How fit is OWL to represent realist ontologies? The semantics of representational units in realist ontologies and the Web Ontology Language

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Abstract: Ontological realism is a philosophical stance that provides a definitional framework for ontologies and is referred to by various applied ontologists. From a computer science perspective, ontologies are often associated with formal languages for the representation of ontologies like the Web Ontology Language (OWL). It has, however, not been made explicit how the realist framework is related to the representation formalism. We analyse how the representational units of OWL can be used for modelling realist ontologies. While OWL is sufficiently close to the realist framework of ontologies to describe them, there are categories in OWL that are alien to realist ontologies or duplicate categories in realist ontologies. This clarification allows separating talk about ontologies in general from talk about their specific representation.

1 Introduction

The formalism to represent ontologies such as the Web Ontology Language (OWL) [Wc12] is what many people associate with ontologies today. For many ontology projects, OWL is the formal language of choice, and OWL is indeed something like an emerging standard in applied ontology. Nevertheless, the focus on the formalism has led to various (mis-)perceptions of what ontologies are, particularly because the specification of OWL does not clarify what its representational units are meant to represent in reality.

A famous slogan defines an ontology in computer science as “an explicit specification of a conceptualisation” [Gr93]. It has, however, been argued that that ontologies that are to support the work of scientist in, e.g., medicine and the life sciences, should not aim at representing human concepts, but the very reality science wants to uncover [Sm04]. The latter approach has been dubbed the “realist” approach in ontology engineering. It comes with strong opinions about what the representational units of an ontology should refer to. In particular, ontological realism comes with rules for selection, naming and definition of representational units, as well as other methods for building ontologies [BDS04, Kuśn06, SKSC06, SmCe10, SSGR12]. The realist framework has also been used to explain the differences and commonalities of thesauri and ontologies [KMK12].

While realism seems to transform into a *de facto* standard in some quarters [Ob12], it is heavily criticised by others [e.g. Merr10a, Merr10b]. Our aim in this paper is not to add to this fundamental discussion, but to discuss how realist ontologies can be appropriately represented by the syntactical categories of a standard ontology description language, namely the widely-used Web Ontology Language (OWL). The relation between ontological realism and representational languages like OWL is generally not explained. The assignments represented in this paper reflect the practise in many existing ontology projects, like, e.g., BioTop [Be08], ChEBI [De07], BFO [Sp06] or many of the ontologies presented in the OBO Foundry [Ob12]. The assignments can, thus, be understood as making explicit the conventions that are implicitly applied when describing ontologies in OWL.

In section 2 we will (a) introduce the syntactical categories that are available in OWL and (b) look at the requirements for representational units of ontologies in the realist framework. Section 3 presents mappings between them, and section 4 gives a couple of recommendations for the representation of realist ontologies in OWL.

2 Background

2.1 Syntactical categories in OWL 2

The Web Ontology Language (OWL) was developed by the World Wide Web Consortium (W3C) and has gained widespread acceptance. A first version of the language was published in 2004 [MH04] as a revision of the DAML+OIL markup language for Web Resources [Co01]. The second and current version of OWL, called OWL 2, was published in 2009 [Wc12]. A detailed and complete explanation can be found in OWL's structural specification [MPP12] or in the primer [Hi09].

By means of headlines, the OWL 2 structural specification [MPP12] distinguishes syntactical categories. We present the rich variety of categories in OWL in table 1. Like in the description logics underlying OWL, there are the two **operators** to express membership conditions of classes: inclusion (SubClassOf) and equivalence (EquivalentTo). The use of the inclusion operator indicates the predication of necessary membership conditions. The equivalence operator is used to assert that the predicate describes necessary and sufficient membership condition and thus defines the class [Ba03, sec.2.2.2]. The operators can also be used between any two class expressions to indicate subsumption or equivalence of classes. Membership conditions can be formulated using specific **connectives**. Various set operators (intersection, union and complement) can be used for constructing class expressions. In addition, OWL contains **quantifiers** like ObjectAllValuesFrom and ObjectSomeValuesFrom that can be used in the formulation of axioms in combination with class names.

