Theory and Applications of Ontology: Computer Applications

Roberto Poli · Michael Healy · Achilles Kameas
Editors

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Preface

After a long period of decline, ontology is back at the forefront of philosophy, science and technology. These days ontology comes in at least two main fashions: the traditional philosophical understanding of ontology has been recently flanked by a new – computer-based – understanding of ontology.

There are scholars from both fields contending that ontology in knowledge engineering and ontology in philosophy are two completely different disciplines. On the one hand there is analysis closely tied to the concrete problems of domain modeling; on the other, difficult and usually very abstract speculations on the world and its most rarified structures. For this reason, it is claimed, those scientists who occupy themselves with ontology in knowledge engineering should not be concerned with what philosophers have to say (and vice-versa).

The thesis defended by *Theory and Applications of Ontology* is exactly the opposite. We shall try to show in this work that – despite their different languages and different points of departure – ontologies in knowledge engineering (let's say: ontology as technology) and ontology in philosophy (let's say: ontology as categorial analysis) have numerous problems in common and that they seek to answer similar questions. And for this reason, engineers and philosophers must devise ways to talk to each other.

The current resurgence of interest in ontological issues displays a number of novel features, both among philosophers and among information technologists. Among philosophers, the revival of a genuine interest in ontology requires the removal of certain prejudices that have profoundly influenced the analytic and the continental camps, both of which have in recent decades systematically delegitimized ontological inquiry in favour of its epistemological transformation (not to say reduction). To this shared error of broadly Kantian (or more properly neo-Kantian) stamp, analytic philosophy has added a linguistic prejudice, and the continental one styles of inquiry and writing that can be described as devoid of methodological rigour.

Behind these obstructions to ontological investigation one perhaps discerns the consequences of another feature common to both camps: the fact that the most influential thinkers of the last hundred years – the reference unquestionably goes back to Wittgenstein and Heidegger, however different their philosophical views may have been – both embraced an a-scientific approach; both, that is, delegitimized alliances, or at least serious contact, between science and philosophy. In consequence, the revival of interest in ontology also provides an opportunity for renewed discussion of the relationships between science and philosophy.

Science continuously advances, and that which it proves to be valid endures. Problem-oriented thinkers try to follow problems, not to anticipate conclusions or to presuppose an image of the world. This perspective is largely correct. It should, however, be qualified if one is not to commit the ingenuous error of believing that it is only "solutions" that advance knowledge. Also attempts and failures, in fact, are instructive. For all these reasons we may accept Aristotle's contention that ontology is *philosophia prima* as regards the problems it seeks to resolve, as long as we remember that it can only be *philosophia ultima* as regards the elaboration of results. And it is here that we discern how ontology concretely operates in harness with science, because it "presupposes the accumulated knowledge of centuries and the methodical experience of all the sciences" (N. Hartmann, *Der Aufbau der realen Welt*, Meisenheim am Glan, 1949, 26).

Besides points of contact, of course, there are also a number of differences, perhaps most notably the fact that ontology in knowledge engineering is a discipline still in its infancy, while ontology in philosophy is as old as philosophy itself. Consequently, the history of philosophy contains ideas, tools and proposals of use for contemporary developments; and it also indicates the options that will lead us into dead ends or nowhere at all. When things are viewed in the light of such a long and articulated history, one knows from the outset that ontology does not permit ingenuous simplifications. For these reasons, philosophical ontology may usefully contribute to ontology in knowledge engineering.

It is true, though, that philosophical ontology addresses questions of a more general nature, ones apparently of no relevance to ontology in knowledge engineering. Consequently, it may appear that certain components of philosophical ontology could be ignored in the passage to ontology as technology. Nevertheless, one should always bear in mind the greater explanatory value and the broader structuring capacity of more general schemes and more comprehensive theories. For this less overt reason, too, philosophical ontology is useful for ontology in knowledge engineering.

The philosophical codification of ontology has often restricted itself to organization of its general architecture, without delving into the details of minute categorization. On the other hand, the concrete, situated practice of ontology as technology may conversely prove useful for the development of philosophical ontology.

For these and other reasons, there is mounting interest in the development of standards, modeling principles, and semantically transparent languages. Ontology thus comes into play as one of the strategies available to developing the semantic web, construct robust data-bases, managing huge amounts of heterogeneous information because ontologically founded knowledge of the objects of the world is able to make codification simpler, more transparent and more natural. The belief is that ontology can give greater robustness to computer-based applications by providing methodological criteria and categories with which to construct and build them, as well as contexts in which to set and re-categorize different data-bases so that they become more mutually transparent. In this way ontology directly contributes to standardization of the life-cycle model, and can therefore serve as an innovative and possibly unexpected component of software quality assurance.

These problems are dramatically magnified by the fact that unlike all the societies of the past, modern societies are no longer afflicted by a lack of information. If anything they suffer from its excess, from having to cope with too much unused and unusable information. It becomes increasingly difficult, in fact, to find the information that one needs, when one needs it, to the extent that one needs it and in the appropriate form. Although the information may be stored somewhere, all too often one does not know where; and even when one is aware of how to find the information, it is often accompanied by further information irrelevant to one's purposes. And when information is available, it is often forthcoming in the wrong form, or else its meaning is not explicitly apparent.

However broad the range of information already gathered may be, a great deal more has still to be assembled and codified. And this inevitably complicates still further the problem of the functional, flexible, efficient and semantically transparent codification of information.

Broadly speaking, the two research communities of philosophers and engineers have still not found a way to relate to each other systematically. While philosophers tend unilaterally to emphasize the need for a conceptual complexity that matches the complexity of the subject-matter, engineers tend equally unilaterally to stress the drawbacks of the tools available and the presence of insuperable computational problems. One side is perhaps too theoretical, the other too pragmatic. In short, taken as they stand, the two views seem difficult to reconcile.

However, in dynamic terms, one easily foresees mounting social and institutional pressure for the development of tools able to model fragments of reality in terms that are both adequate and efficient. And from this point of view, we are all at fault. Those colleagues who concern themselves with technologies seemingly pay closer attention to manipulation than to knowledge. Likewise, those who concern themselves with philosophy suffer from the reverse problem, that of navigating in a sea of theories for which the rationale is sometimes unclear.

