What Is an *Ontology*?

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Summary. The word "ontology" is used with different senses in different communities. The most radical difference is perhaps between the philosophical sense, which has of course a well-established tradition, and the computational sense, which emerged in the recent years in the knowledge engineering community, starting from an early informal definition of (computational) ontologies as "explicit specifications of conceptualizations". In this paper we shall revisit the previous attempts to clarify and formalize such original definition, providing a detailed account of the notions of *conceptualization* and *explicit specification*, while discussing at the same time the importance of *shared* explicit specifications.

1 Introduction

The word "ontology" is used with different meanings in different communities. Following [9], we distinguish between the use as an uncountable noun ("Ontology," with uppercase initial) and the use as a countable noun ("an ontology," with lowercase initial) in the remainder of this chapter. In the first case, we refer to a philosophical discipline, namely the branch of philosophy which deals with the *nature* and *structure* of "reality." Aristotle dealt with this subject in his Metaphysics[1] and defined Ontology[2] as the science of "being *qua* being," i.e., the study of attributes that belong to things because of their very nature. Unlike the experimental sciences, which aim at discovering and modeling reality under a certain perspective, Ontology focuses on the

[1] The first books of Aristotle's treatises, known collectively as "Organon," deal with the nature of the world, i.e., physics. Metaphysics denotes the subjects dealt with in the rest of the books – among them Ontology. Philosophers sometimes equate Metaphysics and Ontology.
[2] Note, that the term "Ontology" itself was coined only in the early seventeenth century [13].

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nature and structure of things per se, independently of any further considerations, and even independently of their actual existence. For example, it makes perfect sense to study the Ontology of unicorns and other fictitious entities: although they do not have actual existence, their nature and structure can be described in terms of general categories and relations.

In the second case, which reflects the most prevalent use in Computer Science, we refer to *an* ontology as a special kind of information object or computational artifact. According to [7, 8], the account of existence in this case is a pragmatic one: "For AI systems, what 'exists' is that which can be represented."

Computational ontologies are a means to formally model the structure of a system, i.e., the relevant entities and relations that emerge from its observation, and which are useful to our purposes. An example of such a system can be a company with all its employees and their interrelationships. The ontology engineer analyzes relevant entities[3] and organizes them into *concepts* and *relations*, being represented, respectively, by unary and binary predicates.[4] The backbone of an ontology consists of a generalization/specialization hierarchy of concepts, i.e., a taxonomy. Supposing we are interested in aspects related to human resources, then *Person*, *Manager*, and *Researcher* might be relevant concepts, where the first is a superconcept of the latter two. *Cooperates-with* can be considered a relevant relation holding between persons. A concrete person working in a company would then be an instance of its corresponding concept.

In 1993, Gruber originally defined the notion of an ontology as an "explicit specification of a conceptualization" [7].[5] In 1997, Borst defined an ontology as a "formal specification of a shared conceptualization" [1]. This definition additionally required that the conceptualization should express a *shared* view between several parties, a consensus rather than an individual view. Also, such conceptualization should be expressed in a (formal) machine readable format. In 1998, Studer et al. [15] merged these two definitions stating that: "An ontology is a formal, explicit specification of a shared conceptualization."

[3] Entity denotes the most general being, and, thus, subsumes subjects, objects, processes, ideas, etc.

[4] Unfortunately, the terminology used in Computer Science is problematic here. What we call "concepts" in this chapter may be better called "properties" or "categories." Regrettably, "property" is used to denote a binary relation in RDF(S), so we shall avoid using it. Also, Smith made us aware that the notion of "concept" is quite ambiguous [14]. A way to solve the terminological conflict is to adopt the philosophical term "universal," which roughly denotes those entities that can have instances; particulars are entities that do not have instances. What we call "concepts" correspond to unary universals, while "relations" correspond to binary universals.

[5] Other definitions of an ontology have surfaced in the literature, e.g., [16] or [11], which are similar to Gruber's. However, the one from Gruber seems to be the most prevalent and most cited.