In table 1 we also show that 18 of the 22 OWL categegories correspond to only five expressions taken from the more general logical terminology, namely class, individual, axiom, relationship, and membership condition [Br67]:

– A **class** is “an object that can contain members but cannot be a member of any object” [Br67, p. 536]. The members of a class are the individuals.
– An **individual**, also called **particular**, is described as “anything considered as a unit.” [Br67, p. 545]. Some individuals in our world are referred to by a **proper name** in human language, e.g. “Michael Jackson” or “the Liberty Statue”.
– An **axiom** is “a basic proposition in a formal system that is asserted without proof and from which, together with the other such propositions, all other theorems are derived according to the rules of inference of the system.” [Br67, p. 535]. Propositions**,** also called statements, are linguistic entities that can be true or false.
– A **necessary condition** is “a circumstance in whose absence a given event could not occur or a given thing could not exist”, while a **sufficient condition** is “a circumstance such that whenever it exists a given event occurs or a given thing exists”. A condition is both **necessary and sufficient** if it is “a circumstance in whose absence the event could not occur or the thing could not exist and which is also such that whenever it exists the event occurs or the thing exists” [Br67, p. 538]. If a class is defined by a **necessary membership condition**, this condition has *always* to be true for *all* members of the class (i.e. under *all* conditions and context-free), but we cannot be sure that something that fulfills the condition is, in fact, a member of the class. In contrast, given a **sufficient membership condition**, one can be sure that anything that fulfills this condition is a member of the class that is described by the condition, while not every class member has to fulfill the condition.

As table 1 shows, several syntactical categories in OWL 2 can correspond to the same syntactic category in classical predicate logic. For example, both object properties and datatypes correspond to relations in predicate logic. There is no straightforward analogue for the following four categories:

– **Entity.** In the OWL specification, “entity” is used as a cover term for every representational unit of an ontology whose reference is uniquely identified by an Internationalized Resource Identifier (IRI). Hence, “entity” can be conceived as the disjunctive union of classes, datatypes, object properties, data properties, annotation properties and named individuals. As these have different analogues in standard logic, no analogue can be specified for entity in general.
– **Literals** are representations of data values like strings or integers. They always belong to a certain datatype . Sign patterns and numbers could well be considered to be members of the universe of discourse in, say, predicate logic. In this case, literals would be individual names. But as the use of literals may vary, there is no clear mapping to a standard logic analogue.
– **Annotation property** and **annotation.** Annotations contain additional information that is not logically formalized. Hence their content is not accessable for automated reasoning programs; they can be considered to be extra-ontological and extra-logical content.

OWL 2 category	Standard logic analogue
Entity	—
Class	Class name
Individual	Individual name
Datatype	Class name
Literal	—
Object property[1]	Relationship name
Data property[1]	Relationship name
Annotation property	—
Data range[2]	Membership condition using constructors
Class expression	Membership condition
Propositional connective	Membership condition using constructors
Object property restriction	Membership condition using quantifiers
Object property cardinality restriction	Membership condition using quantifiers
Data property restriction	Membership condition using quantifiers
Data property cardinality restriction	Membership condition using quantifiers
Axiom	Axiom
Class expression axiom	Axiom using operators[3]
Data property axiom	Axiom using operators[3]
Object property axiom	Axiom
Datatype definition[4]	Axiom
Assertion	Axiom
Annotation	—

[1] Object properties are relationships between classes while data properties are relationships between a class and a literal that is an instance of a datatype.
[2] Data ranges are customised datatypes. They are specified based on existing datatypes.
[3] Only some class expression axioms and data property axioms embody the use of operators. There are also class expression axioms and data property axioms that declare the disjointness, domain and range of range of relationships, for example.
[4] Datatype definitions define new datatypes. They can be used to define new data ranges.

Table 1. Syntactic categories in OWL and corresponding categories in standard logic

2.2 Representational units of realist ontologies

Most fundamentally, realist ontologies distinguish between *particulars* and *universals*. Historically, the term "particular" and its near-equivalent, "individual," were often used as a *de facto* reference to Aristotelian substances – which are concrete, individual and logical subjects, determinate, enduring and unique in space at any time (e.g. my horse or James D. Watson) [Se10]. Today's conception of particulars also includes entities that fulfill just some of these criteria such as numbers, processes, or social systems (e.g. an economy), but also particular properties (like the colour of a plant, the shape of a cell, the length of a protein or my body tempature on a certain morning). A useful minimal criterion for particulars is that they cannot be instantiated or repeated [MR05]. In contrast, **universals** are entities that can be instantiated, i.e. they can have particulars as *instances*. In an ontology, universals are specified *intensionally*, i.e. they are characterized by postulating certain properties of their instances as membership conditions [GOS09].

