLCE physical endurants and physical objects (at a time-boundary). Material/physical objects in both ontologies satisfy the criterion of unity. Altogether, we can say that the DOLCE category of endurant can be reconstructed in GFO terms by using the categories of persistants and presentials, whereas the separation of these two aspects in GFO is prevented in DOLCE, since there are no universals.

DOLCE's deep taxonomy of endurants, especially concerning non-physical objects, is not yet covered by the GFO. Here two remarks seem relevant. First, at present the GFO is not meant to provide a deep taxonomy, neither of endurants nor of any other category. Second, we intend to solve the problem of social and mental entities in a systematic way, based on the theory of levels of reality.

19.1.5 Properties, Property Values, Qualities, and Qualia

The GFO categories that concern properties and their values correspond rather well to DOLCE qualities, qualia and quality spaces. In GFO, qualities are individuals that are existentially dependent on and related to other individuals, called their bearers. Entities of both categories are connected by means of the has-property relation (or inherence, if bearers are restricted to material structures). This corresponds to DOLCE, where qualities inhere in particulars, upon which they depend *specifically constantly*. Moreover, [39] speaks of quality types for domain ontologies, which resemble GFO properties, more precisely property universals. Of course, these are not entities in DOLCE (since they are universals).

The next question concerns interpreting DOLCE quales. On the one hand, they appear as GFO property values, since they may be shared among different particulars. But on the other hand, quales are positions of some quality in a quality space, where the latter is not considered to be universal but individual. Thus, the more difficult question is determing what a quality space in DOLCE is. We believe that the notion of a measurement system (cf. sect. 9.1) comes closest to quality spaces. Accordingly, quality spaces are interpreted as systems of property value universals in GFO. As a consequence, an interpretation of our individual property values is difficult in DOLCE. We have not found any DOLCE category that corresponds to individual property values.

Both ontologies provide the classification of properties with respect to the kind of entity which has the property (i.e., in which it directly inheres in the case of DOLCE). DOLCE distinguishes the categories of physical, temporal and abstract qualities, which directly inhere in physical structures, perdurants and abstracts, respectively. The GFO classification is only preliminary, but one can observe that the qualities of material structures correspond to DOLCE physical qualities, while abstract qualities are not distinguished in GFO. Moreover, we have not yet considered whether all properties of processes have the character of temporal properties. Neither DOLCE nor GFO consider properties of universals. In this regard, DOLCE refers to the meta-ontology in [27] and to the methodology OntoClean [26]. Properties of universals are still a matter of debate in the case of GFO, also in connection with a refined typology of universals.

For properties, we can conclude that the DOLCE model of qualities may be reconstructed in GFO terms, but in the opposite direction, one cannot represent individual property values in DOLCE. On the other hand, GFO supports the DOLCE classification of qualities only partially.

19.1.6 Processes and Perdurants

DOLCE perdurants are introduced in contrast to endurants as entities that happen in time, are partially present in time, have temporal parts and cannot change in time. Intuitively, we can say that the notion of perdurant corresponds to our notion of occurrent. Moreover, it seems that the GFO notions of process, state and change can be interpreted in DOLCE as stative, state and event, respectively.

However, there are several differences. First, states and events are relative categories in the GFO, and there is an additional distinction between intrinsic and extrinsic changes. Secondly, the typologies of occurrents in GFO and of perdurants in DOLCE are not compatible. The typology of perdurants is based on the notions of homeomericity and cumulativity. In section 8.8 we discuss these notions and reject this way of classification for *individual* perdurants.

19.1.7 Further Issues

Apart from space and time boundaries, there are some other kinds of entities in GFO that are not easily interpretable in the current version of DOLCE. In particular, this refers to GFO relations and relators[44], as well as to such entities like situations, configurations, situoids and configuroids. Facts are the only notion that is closely related to those mentioned and indicated in DOLCE.

[44] Of course, in the formalization of DOLCE, relations are used and defined.