All these definitions were assuming an informal notion of "conceptualization," which was discussed in detail in [9]. In the following, we shall revisit such discussion, by focusing on the three major aspects of the definition by Studer et al.:

- What is a *conceptualization*?
- What is a proper *formal, explicit specification*?
- Why is '*shared*' of importance?

It is the task of this chapter to provide a concise view of these aspects in the following sections. It lies in the nature of such a chapter that we have tried to make it more precise and formal than many other useful definitions of ontologies that do exist – but that do not clarify terms to the degree of accuracy that we target here.

Accordingly, the reader new to the subject of ontologies may prefer to learn first about applications and examples of ontologies in the latter parts of this book and may decide to return to this opening chapter once he wants to see the common *raison d'être* behind the different approaches.

2 What is a *Conceptualization*?

Gruber [7, 8] refers to the notion of a conceptualization according to Genesereth and Nilsson [5], who claim: "A body of formally represented knowledge is based on a conceptualization: the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them. A conceptualization is an abstract, simplified view of the world that we wish to represent for some purpose. Every knowledge base, knowledge-based system, or knowledge-level agent is committed to some conceptualization, explicitly or implicitly."

Despite the complex mental nature of the notion of "conceptualization," Genesereth and Nilsson choose to explain it by using a very simple mathematical representation: an extensional relational structure.

Definition 2.1 (Extensional relational structure) An extensional relational structure*, (or a* conceptualization according to Genesereth and Nilsson*), is a tuple* $(D, \mathbf{R})$ *where*

- D *is a set called the universe of discourse*
- $\mathbf{R}$ *is a set of relations on* D

Note that, in the above definition, the members of the set $\mathbf{R}$ are ordinary mathematical relations on D, i.e., sets of ordered tuples of elements of D. So each element of $\mathbf{R}$ is an *extensional* relation, reflecting a *specific* world state involving the elements of D, such as the one depicted in Fig. 1, concerning the following example.

Example 2.1 *Let us consider human resources management in a large software company with 50,000 people, each one identified by a number (e.g., the social security number, or a similar code) preceded by the letter I. Let us assume that our universe of discourse D contains all these people, and that we are only interested in relations involving people. Our* $\mathbf{R}$ *will contain some unary relations, such as Person, Manager, and Researcher, as well as the binary relations reports-to and cooperates-with.*[6] *The corresponding extensional relation structure* $(D, \mathbf{R})$ *looks as follows:*

- $D = \{I000001, ..., I050000, ...\}$
- $\mathbf{R} = \{Person, Manager, Researcher, cooperates\text{-}with, reports\text{-}to\}$

Relation extensions reflect a specific world. Here, we assume that Person comprises the whole universe D and that Manager and Researcher are strict subsets of D. The binary relations reports-to and cooperates-with are sets of tuples that specify every hierarchical relationship and every collaboration in our company. Some managers and researchers are depicted in Fig. 1. Here, I046758, a researcher, reports to his manager I034820, and cooperates with another researcher, namely I044443.

- $Person = D$
- $Manager = \{..., I034820, ...\}$
- $Researcher = \{..., I044443, ..., I046758, ...\}$
- $reports\text{-}to = \{..., (I046758, I034820), (I044443, I034820), ...\}$
- $cooperates\text{-}with = \{..., (I046758, I044443), ...\}$

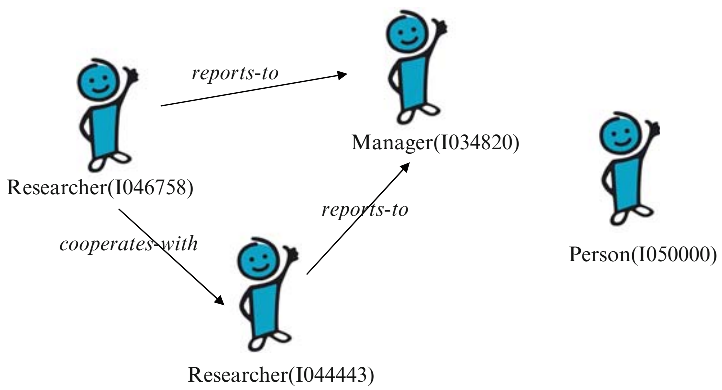

Fig. 1. A tiny part of a specific world with persons, managers, researchers, and their relationships in the running example of human resources in a large software company

[6] The name of a person could also be assigned via relations, e.g., *firstname(I046758,'Daniel')* and *lastname(I046758,'Oberle')*.