For our part, we have grown increasingly convinced that the same problems will force engineers to address theories, and philosophers to address the limitations of our current capabilities. Provided, however, that both sides have the will, the ability, the desire and the courage to do so. If they decide to tackle these problems, it will become reasonable to identify and systematically develop those areas of convergence and contact now existing.

In this sense, the two volumes of *Theory and Applications of Ontology* may play a role in paving the way for a better mutual understanding between engineers and philosophers. Since the two communities are still very different as to their own languages, conceptual tools and problem-sets, we thought that collecting papers within one single volume would have been too constraining. We therefore devised two different volumes, one dedicated to the philosophical understanding of ontology and one to the computer-based understanding of ontologies. Both volumes contain both papers describing the state of the art in their respective topics and papers addressing forefront, innovative and possibly controversial topics.

Roberto Poli

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Introduction

Recent events in information technology have led to a new manifestation of the philosophical field of ontology. In this new manifestation, ontology is also a technological discipline. On reflection, this development can be seen as unsurprising: Ontology arises naturally in investigations of advanced information processing systems such as knowledge-based systems and the world-wide web. The development of knowledge-based systems has lead to computer applications written to manage knowledge expressed in symbolic form, in a variety of domains such as diagnostics and manufacturing engineering and in a variety of programming languages. Each system has its own set of engineering or medical or scientific artifacts for different domains of knowledge, its own rules expressing domain relationships, and its own terminology. This makes interoperability difficult if not intractable. The philosophical notion of ontology suggests a possible solution in the form of a system-neutral repository of abstract knowledge which can be refined to specify system rules and artifacts in the domains to be modeled, accompanied by automated translators mediating between each knowledge system and the repository. Another example concerns the semantic web, a proposed new-generation world-wide web meant to achieve a deeper, more meaningful communication between users, their browsers and the web sites they access than is possible with the purely syntactic medium of key words and "icons". But this begs the question: What can one communicate when there is no common basis for meaning? Again, by appropriating the philosophical notion of ontology, technologists hope to resolve the underlying issues of meaning and communication among users, systems, and content.

The two volumes of Theory and Applications of Ontology (TAO) are intended to inform the scholar in philosophy or the researcher in the sciences, information technology, or engineering, of the present state of the art in philosophical ontology and the systems available for the study, development, and application of ontology as technology. While Volume 1 addresses philosophy, the present volume, Volume 2, addresses the recent flowering of ontology as an all-encompassing field of study and application, which provides a declarative semantic framework for mutual understanding and interoperability between technological system components, models and processes. Volume 2 is intended as a snapshot of much, although not all, of the work in progress on ontology in this new role as a component of technological systems.

The chapters in this second volume of TAO are grouped in four parts. We consider this grouping necessary, in order to help the reader deal with the large volume of knowledge contained in the book. Of course, this grouping does not mean that the chapters are not related or interrelated; in fact, the reader will discover references from chapters that present seemingly different aspects of ontologies to common concepts and entities, which constitutes a proof of the universal application of ontologies. The chapters in the first part of the book support this claim. The chapters in the second and third parts, which constitute the largest part of the book, present the application of ontologies to specific domains, thus justifying the sub-title of the volume at-hand. We do not aim to provide an exhaustive catalogue of ontologies available, but to help the reader in forming the necessary cognitive structures that will allow him to classify ontology applications and evaluate correctly the tools and methodologies. The final part contributes chapters that shed light into the formalisms used to describe and manipulate ontologies, closing in a way the path that started with the chapters in Volume 1 of this set. Nevertheless, each of the two volumes is self-contained and can be studied independently.

As we already mentioned, the first part in Volume 2 contains the chapters that provide an overview of various perspectives of ontology theory, architecture, constructs and application. In this context, Poli and Obrst present an overview of ontology from both the philosophical and technological perspectives. This is by way of introducing Volume 2, the assumption being that this discussion would be unnecessary were the philosophical view the only one to be represented in these volumes. Continuing, Obrst distinguishes between *ontology architecture*, as a distinct discipline in ontology engineering, which includes ontology lifecycle management, and *ontological architecture* as the architecture used to structure ontologies. The latter addresses both ontological levels (foundational, upper, middle, utility, reference, domain, and sub-domain ontologies), and formal constructs used to modularize ontologies in a large *ontological space.* Loebe surveys approaches to handling categorical systems of extensive size, spanning from semi-formal systems in terminology and classification sciences to formal logical approaches. In particular, he reviews the transition from terminologies to ontologies that are formalized in logics, exemplified in the medical domain. Tartir, Arpinar, and Sheth introduce several approaches that have been developed to aid in evaluating ontologies. As part of this, they present highlights of OntoQA, an ontology evaluation and analysis tool that uses a set of metrics measuring different aspects of an ontology's schema and knowledge base. Seremeti and Kameas provide an overview of the available tools and software environments that can be used for building, maintaining, and evolving ontologies. Kotis and Vouros aim to provide an understanding of the functionalities and technologies that need to be integrated in ontology engineering environments by presenting issues that next generation ontological tools must consider.

The second part groups the chapters that discuss specific ontologies, foundational ontologies and ontology engineering systems. Guizzardi and Wagner present the Unified Foundational Ontology (UFO), which was developed to serve as a foundation for general conceptual modeling languages. They demonstrate the use of this foundational ontology in the evaluation and redesign of the Unified Modeling Language (UML) for concept-based software development. Pease and Li introduce the Controlled English to Logic (CELT) system, which translates a restricted English grammar to expressions in formal logic. The logic statements use terms from a large formal ontology, the Suggested Upper Merged Ontology (SUMO). Foxvog presents the Cyc system familiar to AI researchers. The original intent of the Cyc project, begun in the 1980s, was to produce an ontology of "all commonsense knowledge." Borgo and Masolo present the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE), a foundational ontology embracing the notion that there cannot be a unique standard or universal ontology for knowledge representation. Herre has two contributions in this volume. In the first chapter, he presents the General Formal Ontology (GFO), a foundational ontology for conceptual modelling.