GFO	**DOLCE**
Entity	(Entity)
Set	(Set)
Item	–
Category	–
Universal	–
Persistant	(Endurant)
Concept	–
Symbolic Structure	–
Individual	Particular
Space-Time Entity	Temporal Region ∪ Space Region
Chronoid	Time Interval
Time Boundary	–
Region	Space Region
Topoid	–
Spatial Boundary	–
Abstract Individual	Abstract
Concrete Individual	Endurant ∪ Perdurant ∪ Quality
Presential	(Endurant)
Material Structure	Physical Endurant
Material Object	Physical Object
Material Boundary	(Feature)
Configuration	–
Simple Configuration	–
Situation	–
Fact	Fact
Occurrent	(Perdurant)
Process	Stative
Continuous Process	–
Discrete Process	–
State	(State)
Configuroid	–
Situoid	–
Change	(Event)
Instantaneous Change	–
Continuous Change	–
Property	Quality
Property Value	Quale
Relator	–
Material Relator	–
Formal Relator	–

Table 2. Mapping Selected Categories of GFO to DOLCE

DOLCE	GFO
Particular	(Individual)
Endurant	(Presential, Persistant)
Physical Endurant	Material Structure
Amount of Matter	Amount of Substrate
Feature	(Material Boundary)
Physical Object	Material Object
Agentive Physical Object	–
Non-agentive Physical Object	–
Non-physical Endurant	(Levels)
Non-physical Object	–
Mental Object	(Concept)
Social Object	–
Agentive Social Object	–
Social Agent	(Social Role)
Society	–
Non-agentive Physical Object	–
Perdurant	(Occurrent)
Event	(Change)
Achievement	(Achievement)
Accomplishment	(Accomplishment)
Stative	Process
State	State
Process	–
Quality	Property
Temporal Quality	–
Temporal Location	–
Physical Quality	–
Spatial Location	–
Abstract Quality	–
Abstract	(Space-Time-Entity $\cup$ Set $\cup$ Fact)
Fact	Fact
Set	Set
Region	(Space-Time-Entity), (Measurement System)
Temporal Region	Time-Region
Time Interval	Chronoid
Physical Region	–
Space Region	Space Region
Abstract Region	–

Table 3. Mapping DOLCE to GFO categories (roughly)

19.2 Comparison to Sowa's Ontology

The second comparison is concerned with John Sowa's ontology presented in [54]. As his approach is more divergent from ours than DOLCE (cf. figures 3 and 4), we first briefly introduce Sowa's combinatorial approach. After this short introduction, we will discuss the reconstruction of the main distinctions of Sowa's ontology in GFO.

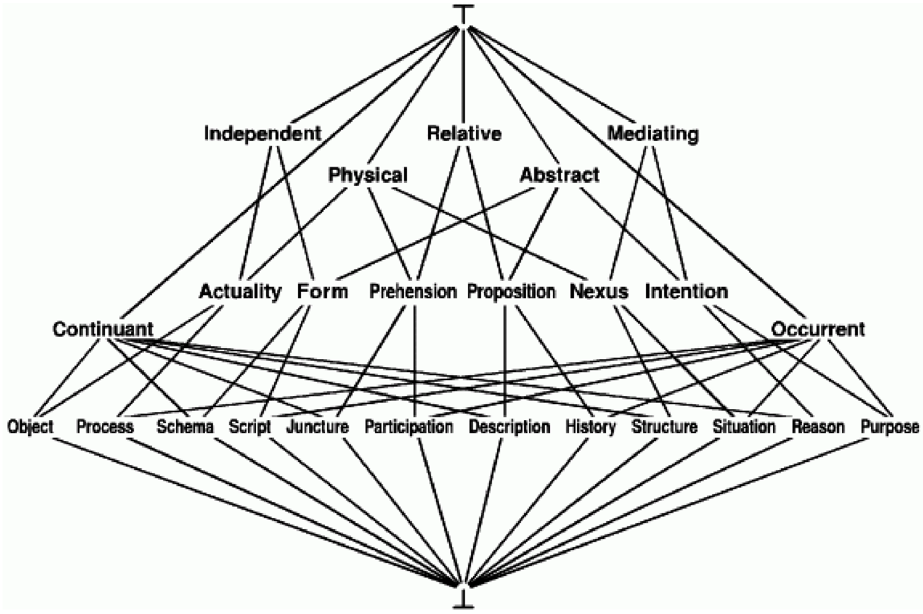

Figure 4. Hierarchy of Top-level Categories from [54, p. 72][45] .