According to Kuśnierczyk [Ku06], particulars can be contrasted both with universals and collections. **Collections** are multiple particulars: The current parliament members, for example, is a collection of multiple persons. In a way, collections are in between individuals and universals. Like universals, they may comprise several individuals; like individuals, they may exist in space and time and could, thus, be considered as higher-order individuals. In the literature, collections are most often thought of as aggregates of particulars that instantiate the very same universal [JS11]. A herd of cows, e.g., is a collection of cows, and cell culture is a collection of cells. Following an inspiration by Armstrong [Ar78], we will distinguish between pure and mixed collections. A collection is a **pure collection** if and only if its members are considered to form a collection because they are instances of the same universal. When its members are considered to form a collection for other reasons, this collection is a **mixed collection**. A stock example for mixed collections is the collection of all vegetables—zucchinis, eggplants, potatoes, cabbage and so forth—or all the specific things that are edible but, not fruits (incl. vegetables, meat and so forth) [St10]; another stock example is the collection of all things called "game" [Wi84, § 66]. There is nothing that the members of mixed collections have *uniquely* in common besides the common name. Mixed collections may be defined through customs, habits, laws, regulations, common practise and so forth—as opposed to some intrinsic feature that the members of such collections share.

Collections exist in time and are individualized via their members; hence, they cannot survive gain or loss of members. Universals, however, exist in a timeless manner. At some times they may be instantiated by different particulars, and at other times they may even have no instances at all. Two distinct universals may have the same instances at a certain point of time, but not two collections (they are the same collection then).

In a formal ontology, a universal is specified intensionally by means of properties and relationships which allow to decide whether it may be instantiated by certain particulars using the means of logic. To achieve useful reasoning results, i.e. results that correspond to reality, ontologies specify universals only by properties that are true *for all particulars* that are present, past or future instances of a universal *under all circumstances* and *during their entire existence*. Thus, the properties express *necessary conditions* for particulars to be instances of a universal (e.g. the ability to think attributed to canonical humans).

Notably, an ontology must *not* state any *accidental* properties of universals that its instances may or may not have. For example, 'being able to walk' or 'having two legs' are accidental properties and not necessary conditions of 'humans' since these properties would exclude infants as well as people that had severe accidents or have disfiguring birth defects. All of them are still humans. An ontology that modeled such properties for 'humans' and subsumed 'human infants' and 'disabled people' under 'humans' would lead to reasoning results that do not match reality. (Things could be different if an ontology restricts its scope strictly to the description of, say, a canonical human.)

Ideally, a universal is not only specified by necessary properties, but defined through *necessary and sufficient* conditions. Necessary conditions, as well as necessary and sufficient conditions, are membership conditions that ontologies use to establish meaning. When using OWL, these membership conditions can be efficiently utilised by reasoning algorithms; although, it may be difficult, if not even impossible at times, to identify such conditions in practise.

There are general terms that can be instantiated and specified through membership conditions, but are not considered universals by at least some philosophers in ontological realism. Armstrong [Ar78, ch.13, section IV], for example, distinguishes various types of predicates, of which only the 'stricly universal predicates' correspond to a single universal (cf. table 2).