The third part presents the application of ontologies in different disciplines as components used to provide semantically rich representations of technological domains. The contributions in this part discuss specific domain ontologies as well as issues in the engineering of ontologies for specific domains. Davies and Kiryakov distinguish *lightweight ontologies* (which roughly correspond to ontologies for application domains in information technology) from the philosophical notion of ontologies and then motivate and describe techniques for translating information modelling schemes into lightweight ontologies.

Natural language (English, German, etc.), usually in some simplified, semi-formalized form making it amenable to computer processing, is often the basis either for expressing ontologies or as a domain for applications of ontology. Bateman discusses approaches to natural language processing where there is a strong interaction with ontological engineering. Fellbaum presents WordNet, a large electronic lexical database for English. WordNet is in fact a semantic network expressing relationships between words with similar meaning and, hence, has become a valuable tool for Natural Language Processing and has spawned research in lexical semantics and ontology.

In his second chapter, Herre applies the GFO as an analysis and development tool for biomedical ontologies. Kelso, Hoehndorf and Pru1fer more generally address ontologies for the biomedical domain. They discuss the formalization of community knowledge in molecular biology along with the provision of a shared vocabulary for the annotation of the growing amount of biological data available. Rittgen discusses a number of approaches, rooted in different fields of research, to modeling the multi-faceted business domain. The emphasis is placed upon pragmatism in modeling enterprise ontologies. Feldkamp, Hinkelmann, and Thoenssen discuss ontologies for e-government. There are issues here similar to those for business, e.g., minimizing the cost of government, except that public service at state, provincial and municipal levels are involved and also regulation of commerce and other activities of businesses and other public/private entities. Goumopoulos and Kameas present an ontology-driven approach and a context management framework for composing context-aware ubiquitous computing applications. The focus is upon applications which combine the services offered by heterogeneous everyday physical objects (e.g., information devices, home appliances, etc) that have been enhanced with sensing, acting, processing and communication abilities.

The fourth and final part of the current volume compiles chapters that bring the notions of ontology formalization and formal ontologies into the realm of mathematical rigor. Healy posits that an appropriate mathematical language for this is category theory, the mathematics of structure. The ensuing discussion introduces this field, which is also referred to as conceptual mathematics, and proceeds from basic-level definitions and explanations to an in-depth exposition of some of its key notions. This serves to introduce the chapters by Kalfoglou and Schorlemmer, Vickers, Kent, and Johnson and Rosebrugh. Each of these chapters approaches the subject of ontology in a different way, yielding an indication of the richness of category theory as conceptual mathematics. Kalfoglou and Schorlemmer discuss the semantic alignment of ontologies as systems of categorical relationships called information systems, which show how the terms in the different ontologies are associated. Vickers discusses the ontological commitments made by a form of categorical logic which has been called the logic of observable quantities; this logic is well-adapted to formalizing ontologies for scientific theories. Kent provides an exposition of work for ontologies over the World-Wide Web that is based upon the work of Joseph Goguen on institutions. The latter are mathematical systems for analyzing and clarifying the semantics of different logics. Johnson and Rosebrugh provide a general scheme for the use of category theory in ontology by presenting a category-theoretic approach to ontology engineering.

The four parts of this volume aim at providing comprehensive coverage of the current uses of ontologies as components of technological systems. They have been structured in a way that guides the reader from overviews of ontology application to mathematical formalization, passing through ontology engineering systems and domain-specific ontologies. This structure reflects the editors' choice of most profitable studying path. However, each part is independent from the others and will equip the reader with updated and complete knowledge under a specific perspective in ontology engineering and application. The reader is advised to study one part thoroughly before moving to the next, as the chapters in each part complement each other under the part's perspective. Each chapter has been authored by distinguished scholars in the various applications of ontologies. Let them guide you, the reader, in a path of knowledge discovery that we, the volume editors, find to be the most fascinating.

Chapter 1
The Interplay Between Ontology as Categorial Analysis and Ontology as Technology

Roberto Poli and Leo Obrst

1.1 Introduction

The notion of ontology today comes with two perspectives: one traditionally from philosophy and one more recently from computer science. The philosophical perspective of ontology focuses on categorial analysis, i.e., what are the entities of the world and what are the categories of entities? *Prima facie*, the intention of categorial analysis is to inventory reality. The computer science perspective of ontology, i.e., ontology as technology, focuses on those same questions but the intention is distinct: to create engineering models of reality, artifacts which can be used by software, and perhaps directly interpreted and reasoned over by special software called inference engines, to imbue software with human level semantics. Philosophical ontology arguably begins with the Greek philosophers, more than 2,400 years ago. Computational ontology (sometimes called "ontological" or "ontology" engineering) began about 15 years ago.

In this chapter, we will focus on the interaction between ontology as categorial analysis ("ontology_c", sometimes called "Big O" ontology) and ontology as technology ("ontology_t", sometimes called "Little o" ontology). The individual perspectives have each much to offer the other. But their interplay is even more interesting.[1]

This chapter is structured in the following way. Primarily we discuss ontology_c and ontology_t, introducting notions of both as part of the discussion about their interplay. We don't think they are radically distinct and so do not want to radically distinguish them, intending by the discussion of the interplay to highlight their distinctions where they occur, but thereby emphasize their correspondences, and, in fact, their correlations, complementarities, interdependencies. They are distinct

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[1] Cf. Daconta et al. (2003, p. 186). The first use of this "Big O, little o" terminology, as known by the authors, is in Guarino (1995). The distinction made between ontology_c and ontology_t is first made in Poli (2001b).

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perspectives after all, we want to emphasize, not distinct analytical methodologies, nor do they provide distinct analytical products. We discuss some of the historical definitions of ontology_t, as they emerged during the 1990s. We then provide our own take on the nature of ontology_t. As part of this exposition, we briefly discuss the levels and representation of ontologies, ranging over the typical levels of upper ontologies, middle ontologies, and domain (and sub-domain) ontologies.

Although we cannot discuss the knowledge representation languages typically used by ontology_t, from Semantic Web languages such as OWL[2] (primarily a description logic) to First-Order Logic (FOL, predicate calculus) languages such as ISO Common Logic,[3] nor the automated reasoning over ontologies that is of potential benefit to ontology_c as well as to ontology_t, we consider these issues important but better exposed in another venue. The interested reader is, therefore, directed to Chapter 2, Ontology Architecture, for a fuller exposition.

