How to Build a Foundational Ontology
The Object-Centered High-level Reference Ontology OCHRE

Luc Schneider

Institute for Formal Ontology and Medical Information Science,
University of Leipzig, Härtelstrasse 16-18, D–4107 Leipzig
E-mail: luc.schneider@ifomis.uni-leipzig.de

Abstract. Foundational ontologies are axiomatic accounts of high-level domain-independent categories about the real world. They constitute toolboxes of reusable information modeling primitives for building application ontologies in specific domains. As such, they enhance semantic interoperability between agents by specifying descriptively adequate shared conceptualisations. The design of foundational ontologies gives rise to completely new challenges in respect of their content as well as their formalisation. Indeed, their underlying modeling options correspond to the ontological choices discussed in classical metaphysics as well as in the research on qualitative reasoning. Building a foundational ontology is thus an eminently interdisciplinary task. As a case study, this article sketches the formalisation of the Object-Centered High-level REference ontology OCHRE, emphasising in particular the problem of achieving formal simplicity within the limits of descriptive adequacy.

1 Introduction

Foundational ontologies are axiomatic theories about domain-independent top-level categories such as *object*, *attribute*, *event*, *parthood*, *dependence* and *spatio-temporal connection*. They amount to repositories of highly general information modeling concepts that can be reused in the design of application ontologies for all kinds of domains (Gangemi et al. 2002). By providing toolboxes of standardised knowledge representation primitives, foundational ontologies also enhance the semantic interoperability between the communicating agents (ibid.).

According to received AI wisdom, an ontology is nothing other than the formal statement of a shared conceptualisation (Gruber 1991, Guarino 1998). However, it is not sufficient for an ontology to be merely consensual. The fact that ontologies, whether in the medical field or in the area of business operations, have to be updated and revised, reveals the need for acknowledging the constraint of *descriptive adequacy*. Ontologies which are designed to describe a certain domain adequately, will be called *reference ontologies* (Smith 2003). Foundational ontologies are top-level reference ontologies; though their starting point is the set of common-sense intuitions that make up the human conceptualisation of reality, they ultimately aim at describing the categorial structure of the world as a whole.

The challenges of building foundational ontologies are unfamiliar to most knowledge engineers. Indeed, the design options for top-level ontologies are identical to the ontological choices discussed in the branch of philosophy called *metaphysics* as well as in the research on qualitative reasoning. Although down-to-earth pragmatical considerations regarding simplicity and contextual applicability help to avoid getting bogged down in spurious details, a good knowledge of the recent advances in metaphysics as well as in qualitative reasoning is still necessary to gauge different ontological positions and approaches. Building foundational ontologies is thus an eminently interdisciplinary task.

As an illustration of current approaches to the design of foundational ontologies, the present paper outlines the formalisation of the Object-Centered High-level REference ontology OCHRE, elucidating and motivating its basic modeling decisions. The purpose of this article is not only to present a particular basic ontological framework, but also to demonstrate how the quality of a foundational ontology depends on maximal formal elegance and transparency in the limits of descriptive adequacy.

The paper is structured as follows. Section 2 treats the theory of parts and wholes, presenting a simple algebraic framework for mereology. Section 3 defends a qualitative account of objects as bundles of attributes and defines the relation of similarity between individual features. Section 4 outlines a theory of dependence grounding the ontological priority of objects over other entities. Section 5 discusses the problem of change, contending a distinction between objects and their short-lived stages, and axiomatises spatio-temporal connection between such stages of objects. Section 6 analyses the relations between attributes and objects and addresses the issue of constitution by a theory of guises. Section 7 formalises the relation of temporal succession between object-stages and offers an account of events in terms of ensuing object-stages.

It should be pointed out that the axioms (**XA n**), theorems (**XT n**), and definitions (**XD n**) given in this paper only aim at a minimal formal characterisation of the ontological primitives. The meaning of these primitives can only be constrained by referring to the ontological intuitions underlying human world knowledge. The informal parts of this essay are intended to clarify these intuitions and thus form an integral part of the specification of OCHRE.

2 Parts and Wholes

Mereology, the formal theory of parthood, has grown out of early-20th-century mathematical research into a calculus of individuals capturing relations between set-theoretical *urelemente* (Leonard and Goodman 1940). Classical mereology, namely *General Extensional Mereology (GEM)*, amounts to a Boolean algebra without a null element (Simons 1987, chap. 1; Casati and Varzi 1999, chap. 3). In particular, OCHRE is based on the atomistic version of GEM.