Kind of predicates	**Relation to universals**
Strictly universal predicates	apply in virtue of exactly one universal (which might be a conjunctive universal)
Homogenous predicates	apply in virtue of some member of a range of universals that are tied together by some formal structure, like "having a mass" (and predicates for determinables in general)
Family predicates	apply in virtue of some member of a class of universals that are tied together by some informal unifying structure
Heterogenous predicates	apply in virtue of some member of a class without any unity (like purely disjunctive predicates)
Empty predicates	either have no application or, if they apply, do not apply in virtue of universals at all (like tautological predicates)

Table 2: Classification of predicates according to Armstrong [Ar78]

According to Armstrong, membership conditions for identifying universals typically have the following characteristics [Ar78, ch.13-16]:

- All instances have something uniquely in common.
- Instances have special causal roles because they instantiate a universal.
- They use at most logical conjunction (e.g. 'being cubic *and* weighing one kilo exactly').
- They refer to properties that describe active or passive powers ('watching football', but not 'doing *nothing*').
- They are absolutely determinate ('weighs one kilogram *exactly*', but not 'having a mass').
- It is an empirical question whether something is an instance of an universal or not. For example, for logical reasons the predicate "… is identical with itself" applies to everything; hence, it is *intensionally empty* insofar as it has no empirical content. For this reason, it cannot correspond to any universal. Other predicates like "… is bewitched" are *extensionally empty* because, as a matter of fact, they have no instances at all.

Armstrong also lists a few characteristics of membership conditions that generally speak against the described entities being a universal:

- No unique common feature.
- Not connected to a specifique causal role.
- Use of disjunction (logical OR; e.g. ‘being sweet or spicy’).
- Use of negation (logical NOT; e.g. ‘not being a material’).
- Reference to particulars (e.g. ‘*descended from* Charlemagne’, ‘*identical with* the planet Venus’).
- Logical restrictions to a finite number of instances (e.g. ‘the *wisest of* men’, ‘*identical with* the planet Venus’).

Armstrong warns us that these criteria cannot be used in merely syntactical tests to distinguish predicates that correspond to universals from those that do not [Ar78, p. 19]. In fact, Armstrong considers it the task of ultimate science to tell us which universals there are. This is, of course, a difficult position for today’s ontology developers. On the one hand, the ontology developers of today cannot wait for ultimate science. They can only restrict themselves to what they hypothesise to be universals and then revise their ontology as science proceeds. On the other hand, a lot of predicates in scientific language may be required in certain domain ontologies, though it is granted that they are not strictly universal.

Figure 1 does not only show the various types of predicates distinguished by Armstrong, but also their relationships to other fundamentals, like the ‘instance of’ relation. We use here the relation ‘collection of instances of’ to emphasize the possibility of *multiple* instantiation, that is, every member of the collection is an instance of the universal. A strictly universal predicate is the only type of predicate that is, in this way, related to pure collections. All other types of predicates correspond, on the level of collections of their instances, to mixed collections. Extensionally empty predicates, by definition, do not have any instances at all while everything instantiates intensionally empty predicates.

Starting from Armstrong’s typology of predicates and the conditions he imposes on membership conditions for universals, we can distinguish between a liberal and a strict concpeption of universals. The liberal understanding is the one by Kuśnierczyk introduced above. According to his definition, a universal is any entity that (a) can be instantiated, (b) is intensionally defined through membership conditions or by other means and (c) cannot be an instance of any kind of entity. We will Whatever is a universal according to this understanding we will call a “liberal universal”. Restriction (c) forbids, e.g., metamodelling techniques [MPP12, sect. 5.9]: That *Dog* is a species cannot be modelled as the class *Dog* instantiating a metaclass *Species*, but needs some other solution [Sc08].

On the other side of the spectrum there is Armstrong’s understanding of a universal corresponding to specific causal roles in which (a) the restrictions on using membership conditions for describing a universal have to be respected, and (b) the universal is neither extensionally nor intensionally empty, nor heterogeneous, a family or homogenous. We will use the term “strict universal” to refer to Armstrong’s understanding of universals, which is ,at least in part, reflected by ontological realism as advocated in Smith & Ceusters [SC10, sect. 5]. Any strict universal is, of course, also a liberal universal.