We do, however, lay down some principles by which we believe ontologies_t should be developed, based on analysis from ontology_c, and introduce the notion of "levels of reality". We illustrate the interplay of the two notions of ontology by providing an extended discussion of ontological entities in a hypothetical biology ontology.

Finally, we conclude by looking to the increasing interaction between these two aspects of ontology in the future. We briefly discuss some common problems which require the interplay of ontology_c and ontology_t, and which will assume much greater prominence once the more basic issues are elaborated on and scientific concensus established, i.e., ontology modularity, mapping, context-determination and representation, and vagueness and uncertainty. Ontology_t needs to be informed by ontology_c and its analytical methods. Ontology_c will increasingly benefit from the sound and consistent software engineering products arising from ontology_t.

1.2 Ontology_c

Ontology and ontologies have been given many different definitions, both on the philosophical side and on the technological side.

From the perspective of categorial analysis in philosophy, ontology has been viewed as both a part of metaphysics and as a part of science. Historically, ontology has been a branch of metaphysics, interested in formulating answers to the question of what exists, i.e., what's the inventory of reality, and consequently in defining categories (kinds) of entities and the relationships among the categories. Metaphysics asks different questions than does ontology, notably the question about the nature of being as a whole.

In our understanding, ontology should also be viewed as following along the same path as science, i.e., that ontology organizes and classifies the results from that which science discovers about reality. Furthermore, ontology not only depends

[2] Bechhofer et al. (2004).

[3] ISO Common Logic: Common Logic Standard. http://cl.tamu.edu/.

on science but can also provide tools for the clarification of science itself, in the form of ontologically clarified and reconstructed sciences. Ontology and science can therefore support one another.

A further point of contention or at least confusion is that between ontology and epistemology, i.e., on the study of what is vs. the study of what is ascertained and how it is ascertained. Ontology requires knowledge about what is, and if knowledge is described as, for example, justified belief, then ontology may be thought to devolve to knowledge and from thence to belief and justification for belief, i.e., the realm of evidence, manners and methods by which one adjudicates evidence to form belief, and thus epistemology.

Ontology is not epistemology, but has a complex relationship to epistemology. Ontology is primarily about the entities, relations, and properties of the world, the categories of things. Epistemology is about the perceived and belief-attributed entities, relations, and properties of the world, i.e., ways of knowing or ascertaining things. So epistemology is about empirical evidence gleaned that will be described or characterized by ontology.

Contemporary ontology can be characterized in a number of ways, all of which can be considered layers of theory (Poli, 2003):

(1) *Descriptive ontology* concerns the collection of *prima facie* information either in some specific domain of analysis or in general.
(2) *Formal ontology* distills, filters, codifies and organizes the results of descriptive ontology (in either its local or global setting). According to this interpretation, formal ontology is formal in the sense used by Husserl in his *Logical Investigations* (Husserl, 2001; originally 1900–1901). Being "formal" in such a sense means dealing with categories like *thing*, *process*, *matter*, *form*, *whole*, *part*, and *number*. These are pure categories that characterize aspects or types of reality and still *have nothing to do with the use of any specific formalism*.
(3) *Formalized ontology:* Formal codification in the strict sense is undertaken at this third level of theory construction. The task here is to find the proper formal codification for the constructs descriptively acquired and categorially purified in the way just indicated. The level of formalized constructions also relates to evaluation of the adequacy (expressive, computational, cognitive) of the various formalisms, and to the problem of their reciprocal translations. In this sense, formalized ontology refers to the actual formalization of ontology in a logical language, typically but not always First Order Logic (FOL). In ontology_t, this could be rendered in a knowledge representation language such as the FOL-based ISO Common Logic or in the description logic-based Web Ontology Language OWL.

The close similarity between the terms "formal" and "formalized" is rather unfortunate. One way to avoid the clash is to use "categorial" instead of "formal".[4]

[4]Note the philosophical, common use of "categorial" instead of the term "categorical" employed in this chapter, which comes closer however to the mathematician and logician's use of the term "categorical", as for example in Category and Topos Theory.

Most contemporary theory recognizes only two levels of work in ontology and often merges the level of the formal categories either with that of descriptive or with that of formalized analysis. As a consequence, the specific relevance of categorial analyses is too often neglected.

The three levels of ontology are different but not separate. In many respects they affect each other. Descriptive findings may bear on formal categories; formalized outcomes may bear on their formal equivalents, etc. To set out the differences and the connections between the various ontological facets precisely is a most delicate but significant task (Poli, 2003).

1.3 Ontology_t

Ontological engineering, i.e., ontology from the perspective of computer science, has issues comparable to that of philosophical ontology, but reflected technologically in the attempt to develop ontologies as software usable models. So ontology from the perspective of computer science is both a computer science and a computational or software engineering problem. On the one hand, "ontological engineering"[5] historically had its origins as an engineering problem, as an attempt to create software usable models of "the ways things are, with the things that are" to endow software with human level representations of "conceptualizations" or semantics. On the other hand, there are efforts that intend to make an "ontological science", as for example, that of the National Center for Ontological Research (NCOR) (Obrst, Hughes and Ray, 2006).[6] Such an effort would include strong evaluation criteria and possibly ontology certification.

Although having antecedents in the late 1980s, as formal ontology in philosophy and formal semantics in linguistics began to impact computer science and especially artificial intelligence, ontological engineering as a discipline can be marked as originating approximately in 1991, with Neches et al. (1991) reporting on the United States Defense Advanced Research Projects Agency's (DARPA) Knowledge Sharing Initiative, and Gruber (1991), followed soon after by work by Gruber (1993), Guarino (1994), and Guarino and Poli (1995).

1.3.1 Ontology_t Definitions

The first proposed definition of ontology in computer science was that of Gruber (1993)[7]: "an ontology is an explicit specification of a conceptualization", which

[5]The first occasion of use of the term "ontological engineering" is apocryphal: perhaps it occurred as part of the Cyc project (Guha and Lenat, 1990).

[6]National Center for Ontological Research (NCOR): http://ncor.buffalo.edu/.