19.2.1 Introduction: Construction Method

The upper level ontology of John F. Sowa was developed in pursuit of a combinatorial approach based on orthogonal distinctions. This method always generates highly symmetric structures. We confine out analysis to the 27 categories in figure 4, although Sowa discusses further, yet more specific ontological distinctions. The lattice is developed top-down by combining categories that originate from three distinctions: (i) physical vs. abstract, (ii) firstness, secondness, thirdness, (iii) continuant vs. occurrent. We will use the above distinctions as a route for the comparison.

[45] This figure differs from the one in the book in having ,,Structure" and ,,Situation" as children of Nexus, instead of ,,Situation" and ,,Execution" (in this order). However, this figure corresponds to the text in the book. It is available from http://www.jfsowa.com/ontology/toplevel.htm.

19.2.2 Physical and Abstract Categories

Sowa distinguishes between physical and abstract entities. Following Plato and Whitehead, abstract entities are understood as eternal, mathematical objects, and as such, they do not have a location in space or in time. In contrast to this, physical entities are located in space and time. The relation that holds between physical and abstract entities is that of characterization / representation (in terms of Sowa; our instantiation). An abstract entity characterizes, and is represented, in zero or more physical entities. Sowa observes that the same physical object may be characterized by more than one abstract entity; thus, the relation of characterization / representation is a many-to-many relation.

Intuitively, the notions of physical and abstract entities correspond to the GFO notions of individual and category, respectively. We say that a category is an entity that may be predicated of other entities, and represented by predicative terms. More specifically, we introduce the instantiation relation as a special type of predication, namely as a basic relation between items and immanent universals. Universals, concepts and symbolic structures are not explicitly distinguished in Sowa's ontology. The same holds true for primitive and higher-order categories, where we explicitly allow for categories of a second and even higher order.

We agree with Sowa that one primitive category (abstract) can be predicated of (characterize) several individuals (physical). Also, more than one category can be predicated of a single individual, even if these categories do not stand in a subsumption relation.

The distinction between physical and abstract is the only distinction in Sowa's ontology that he considers context-independent, which is a significant difference with respect to the remaining two differentiations. A physical entity remains physical in all contexts. This also corresponds to our intuitions since, for example, we do not permit individuals to evolve into categories.

19.2.3 Firstness, Secondness and Thirdness

Sowa's ontology is founded on the Peircean notions of firstness, secondness and thirdness. Firstness is introduced as an independent category, which is represented in logic by a monadic predicate $P(x)$, "which describes some aspect of x without taking into account anything external to x" [54, p. 70]. Secondness is a Relative category, which can be represented as a dyadic predicate. Relatives grasp the external relationship to some other entity. Thirdness is a Mediating category that can be represented by means of triadic predicate. The Mediating binds together the Independent and the Relative.

The Peircean distinction is not included explicitly in GFO. Nevertheless it seems that it may be reconstructed in GFO by means of the notions of relators, roles, and players. We interpret relators as mediating category, roles as the relative, and players (independently of that playing) as a category comprising Sowa's independent entities. Let us consider the material relator z, founded on some marriage between a man x and a woman y. This relator consists of two roles, where the man plays the role of a husband and the woman the role of a wife. Hence, husband and wife – understood as categories on players defined by these roles – are relative categories. Moreover, the particular relator z mediates between x and y, through roles as the basis of relative categories of independent entities.

A separate problem is the interpretation of Sowa's category of independents. In the presented example, Woman and Man are subcategories of Independent, which are also material structures. However, one could easily argue that they are not independent, as it is required in Sowa's ontology. The most independent entities from the point of view of GFO are situations and situoids, hence only these might be interpreted as independent entities in Sowa's terms. However, we feel that this interpretation would be too restrictive, and adopt the view that Independent in Sowa includes a cross-cutting collection of GFO categories, among them material structures, processes, chronoids and others.