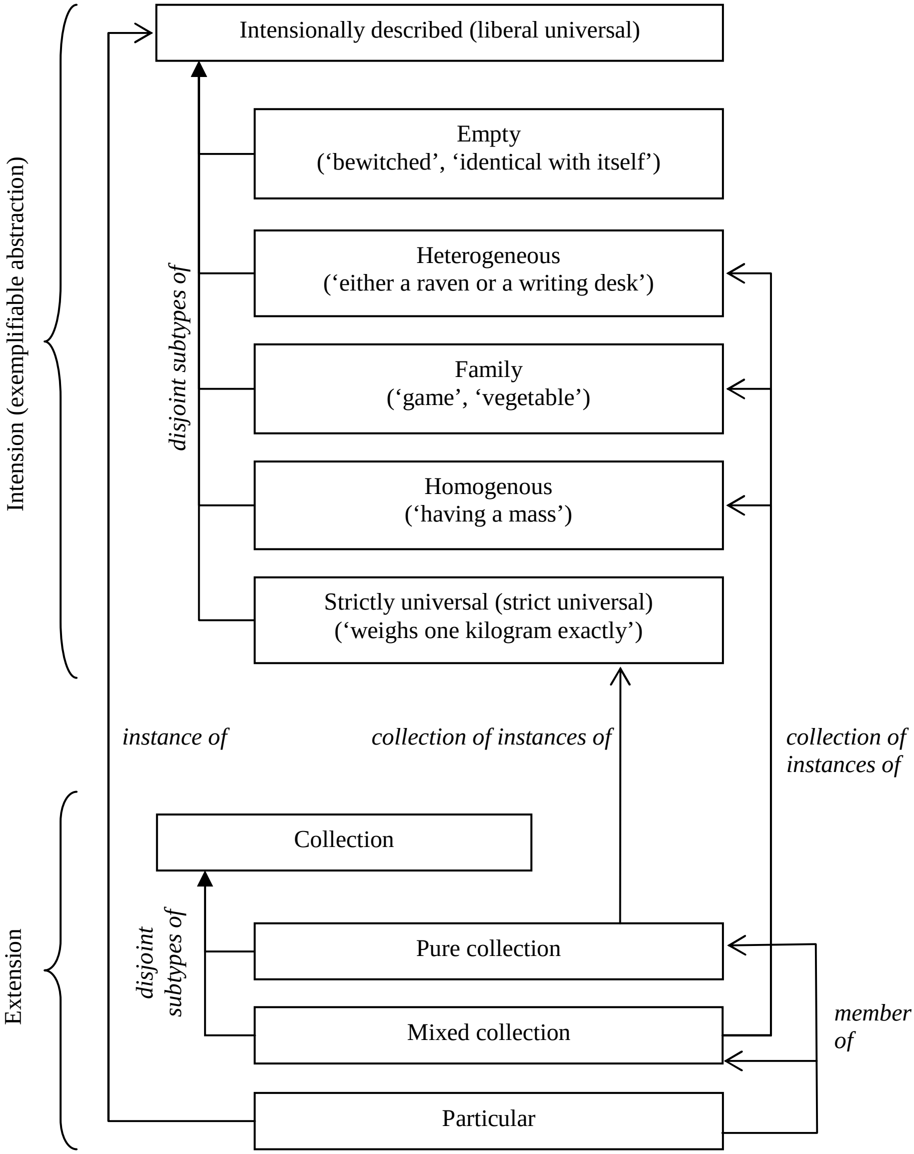

Figure 1. Kinds of predicates and their relation to particulars and collections according to [Ar78]

There is no restriction per se with respect to the kinds of relationships that can be modelled in ontologies [KMK12]. In the context of this paper, it is sufficient to highlight two relationships:

1. Instantiation (*instance of*) is a relation that holds between an individual and a universal if and only if that individual is an instance of this universal. It is irreflexive, asymmetric and intransitive because nothing can be an instance of an individual.
2. The *is-a* relationship (also called subclass relation or subsumption) can only hold between universals. It is a reflexive and transitive relationship that holds between a universal A and a universal B if and only if every instance of A is also an instance of B. The is-a relationship holds, for example, if the term of the superordinate universal has a smaller intension (i.e. a smaller set of defining properties) than the term of the subordinate one.

The logic of these two relations is insensitive to the question whether we decide to adopt the liberal or the strict understanding of universals.