[7]Anecdotally, the term "ontology" had been used in computer science and artificial intelligence since the late 1980s. One of the authors of this chapter described the use of ontologies and rules in Obrst (1989).

was intended to contrast with the usual definition of ontology in philosophy, i.e., to emphasize that what was being talked about was ontology_t in our terminology: ontology as a computational engineering product. The notion of "conceptualization" was defined in Genesereth and Nilsson (1987) to be "the objects, concepts, and other entities that are presumed to exist in some area of interest and the relationships that hold them" (Gruber, 1993) and presumably the "area of interest", now typically called "domain", is a portion of the world.

Guarino and Giaretta (1995) took up the challenge to clarify what was meant by this and other emerging definitions of ontology_t. In Guarino's and Giaretta's analysis, there were a number of ways to characterize ontology (quoted from Guarino and Giaretta, 1995, p. 25):

1. Ontology as a philosophical discipline
2. Ontology as an informal conceptual system
3. Ontology as a formal semantic account
4. Ontology as a specification of a conceptualization
5. Ontology as a representation of a conceptual system via a logical theory

   5.1 characterized by specific formal properties
   5.2 characterized only by its specific purposes

6. Ontology as the vocabulary used by a logical theory
7. Ontology as a (meta-level) specification of a logical theory.

By way of a summary: "ontology: (sense 1) a logical theory which gives an explicit, partial account of a conceptualization; (sense 2) synonym of conceptualization." (Guarino and Giaretta, 1995, p. 32)

Note that characterization (4) invokes Gruber's definition. Part of Guarino's and Giaretta's explication involves analyzing Gruber's [derived from Genesereth and Nilsson's (1987)] notion of a conceptualization as being extensional. Instead, Guarino and Giaretta (1995) argue that it should be an intensional notion. Rather than Genesereth and Nilsson's (1987) view of conceptualization as "a set of extensional relations describing a particular state of affairs," in Guarino's and Giaretta's view, it "is an intensional one, namely something like a conceptual grid which we superimpose on various possible states of affairs." (Guarino and Giaretta, 1995) The definition that Guarino and Giaretta end up with is that an ontology is an ontological theory, and as such that it "differs from an arbitrary logical theory (or knowledge base) by its semantics, since all its axioms must be true in every possible world of the underlying conceptualization."

1.3.2 Ontology_t and Epistemology

A further issue about ontology and epistemology should be brought out now, as it relates to ontology_t. We have mentioned that epistemology deals with how knowledge is known. How do my perception and understanding, my beliefs, constrain my arrival at real knowledge or assumed belief, i.e., evidence, knowledge hypotheses prior to their becoming theorems about knowledge (and there should be a clear path from hypothesis to theorem to true theorem, but often there is not). So if an ontology is a theory about the world, epistemology addresses the ways of acquiring enough knowledge (and the nature of that) so that one can eventually frame a theory. In ontology_t, the engineering artifact of the ontology model (a theory) will require epistemological linkage to data. That data can be inaccurate, contain uncertainties, and lead to partially duplicate but inconsistent instances of ontology classes. Epistemology thus is employed in the use and qualification of data and as stored in databases or tagged or indexed in documents.

If ontology states that human beings have exactly one birth date, the data about a specific person is epistemological: in a given set of databases the person instance named John Smith (we assume we can uniquely characterize this instance) may have two or more attributed birth-dates, not one of which are known to be true. Epistemological concerns distort and push off needed ontological distinctions. Evidence, belief, and actual adjudication of true data is epistemological. What the real objects, relations, and rules are of reality are ontological. Without ontology, there is no firm basis for epistemology. Analysts of information often believe that all is hypothesis and argumentation. They really don't understand the ontological part, i.e., that their knowledge is really based on firm stuff: a human being only has one birth date and one death date, though the evidence for that is multivarious, uncertain, and needs to be hypothesized about like the empirical, epistemological notion it is.

In fact, much of so-called "dynamic knowledge" is not ontological in nature (ontological is relatively static knowledge), but epistemological. What is an instance that can be described by the ontology? How do I acquire and adjudicate knowledge/evidence that will enable me to place what I know into the ontological theory? Instances and their actual properties and property values at any given time are dynamic and ephemeral (this particular event of speaking, *speaking_event_10034560067800043,* just occurred; however the speaking_event ontology class has not changed).

1.3.3 Ontology_t as Theory with Philosophical Stances

Ontology_t often considers an ontology to be a logical theory about some portion of the world.[8] Philosophical stance towards theories is therefore quite important, because a given ontological engineer will typically imbue his ontology_t engineering model with constructs aligned with his or her philosophical stance, e.g. as to the preferred theory of universals (nominalism, conceptualism or realism).

[8] See for example, the discussion of what an ontology is on the Ontolog Forum site: http://ontolog.cim3.net/cgi-bin/wiki.pl?, i.e., Obrst (2006).

1.4 Interplay Between Ontology_c and Ontology_t

The issues we discuss in this section involve the complex interplay between ontology_c and ontology_t. Two main points are discussed: (1) the proper way of developing formalized ontologies; (2) an illustration of one case in which the interplay between philosophy and computer science can be explicitly seen. We discuss the problem of the "natural" boundaries of a domain ontology and how different types of domain ontologies should be distinguished.[9]

We take both Guarino's and Giaretta's position (Guarino and Giaretta, 1995; ontology as interpreted formal system, i.e., a logical theory) and Gruber's position (Gruber, 1993; ontology as specification of a conceptualization) as problematic. Concerning the former, we think focusing on ontology as interpretation only is insufficient. As reflected in Guarino and Giaretta (1995), in this view ontology is more focused on the interpretation (semantics) of a logical theory, i.e., has more of a conceptual-flavored and model-theoretic position ultimately. A consistent logical theory can be developed about nonsense, for example, with no intent to describe a portion of the real world, the task of philosophical ontology as we see it. Subsequent discussions by Guarino (e.g., Guarino, 1998a, 2002; Masolo et al., 2003) have pointed to a better reconciliation between logical theory and realist-based formal ontology, which is more closely aligned with our view, as discussed next.