19.2.4 Continuants and Occurrents

Sowa defines continuants and occurrents as follows:

"A continuant has stable attributes or characteristics that enable its various appearances at different times to be recognized as the same individual.

An occurrent is in a state of flux that prevents it from being recognized by a stable set of attributes. Instead, it can only be identified by its location in some region of space-time." [54, p. 71]

Moreover, Sowa remarks that the continuant categories are characterized by a predicate that does not involve time or a time like succession, while occurrents are characterized by a predicate that depends on time or a time like succession. One can observe that the notions of continuant and their appearances correspond fairly well to our combination of persistant and presential. Persistants provide the principle of identity to the presentials instantiating them. Furthermore, persistants as universals are not directly related to time and space. However, attribute assignments to persistants in the sense of referring to stable attributes of their presentials should be grasped in terms of relations between persistants and property universals. Further, presentials may not necessarily share a stable set of properties to be identified as the appearances of the same entity. Ontological identity is provided in GFO not by the exhibition of "the same" qualities, but by ontically connected instances of the same persistant.

The occurrent category of Sowa, on the one hand, appears to correspond to our notions of processes. In GFO, processes are entities that develop over time, unfold in time or perdure. Processes are related to time regions by the projection relation, which seems similar to demanding the identification of occurrents by their location in some region of space-time. Note that this location in space-time can only apply to individual processes, at least in GFO terms. On the other hand, Sowa's occurrents may be interpreted as GFO occurrents, if figure 4 is considered. The specialization of occurrent into, among others, process, history and situation is similar to the GFO categories of processes, histories, and situoids. In summary, we find it more appropriate to map Sowa's occurrents into GFO occurrents rather than processes.

19.2.5 Combination of the Distinctions

The combination of the above three distinctions made by Sowa results in six intermediate and twelve leaf categories.[46] The preliminary and intuitive mapping of those with GFO categories is presented in the tables 4 and 5 (p. 77 and 78). We observe that each of Sowa's categories appears reconstructible in GFO, except for three of them, namely: Intention, Reason and Purpose. The reason for this is that GFO is based on the theory of levels, but the mental and social levels to which the notions of intention, reason and purpose belong are only indicative.

19.2.6 Conclusion

We have presented the interpretation of the main distinctions of Sowa's ontology in GFO. Further, an intuitive mapping of GFO and Sowa's categories is provided in tabular form. We observe that all of Sowa's categories except for three can be reinterpreted in GFO. However, mapping in the opposite direction seems to be more problematic. For many of our categories, we have not found the corresponding notions in Sowa's ontology. Although deeply analyzed in [54], neither a space-time model nor a property model is included in Sowa's ontology.[47]

In general, the construction method of GFO is not as strictly combinatorial as is Sowa's ontology. Indeed, most of the categories of GFO do not have a combinatorial character. Apart from that, the actual structure of GFO categories is a (less symmetric) lattice. Note that the category tree presented on page 80 is a simplification, for the purpose of conveying first intuitions to the reader.

19.3 Comparison to SUMO

19.4 Comparison to BWW-Ontology

[46] We ignore the absurd category $\perp$ here, which is a subcategory of every category for Sowa. In contrast, GFO does not have a single intensional equivalent of the (extensional) empty set.

[47] That means, there are discussions on time and space as well as on properties in [54], but it is difficult to determine whether these belong to the ontology actually promoted. With restriction to the lattice presented in figure 4, the statement is correct.