3 Representation of ontology relata in OWL

3.1 Representation of relata in OWL: Classes and datatypes

We first discuss how the *relata* of realist ontologies can be represented in OWL and then turn our attention to the representations of the respective *relations*. The first question that one encounters with relata in OWL is the distinction between classes and datatypes. This issue is not dealt with in the documentation of OWL. Datatypes and classes are, however, well known from conceptual data modeling or UML class diagrams. These have obviously inspired the design of the ontology language OWL. While it might be difficult to spell out an ontologically clear distinction between datatypes and classes, these may be regarded as a form of *construct redundancy* where two or more language constructs stand for a single ontological construct [WW93]. The principles of realist ontology are fulfilled well with the construction of a class hierarchy; they do not leave much space for distinct datatypes. We will not further investigate this question here. We will match classes and datatypes together, but only mention classes explicitly.

A second issue in OWL is that classes and datatypes can be intensionally as well as extensionally specified. Most axioms in OWL result in an intensional specification of a class. Nevertheless, the *ObjectOneOf* axiom (for classes) or the *DataOneOf* axiom (for datatypes), for example, can be used to specify a class/datatype extensionally because they enumerate individuals that instantiate that class/datatype. While any mapping to realist ontologies has to distinguish between intensionally and extensionally specified classes, this distinction cannot be used in practise because in OWL an extensionally defined class cannot be asserted to be the collection of all instances of an intensionally defined class.

A third problem is that OWL does not provide any built-in means to distinguish between particulars and collections of particulars. Some authors explicitly introduce classes of collections that are instantiated by collections of particulars only [JS11] – as it is the case, e.g., in BioTop [Be08]. This account presupposes that collections of particulars are themselves particulars (which might be called higher-order particulars). But whoever sees a categorical distinction between individuals and collections has to object that the category of an individual is *overloaded* [WW93] – that it is used in virtue of several types of entities, namely particulars and pure collections of particulars. Construct overload is problematic because it leads to semantic ambiguity – the very thing ontologies are intended to dissolve. If a model contains ambiguous sentences, this can lead to unintended and wrong implications.

The combination of these issues and their respective solution result in a somewhat cumbersome situation when mapping OWL to ontological realism. Since some intensionally specified classes/datatypes are instantiated by collections (solution for the third issue), and because the extension of classes in OWL always consists of individuals, it follows that collections (e.g. a collection of grains of rice) *are* individuals. Collections can also be *referenced* by extensionally defined classes (distinguished in response to the second issue). For example, the collective term “Rocky Mountains” refers to a collection of specific mountains. We could now introduce a class labeled “[Mountain of the] Rocky Mountains” that is instantiated by specific mountains, each of which is to be represented as an individual in OWL. We do not recommend the creation of such classes and reject the application of the *ObjectOneOf* and *DataOneOf* axioms in OWL overall. The relation between the Rocky Mountains and the individual mountains that form the Rocky Mountains are better described using a *physical-part-of* relationship at an individual level.

Some reverse correspondences are more straightforward to map: All extensionally defined classes *reference* collections and all particulars in realism correspond to individuals in OWL (e.g. Charlie Chaplin). Also mapping universals does not necessitate any further explanations: universals in their liberal interpretation fully correspond to intensionally specified classes (e.g. vegetable), but only some classes correspond to strict universals (e.g. zucchini).

3.2 Representation of ontological relationships in OWL

After this discussion of relata, we will now ask how relationships can be asserted in OWL. There are six language elements in OWL that can represent or assert the relationships of realist ontologies: object properties, data properties, the subclass relation, the data subproperty relation, the object subproperty relation and the class assertion. These language elements and their mapping to realist ontologies are depicted in figure 3 and will be explained in due course. Note that the meaning of the term “property” in the names of the OWL primitives is different from the one in ontological realism and should not be confused with this.

The object property and data property are the two types of elements in OWL that can be used for the free definition of relationships. The distinction between object properties and data properties is based on the distinction of classes and datatypes discussed earlier.