Against both of these views, however, we would rather say that ontology starts to be something relevant only when specifically ontological axioms are added to some formal basis (say, FOL). The definition of new concepts without the introduction of new axioms has limited value. In this regard, we consider as exemplar the General Formal Ontology (GFO) (Herre et al., 2006).[10] But we also admire other upper or foundational ontology efforts which have sought to axiomatize their distinctions, including, Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE),[11] Basic Formal Ontology (BFO),[12] Object-Centered High-level Reference Ontology (OCHRE), Suggested Upper Merged Ontology (SUMO),[13] Upper Cyc,[14] etc. Recently there was an effort to reconcile or at least map among many of these upper or foundational ontologies by the Ontolog Forum (Obrst et al., 2006).[15]

[9]We do not discuss ontological layers here in any detail. The interested reader instead is pointed toward the chapters on the Categorial Stance and on Ontological Architectures in this volume.

[10]General Formal Ontology (GFO): http://www.onto-med.de/en/theories/gfo/index.html. See also Herre's chapter in this volume.

[11]For DOLCE and OCHRE, see Masolo et al. (2003) and the site: http://www.loa-cnr.it/DOLCE.html.

[12]Basic Formal Ontology (BFO): http://www.ifomis.uni-saarland.de/bfo.

[13]Suggested Upper Merged Ontology (SUMO): http://www.ontologyportal.org/.

[14]Upper Cyc: http://www.cyc.com/cycdoc/vocab/vocab-toc.html.

[15]Ontolog Forum: http://ontolog.cim3.net/cgi-bin/wiki.pl?.

1.4.1 Developing Formalized Ontologies

Concerning the second issue, the interplay of ontology_c and ontology_t, we provide an example that illustrates some domain ontology distinctions. We initially assume that the basic distinction between domain ontologies (DO) and upper ontologies (UO) are given. We further assume that a boundary has been established between a selected UO and the DOs which are or could be subsumed under it. Consequently, it should be clear which concepts pertain to the UO and which pertain to its DOs. Typically, highly general concepts like "process", "part", and "boundary" are likely to be included in a UO, while concepts like "gene", "cell" and "membrane" are likely to be included in a domain ontology for, say, biology. Note that we do suppose that a domain ontology for biology may be considered a domain-specific UO, since the constructs of the domain ontology may correctly have to be made general enough to encompass prospectively an entire science. Considering biology as a domain with respect to a true UO, then in turn a biology domain ontology may be considered a domain-specific UO with respect to many complex sub-domains. These sub-domains can be considered domains in their own right (perhaps also incorporating other domain ontologies, say that of public administration for the case of public health), given the complexity of their subject matter, e.g., mammalian anatomy, neuropathology, genetic engineering, clinical medicine, public health, pharmacology, etc. We might call such a domain-specific UO a middle ontology (that spans multiple domains), a "superdomain" ontology, or simply a domain-specific UO.

Figure 1.1[16] depicts the basic layers and the nomenclature we employ. By "utility ontology" in the above, we mean an ontology that represents commonly used

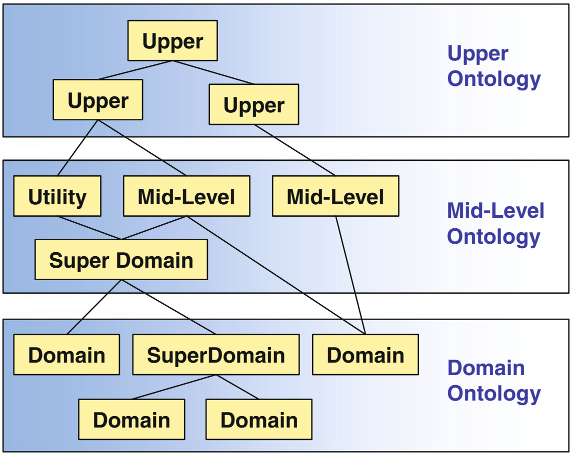

Fig. 1.1 Ontology layers

[16]From Fig. 9.1 in Chapter 8, Ontological Architecture; also see Semy, Pulvermacher and Obrst (2005, p. 8).

concepts, such as Time and Location. However, there is no crucial distinction between a "utility" and a "mid-level" ontology. We do note that in general, a mid-level ontology more concretely represents concepts that are defined more abstractly at the UO level.

To establish our ideas, the two following situations offer useful hints.

Case 1. At the beginning of the previous century the Polish-Russian philosopher of law Leon Petrazycki called attention to a basic theoretical requirement of theory development. We quote one relevant passage:

> "Many theories, comprising no fallacy, are yet inadequate: one may form the concept of "a cigar weighing five ounces", predicate about that class everything known about material things in general (about solid bodies in general, the chemical properties of the ingredients of these cigars, the influence of smoking them on health, and so on); these "theories" while perfectly correct are manifestly inadequate since what is predicated with respect to "cigars weighing five ounces" is also true of innumerable objects which do not belong to that class, such as cigars in general. A theory may be inadequate either (1) because the predicates are related to classes which are too narrow . . . or (2) because the predicate is related to a class which is too broad (such as various sociological theories which attribute "everything" to the influence of one factor which in fact plays a much more modest part)" (Petrazycki, 1955, p. 19).

We may well read "ontologies" where Petrazycki writes "theories". In fact, one may well read "concepts", since cognitive science has a comparable notion concerning "concepts", i.e., that they be non-profligate in a similar manner; especially with respect to what is called the "theory–theory of concepts", concepts as "mental theories" (Laurence and Margolis, 1999, p. 43), and with respect to profligacy: the potential concepts "the piece of paper I left on my desk last night", "frog or lamp", "31st century invention" (Laurence and Margolis, 1999, p. 36). Interestingly, it seems conceptual analysis is recapitulating ontology and semantics, since the former is also addressing categorization, analyticity, reference determination, and the notion of a "prototype" including the notion of "evidential" vs. "constitutive" properties (Laurence and Margolis, 1999, p. 33), which stumbles on the epistemology vs. ontology conundrum.

The point here is that an ontology (viz. a *domain* ontology) may then be inadequate if its boundaries are badly cut. But how should one know where to draw "natural" or "appropriate" boundaries? Some will say that many ontologies at the domain and middle levels correspond to scientific disciplines, i.e., that science and scientific theories apportion the areas of interest. This is partially true, but of course it dismisses intuitive or common-sense ontologies that humans may have, each even considered a logical theory about the world, because they are based on non-scientific generalizations. A theory of parenthood, for example, may not be scientific *yet*, i.e., not based on a combination of sociology, anthropology, biology, psychology, economics, political science, and everything else that might be scientifically known, but it may be a reasonable approximation of reality for the short or mid term, since it's very doubtful those combination of scientific theories will be reconciled anytime soon. This point argues for the inclusion of commonsense theories in lieu of established scientific theories, the latter which may not ever be forthcoming.