Despite its simplicity, this extensional notion of a conceptualization does not really fit our needs and our intuition, mainly because it depends too much on a specific state of the world. Arguably, a conceptualization is about concepts. Now, should our concept of *reports-to* change when the hierarchical structure of our company changes? Indeed, as discussed in [9], a conceptualization should not change when the world changes. Otherwise, according to the Genesereth and Nilsson's view given in Definition 2.1, every specific people interaction graph, such as the one depicted in Fig. 1, would correspond to a different conceptualization, as shown in Example 2.2.

Example 2.2 *Let us consider the following alteration of Example 2.1 with* $D' = D$ *and* $\mathbf{R}' = \{Person, Manager, Researcher, \textit{reports-to'}, \textit{cooperates-with}\}$ *where* $\textit{reports-to'} = \textit{reports-to} \cup \{(I034820, I050000)\}$.

Although we only added one new reporting relationship, it is obvious that $(D, \mathbf{R}) \neq (D', \mathbf{R}')$ and, thus, we have two different conceptualizations according to Genesereth and Nilsson.

The problem is that the extensional relations belonging to $\mathbf{R}$ reflect a specific world state. However, we need to focus on the meaning of the underlying concepts, which are independent of a single world state: for instance, the meaning of *cooperates-with* lies in the particular way two persons act in the company.

In practice, understanding such meaning implies having a rule to decide, observing different behavior patterns, whether or not two persons are cooperating. Suppose that, in our case, for two persons *I046758* and *I044443* to cooperate means that (1) both declare to have the same goal; (2) both do something to achieve this goal. Then, the meaning of "cooperating" can be defined as a *function* that, for each global behavioral context involving all our universe, gives us the list of couples who are actually cooperating in that context. The reverse of this function *grounds* the meaning of a concept in a specific world state. Generalizing this approach, and abstracting from time for the sake of simplicity, we shall say that an *intensional* relation[7] (as opposed to an *extensional* relation) is a function from a set of maximal world states (the global behavioral contexts in our case) into extensional relations. This is the common way of expressing intensions, which goes back to Carnap [2] and is adopted and extended in Montague's semantics [4].

To formalize this notion of intensional relation, we first have to clarify what a "world" and a "world state" is. We shall define them with reference to the notion of "system," which will be given for granted: since we are dealing with computer representations of real phenomena, a system is simply the given piece of reality we want to model, which, at a given degree of granularity, is

[7] To underly their link with conceptualizations, Guarino has proposed to call such intensional relations "conceptual relations" in [10].

"perceived" by an observing agent (typically external to the system itself) by means of an array of "observed variables."[8]

In our case, this system will be an actual group of people interacting in certain ways. For the sake of simplicity, we shall assume to observe this system at a granularity where single persons can be considered as atoms, so we shall abstract, e.g., from body parts. Moreover, we shall assume that the only observed variables are those which tell us whether a person has a certain goal (belonging to a pre-determined list), and whether such person is actually acting to achieve such goal. Supposing there is just one goal, we have $50{,}000 + 50{,}000 = 100{,}000$ variables. Each combination of such variables is a world state. Two different agents (outside the observed system) will share the same meaning of "cooperating" if, in presence of the same world states, will pick up the same couples as instances of the *cooperates-with* relation. If not, they will have different conceptualizations, i.e., *different ways of interpreting their sensory data.* For instance, an agent may assume that sharing a goal is enough for cooperating, while the other may require in addition some actual work aimed at achieving the goal.