GFO	**Ontology of John Sowa**
Entity	Entity
Set	(below Schema)
Item	–
Category	Abstract
Immanent Universal	–
Persistant	(Continuant)
Concept	–
Symbolic Structure	(below Schema)
Individual	–
Space-Time-Entity	–
Chronoid	–
Time-Boundary	–
Region	–
Spatial Boundary	–
Abstract Individual	–
Concrete Individual	Physical
Presential	(Continuant)
Material Structure	–
Material Object	(Object)
Material Boundary	–
Configuration	–
Simple Configuration	–
Situation	–
Fact	–
Occurrent	Occurrent
Process	Process
Continuous Process	–
Discrete Process	–
State	–
Configuroid	–
Situoid	–
Change	–
Instantaneous Change	–
Continuous Change	–
Property	–
Property Value	–
Relator	(Mediating)
Material Relator	–
Formal Relator	–

Table 4. Mapping Selected GFO Categories to John Sowa's Categories (roughly).

Ontology of John Sowa	**GFO**
Entity	Entity
Independent	(Situoid)
Physical	Individual (intuitively); Presential (by axioms)
Relative	(Universal defined by a relational role universal)
Abstract	Category
Mediating	Relation
Continuant	(Presential ∪ Persistant)
Occurrent	Occurrent
Actuality	(Material structure ∪ Process)
Form	(Category of material structures or process)
Prehension	(Material structure in a role)
Proposition	(Instantiation)
Nexus	(Relator or foundation of a relator)
Intention	–
Object	Material structure ∪ Persistant
Process	Process
Schema	Category of material structures
Script	Category of processes
Juncture	(Relational role)
Participation	(Processual role)
Description	Symbolic structure of material structures
History	Symbolic structure of histories
Situation (Structure)	(Material structure as a foundation of a relator)
Execution (Situation)	(Process as a foundation of a relator)
Reason	–
Purpose	–

Table 5. Mapping John Sowa's to GFO categories (roughly). Note that this mapping is provided with reservations, and detailed explanations of the individual mappings remain to be stated.

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20 Appendices

20.1 Principles of Ontology Building

20.2 GFO Hierarchy

The following diagram depicts subsumption relations among a number of selected GFO categories. Please note that this representation is highly incomplete compared to the set of GFO categories as a whole, and is meant to provide a comprehensible starting point for approaching GFO.

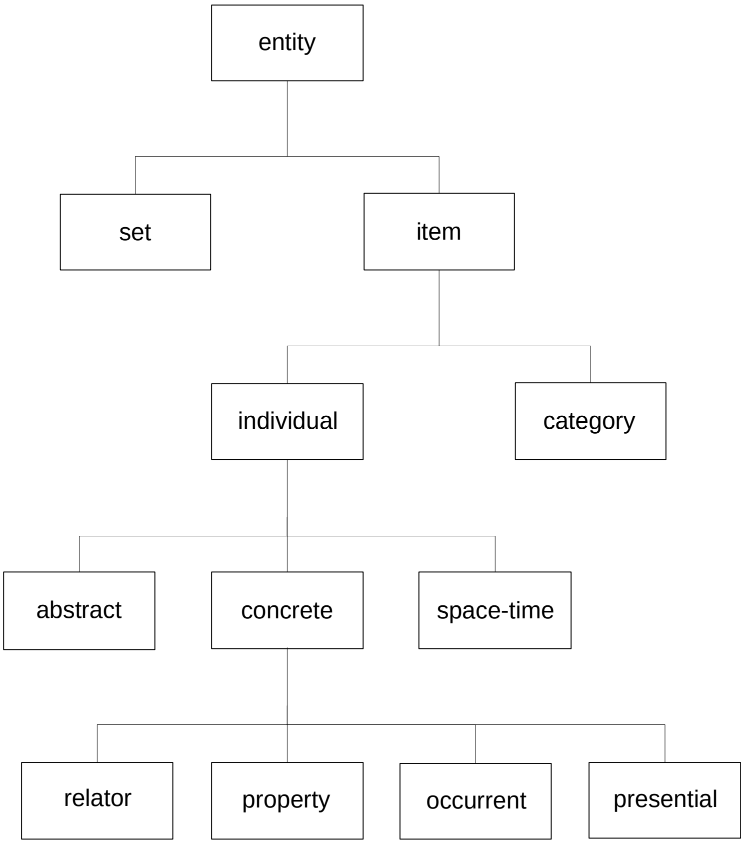

Figure 5. Overview of Selected GFO Categories

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