Case 2. It is well known that for decades classification theory has labored under an unresolved split between two different methodologies. This split is particularly pronounced in the case of frameworks elaborated by librarians, where it takes the form of the difference between enumerative or taxonomical (Dewey Decimal Classification (DDC), Library of Congress Classification (LCC), etc) classification and faceted classification, also called colon classification, originating from the analysis of Ranganathan (1962). Since faceted classifications are now being proposed for Web construction and other computer-based applications as a more effective way to organize information, a proper understanding of its nature is becoming increasingly relevant. Unfortunately, what is not clear is whether any criteria is available for deciding whether an enumerative or a faceted style of classification should be adopted.

Where lies the *natural* boundary of an ontology_t? The question is both difficult and subtle. May it not be that the boundaries of an ontology may depend on subjective intentions? Just as semantics-pragmatics in linguistics and philosophy of language represents a spectrum, with the latter pole being focused on "semantics in context, with respect to a given use and intent", there are subjective intentional issues here. However, the problem of subjective reasons or needs ("I am developing this ontology for this and that reason, based on these use cases") subtly misses the point. Subjective motivations are always there, and they may more or less severely constrain the ontology to be build. We think that even moderate subjectivism is problematic. So it is for this reason that we don't consider an ontology_t as a standard or an agreement: an ontology is not the result of a standards-based concensus of opinion about a portion of the world, because, in general, the effort and thus the result will devolve to the lowest common denominator, and generally end up worthless – because it is inconsistent, has uneven and wrong levels of granularity, and doesn't capture real semantic variances that are crucial for adoption by members of a community. Users of ontology_t cannot be the developers of ontology_t, for much the same reason as users should not develop their own databases: users intuitively know their own semantics, but typically cannot express the ontological and semantic distinctions important to them, nor therefore model them – even though the real world referents are common to everyone.

This avoidance of subjectivism is notwithstanding the established or preferred methodology for developing a specific ontology_t, i.e., that one must focus on the use cases, anticipated scenarios that instantiate those, and therefore the software modeling requirements and "competency questions" (the queries you want answered, i.e., theorems with instantiations which make them true, or the queries you would like to have answered if it were possible for this new ontology-based system to provide you with such), as Fox and Gruninger (1994) and Uschold and Gruninger (1996) clarify. So ontology_t's methodology is to proceed both bottom-up and top-down, i.e., analyze the data sources with respect to their semantics which will have to be captured by the resulting domain ontology and the questions end users (domain experts) would like to ask if they could (and can't typically ask using database and mainstream computing technology). Concerning the latter, typically end users can't formulate these kinds of questions because their imagination is constrained by their current systems. It takes patient knowledge elicitation and knowledge of comparable kinds of value by the working ontology engineer to eke out this kind of knowledge question.

The *focus* of ontological analysis is not centered on the subjective intentions motivating the constructions of the ontology but on the item to be modelled. The reasons for which one is modeling this or that item (or class thereof) may and do interfere, even dramatically, but it is the item itself that is relevant. It is the thing in the world that the ontology is grounded on.

The problem is the old philosophical problem of the connections between epistemology and ontology_c, as we mentioned earlier. The problem has been made obscure by the attitude widely prevalent in recent mainstream philosophy according to which epistemology prevails over ontology.

Ontologies_t could be more or less detailed; their existence may even – at least in some cases – modify the functioning of the modelled system. However, the main question is: does the *existence* of the item/system under observation depend on the ontology? When the answer is negative – as it is for the overwhelming majority of cases – we have a basis for severing the ontological core from all the rest.

The first criterion is then to look for what exists. A number of relatively easy qualifications should now be taken into consideration. The easiest one is to consider only directly observable items, i.e. actually existent items, but also items that existed in the past. They are no more directly observable but we could observe them were we living at their time (This is the pragmatist criterion firstly devised by Peirce. The case where one can *now* observe the traces left by no more existent items is trivially unproblematic). By adopting the same criterion, one may eventually include also items possibly existing in the future.

More demanding is the question about what is said to exist, i.e., the primary interest of ontology_c. For example, we may say that there are material things, plants and animals, as well as the products of the talents and activities of animals and humans in the world. This first prosaic list already indicates that the world comprises not only things, animate or inanimate, but also activities and processes and the products that derive from them. For human-developed products, for example, functional properties are significant (a claw hammer is meant to pound and remove nails; its head and handle are therefore of length and material composition that is appropriately leveragable for those operations). It is likewise difficult to deny that there are thoughts, sensations and decisions, and in fact the entire spectrum of mental activities. Similarly, one is compelled to admit that there are laws, languages, and factories.

We can set about organizing this list of items by saying that there are material items, psychological items and social items (Poli, 2001a), as displayed in Fig. 1.2 below, which depicts dependence of these categories.[17] In turn, each of them presents a vast array of subtypes (material items include physical, chemical, and

[17] Poli's Ontology: The Categorial Stance (TAO-1) discusses these issues in more detail.

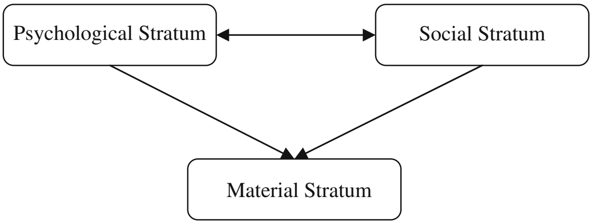

Fig. 1.2 Ontological strata

biological items, psychological items include representation and emotions, social items include laws, languages and many other types of pertinent items).

This section started by asking the natural boundaries of an ontology, how do we determine what an ontology includes or does not include? In trying to provide an answer we found ourselves involved in classical philosophical problems, which is not at all surprising.