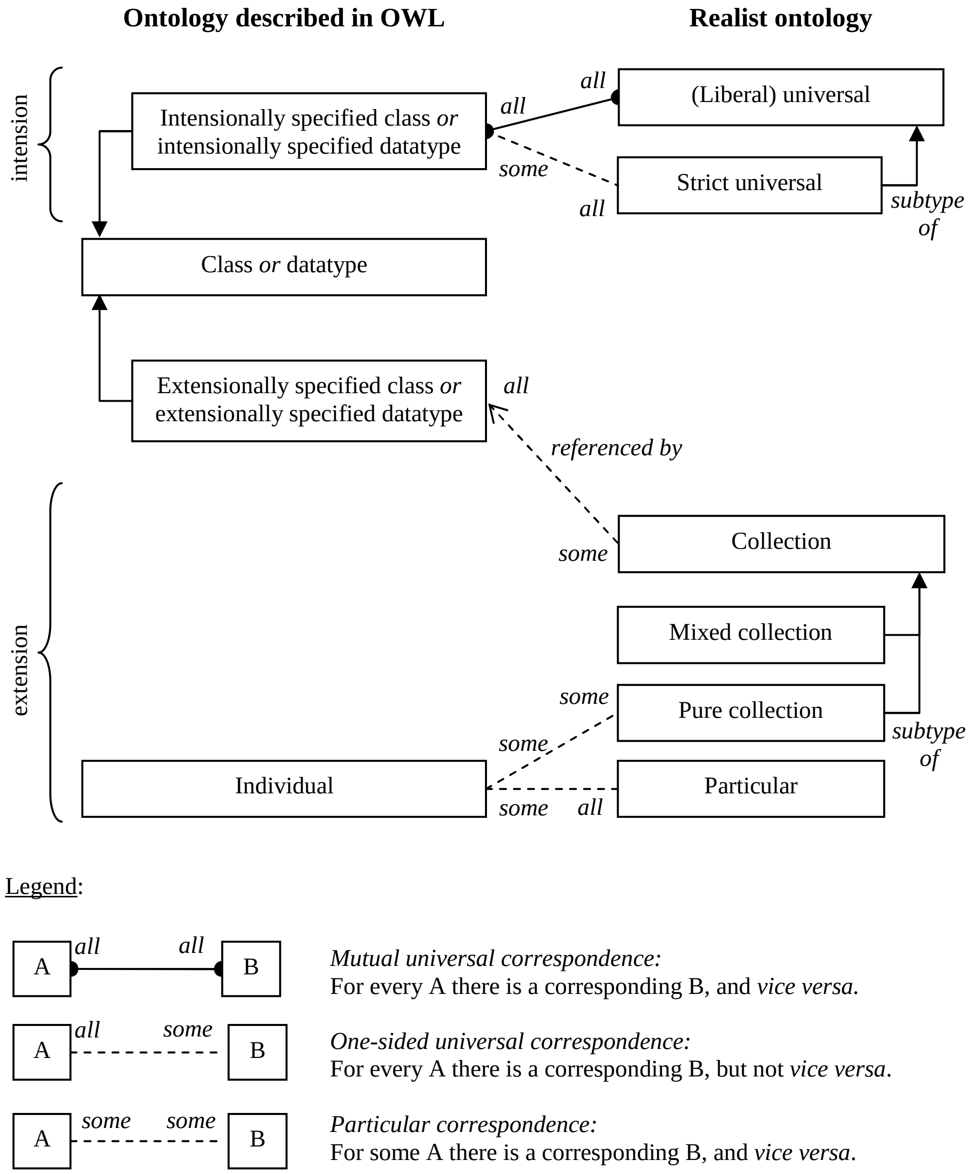

Figure 2. Assignment of relata in realist ontologies to categories in OWL

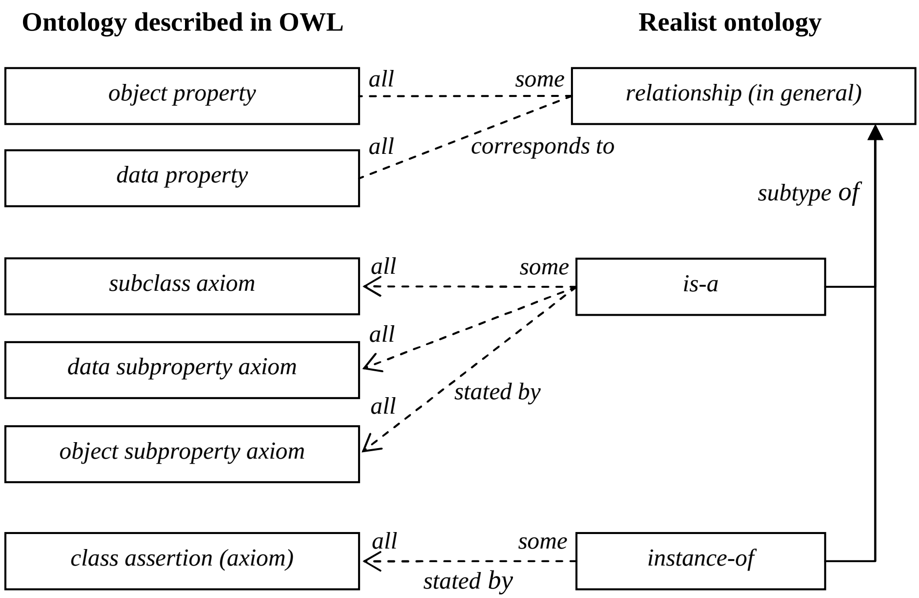

Figure 3. Assignment of relationships in realist ontologies to properties and axioms in OWL

The subclass, data subproperty and object subproperty relations as well as the class assertion are all modeling primitives that allow *stating* the existence of relationships between entities. The first three of these – subclass, data subproperty and object subproperty – can be used to declare is-a relationships between entities in realist ontologies. The assertion of a subclass relationship applies between classes (e.g. class "tiger" *subclass of* class "animal") while the data subproperty axiom is stated between two data properties (e.g. data property "has surname" *data subproperty of* data property "has name") and the object subproperty axiom can be declared between two object properties (e.g. object property "has agent" *object subproperty of* object property "has participant").

The class assertion axiom expresses an instance-of relationship (e.g. "Charlie Chaplin *instance-of* human being"). The instance-of relationship of realist ontologies does not fully correspond to what can be expressed with the class assertion axiom. The reason is that the distinction between classes and datatypes does not exist in ontological realism and, consequently, the class assertion cannot state all possible instance-of relations. More precisely, it cannot express that a specific data value is an instance of a specific datatype (e.g. that the number one is an *instance-of* natural numbers). This problem is, of course, made obsolete if modellers refrain from using datatypes in the first place.

4 Conclusion

The assignments that have been presented in this paper reveal that OWL is not a perfect language for describing realist ontologies. There is no one-to-one mapping between syntactical categories in OWL and the elements of realist ontologies. Especially the use of data properties is unclear. The reason for this is the independent history of description logic and OWL on the one hand and ontological realism on the other. Nevertheless, together with its description logic semantics, OWL is close enough to the realist framework of ontologies to describe them. Certain syntactical categories of OWL, however, seem to be either alien to realist ontologies or duplications. In particular, we identified the following problems:

Classes vs. universals. While realist ontologists can have quite strong conceptions of universals, OWL is very flexible as to what counts as a OWL class. For this reason, we suggest to understand OWL classes as corresponding to 'liberal universals' only. Stronger conceptions of universals can be seen as dietary rules for ontology developers for deciding which classes to include in scientific ontologies.

Individuals. While OWL allows expressing assertions about individuals, this is not considered proper ontological content by the realist paradigm. Individuals are, in fact, important for the formal definition of ontological relations. Nevertheless, the aim of a realist ontology is the representation of general features of a certain domain and not knowledge about individuals. Hence, ontology developers are advised not to use these functions of OWL as part of the ontology proper.

Datatypes and data properties. Datatypes have a long tradition in computer science. They facilitate automated processing by computers and exchange of data with other information systems. Hence, there are good historical and pragmatic reasons for their inclusion in OWL. From the point of view of the realist paradigm, however, they appear as an unnecessary and potentially misdirecting duplication of the proper class hierarchy. Datatypes should probably be integrated within the usual as part of an ontology of information artifacts [Ia13].

Annotations. Annotations typically contain metadata of entities or whole ontologies. Due to the restricted expressibility of OWL, it might also be necessary to store proper ontological content (like a definition) as an annotation. Ontology developers have to bear in mind, however, that annotations are accessible to human users, but not to automated reasoning algorithms.

In the end, these findings confirm that being written in OWL is neither necessary nor sufficient for being an ontology. Not everything that can be coded in OWL is proper ontological content according to the realist paradigm.

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