Definition 2.2 (World) *With respect to a specific system S we want to model, a* world state *for S is a maximal observable state of affairs, i.e., a unique assignment of values to all the observable variables that characterize the system. A* world *is a totally ordered set of world states, corresponding to the system's evolution in time. If we abstract from time for the sake of simplicity, a world state coincides with a world.*

At this point, we are ready to define the notion of an intensional relation in more formal terms, building on [9], as follows:

Definition 2.3 (Intensional relation, or *conceptual relation*) *Let S be an arbitrary system, D an arbitrary set of distinguished elements of S, and W the set of world states for S (also called worlds, or possible worlds). The tuple $<D, W>$ is called a* domain space for S, *as it intuitively fixes the space of variability of the universe of discourse D with respect to the possible states of S. An* intensional relation *(or conceptual relation) ρ^n of arity n on $<D, W>$ is a total function $\rho^n : W \to 2^{D^n}$ from the set W into the set of all n-ary (extensional) relations on D.*

Once we have clarified what a conceptual relation is, we give a representation of a conceptualization in Definition 2.4. Below, we also show how the conceptualization of our human resources system looks like in Example 2.3.

Definition 2.4 (Intensional relational structure, or *conceptualization*) *An* intensional relational structure *(or a* conceptualization *according to Guarino) is a triple $\mathbf{C} = (D, W, \Re)$ with*

[8] It is important to note that, if we want to provide a well-founded, grounded account of meaning, this system needs to be first of all a physical system, and not an abstract entity.

- D *a universe of discourse*
- W *a set of possible worlds*
- $\Re$ *a set of conceptual relations on the domain space* $<D, W>$

Example 2.3 *Coming back to the Examples 2.1 and 2.2, we can see them as describing two different worlds compatible with the following conceptualization* **C***:*

- $D = \{I000001, ..., I050000, ...\}$ *the universe of discourse*
- $W = \{w_1, w_2, ...\}$ *the set of possible worlds*
- $\Re = \{Person^1, Manager^1, Researcher^1, cooperates\text{-}with^2, reports\text{-}to^2\}$ *the set of conceptual relations*

For the sake of simplicity, we assume that the unary conceptual relations, viz., Person^1*, Manager*^{1}*, and Researcher*^{1}*, are rigid, and, thus, map to the same extensions in every possible world. We do not make this specific assumption here for the binary reports-to*^{2} *and cooperates-with*^{2}*:*

- *for all worlds w in W:* $Person^1(w) = D$
- *for all worlds w in W:* $Manager^1(w) = \{..., I034820, ...\}$
- *for all worlds w in W:* $Researcher^1(w) = \{..., I044443, ..., I046758, ...\}$
- $reports\text{-}to^2(w_1) = \{..., (I046758, I034820), (I044443, I034820), , ...\}$
- $reports\text{-}to^2(w_2) = \{..., (I046758, I034820), (I044443, I034820), (I034820, I050000), ...\}$
- $reports\text{-}to^2(w_3) = ...$
- $cooperates\text{-}with^2(w_1) = \{..., (I046758, I044443), ...\}$
- $cooperates\text{-}with^2(w_2) = ...$

3 What is a Proper *Formal, Explicit Specification*?

In practical applications, as well as in human communication, we need to use a *language* to refer to the elements of a conceptualization: for instance, to express the fact that *I046758* cooperates with *I044443*, we have to introduce a specific symbol (formally, a predicate symbol, say *cooperates-with*, which, in the user's intention, is intended to represent a certain conceptual relation. We say in this case that our language (let us call it **L**) *commits* to a conceptualization.[9] Suppose now that **L** is a first-order logical language, whose nonlogical symbols (i.e., its *signature*, or its *vocabulary*) are the elements of the set $\{I046758, I044443, cooperates\text{-}with, reports\text{-}to\}$. How can we make sure

[9] Of course, properly speaking, it is an *agent* who commits to a conceptualization while using a certain language: what we call the *language commitment* is an account of the competent use of the language by an agent who adopts a certain conceptualization.