1.4.2 Ontology, Science, and Levels of Reality

Returning to our main question, any possibly correct answer concerning what an ontology should include will have to start articulating its proposal with respect to some existing item (or type of). Subsequent steps may follow a variety of different paths. However, for most cases one route seems particularly prominent: that adopted by science. For apparently good reasons, science has been developing in different branches (including physics, economy, biology and cognitive science), the idea being that there are classes of items that "go together", constituting at least a description and possibly an explanation over some portion of reality. In this regard, ontology may follow the same route successfully traversed by science. However different they are, ontology and science are allies. This view intends to convey that between ontology and science there is a mutual exchange, from science to ontology and from ontology to science. That ontology may have something to offer science can be seen from the idea of an ontologically reconstructed and clarified science.

The suggestion is therefore to start from well established scientific partitions. Even if something more will later be required, this initial step will nevertheless help in avoiding two opposed risks. A truly atomistic vision claims that atoms are the only authentically existing items, and that all the other items we recognise are ephemeral. On the other hand, the followers of a boldly holistic vision will claim that the only autonomously existing item is the universe as a whole. Neither of these visions suits ontology. By relying on the multiplicities of sciences one automatically advocates a molar strategy: there are many different items, of different types, requiring different categorial frameworks.

So far so good. The point we arrive at, however, represents both a safe result and one of maximal difficulty. As a matter of fact, so far modern science has relied on an essentially analytic strategy. Different sciences have been developed in order to efficaciously segment the whole of reality into classes of more or less uniformly connected phenomena. The guiding idea has been that phenomena occurring within each class are more causally homogeneous than phenomena pertaining to other classes, so that the task of explaining their behavior should be more easily accomplished. This divide and conquer strategy has proved immensely successful, at least for some regions of reality. Other regions have proved more refractory, for a number of serious reasons. The first is that different regions may require different types of causation, some of which are still unknown, or only partially known (Poli, 2007). A second reason is that for some regions of reality the analytic strategy of breaking items into pieces does not work properly. A third and somewhat connected reason is the lack of a synthetic methodology.

The complexity of reality requires the analytic strategy of segmentation into *categorially* homogeneous regions. This first move is not questioned. However, some regions contain only items that can be further analytically segmented into pieces. These items are entirely governed by their parts (from below, so to speak). Other regions contain items following different patterns: they depend on both their parts and the whole that results from them. Our understanding of these more complex items is still deficient. Recent theories about *granular partitions* (Bittner and Smith, 2001, 2003; Bittner et al, 2007; also see Rogers and Rector, 2000) attempt to remedy this situation.[18] Even so, unfortunately, this is not the end of the story. Something more is further required: sooner or later the products arising from the segmentation into categorially homogeneous regions should be synthesized. For we all live in *one* world. This second synthetic move has proved much more troublesome than the original analytic move.

A properly developed synthetic strategy still awaits us. However, the theories of levels of reality may represent a helpful step toward the elaboration of a fully developed synthetic strategy.[19] Each layer of reality requires (1) specific kinds of items, (2) appropriate categories, and (3) links to its bearing (i.e. based on building-above

[18]Bittner and Smith's (2003) framework tries to uphold the strengths of set theory and mereology for modeling parts and wholes but avoid their respective weaknesses by building on the distinction between *bona fide* (objects which exist independently of human partioning efforts and *fiat* objects (objects which exist only because of human partitioning efforts) (Smith, 2001). As such, their theory of granular partitions begins to impinge on the distinction too between the semantic notions of intension and extension – because on one view, two intensional descriptions ("the morning star", "the evening star") can be seen as human partitions, even though both extensionally refer to the same object, Venus. In their view, "partition is a complex of cells in its projective relation to the world" (Bittner and Smith, 2003, p. 10), and so a triple is established: a granular partition, reality, and the set of "projections" or mappings to and from the items of the partition and reality. Whether this is ontology or ontology intermixed with epistemology remains to be clarified.

[19]Note that we use "level" to refer in general to the levels of reality, restricting the term "layer" to over-forming relationships, and the term "stratum" to building-above relationships. The interested reader is directed to Poli, "Ontology. The Categorial Stance" (TAO-1) for a fuller exposition of this topic.

relations (*Überbauung*), and conditioning (i.e. based on over-forming relations, or *Überformung*)[20] layers as described in Chapter 1, TAO_1.

These are precisely the lacking elements needed to answer the question above asked on the natural boundaries of an ontology: the boundaries of a domain ontology are the top domain categories needed for defining the domain items, plus eventual bearing and conditioning links.

1.4.3 Example: An Ontology of Biology

Using our suggested methodology, we now describe the domain ontology of biology.

Many ontologies_t have been recently developed in the field of biology. Most of them are found at the OBO website.[21] Bio-ontologies offer a nice case for discussing ontological integration. By looking at the ontologies collected by the OBO initiatives one may wonder whether (and how) they could be coordinated and eventually integrated. The problem we would like to address is whether a methodology – here understood as a set of instructions or guidelines – could be devised for developing easy-to-integrate ontologies. Generally speaking, this will comprise minimally three cases: (1) *vertical integration,* i.e., specific ontologies integrable within more general ontologies; e.g. anatomy within biology, (2) *horizontal integration,* i.e., integration among ontologies modelling categorially disjoint phenomena, e.g., business and legal ontologies, and (3) *cross-domain ontologies*, where a number of ontologies pertaining to different levels of reality should be both joined and pruned, e.g., medicine, which may require chemical, biological, psychological, economic, legal and religious information, among others. Some of the mentioned ontologies may further have to be pruned in order to include only information relevant to human pathologies.

The domain top level of our proposed biology ontology will be based on the following three concepts (Hohendorf et al., 2008):

- *Biological entity (BE).*
- *Living entity (LE)*
- *Organism (OR).*

Any biological item is a *biological entity*. The concept of BE refers to anything organic: DNA, mRNA, the nucleus of a cell, the membrane of a cell, its organelles, urine are bioentities. The main function of the concept of BE is to delimit the field. This will prove especially relevant when different ontologies_t are merged together. If all the merged ontologies_t define their most general domain concepts, their management will prove much easier (and safer).

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[20] Over-forming relations (*Überformung*) and building-above relations (*Überbauung*) are from Hartmann (1952).

[21] Open Biomedical Ontologies (OBO) Foundry. http://obofoundry.org.