The *parthood* relation is reflexive, antisymmetric and transitive.

MA 1. Pxx *(reflexivity)*

MA 2. $(\,Pxy \wedge Pyx\,) \;\rightarrow\; x = y$ *(antisymmetry)*

MA 3. $(\,Pxy \wedge Pyz\,) \;\rightarrow\; Pxz$ *(transitivity)*

As a direct consequence of the reflexivity of parthood (**MA 1**), identity implies mutual parthood. In other words, parthood is partial identity (Armstrong 1997, p. 17; Lewis 1991, pp. 81–82).

MA 4. $x = y \;\rightarrow\; (\,Pxy \wedge Pyx\,)$ *(parthood is partial identity)*

The irreflexive variant of parthood is called *proper parthood*.

MD 1. $PPxy \;\equiv_{df}\; Pxy \wedge \neg\, x = y$ *(proper parthood)*

Two individuals *overlap* iff they have common parts.

MD 2. $Oxy \;\equiv_{df}\; \exists z\,(\,Pzx \wedge Pzy\,)$ *(overlap)*

An *atom* is an entity that has no proper parts.

MD 3. $\mathcal{A}x \;\equiv_{df}\; \neg\,\exists y\, PPyx$ *(atom)*

An atomistic mereology is based on the thesis that everything has atomic parts:

MA 5. $\exists y\,(\,\mathcal{A}y \wedge Pyx\,)$ *(atomicity)*

Parthood is assumed to be extensional, i.e. an individual is part of another if every atomic part of the first is also a part of the second.

MA 6. $(\,(\,\mathcal{A}z \wedge Pzx\,) \rightarrow Pzy\,) \;\rightarrow\; Pxy$ *(extensionality)*

The basic mereological operation is the *(generalised) sum* or *fusion* of all φ-ers which yields the individual containing the atomic parts of entities satisfying the condition φ.

MD 4. $SM(x, \lambda y\varphi y) \;\equiv_{df}\; \forall z\,(\,\mathcal{A}z \rightarrow\; (\,Pzx \leftrightarrow \exists w\,(\,\varphi w \wedge Pzw\,)\,)\,)$ *(sum)*

The *General Sum Principle* stipulates that, for every satisfiable condition φ, there is a unique sum of all φ-ers.

MA 7. $\exists x \varphi x \;\leftrightarrow\; \exists! y\, SM(y, \lambda z\varphi z)$ *(general sum principle)*

As a consequence, there is a least upper bound for parthood, some entity of which everything is a part, namely the fusion of all self-identical entities.

MD 5. $\mathcal{U}x \;\equiv_{df}\; SM(x, \lambda y(\,y = y\,)\,)$ *(least upper bound)*

The mereological operations of *(binary) sum*, *product* and *difference* correspond to the set-theoretic operations of union, intersection and set difference:

MD 6. $SM(x, y, z) \;\equiv_{df}\; SM(x, \lambda w\,(\,Pwy \vee Pwz\,)\,)$ *(binary sum)*

MD 7. $PR(x, y, z) \;\equiv_{df}\; SM(x, \lambda w\,(\,Pwy \wedge Pwz\,)\,)$ *(product)*

MD 8. $DF(x, y, z) \;\equiv_{df}\; SM(x, \lambda w\,(\,Pwy \wedge \neg\, Owz\,)\,)$ *(difference)*

This concludes the axiomatisation of Atomistic General Extensional Mereology, which has the advantage of being both formally elegant and simple.

3 Similarity

Repeatable and Non-repeatable Properties A fundamental ontological choice in an atomistic mereology pertains to the nature of the building blocks of reality. Ontologists agree that the denizens of reality fall into three main categories: *objects* (like quarks, tables, stones, companies, and solar systems), *attributes* or particular properties and relations (like the various shades of colour on a soap bubble, the mass and velocity of a bullet, your intelligence, and your relationship with your parents), as well as *events* (like runnings, hugs, bank transfers, perceptions, and thinkings). In the final section of this paper, events will be reconstructed as successions of attribute bundles.

A descriptively adequate ontology like OCHRE has to account for both *objects* and *attributes.* This does not contradict considerations of conceptual economy that motivate defining references to entities of one category in terms of references to entities of the other. The so-called *Qualitative Account* of objects as bundles of attributes is favoured by many ontologists, such as e.g. Williams (1953), Campbell (1990), Denkel (1996), and Simons (1994), since it avoids the problematic notion of objects as unscrutable blobs which attributes somehow adhere to. Nevertheless, as Denkel (1996, pp. 16–17) rightly emphasises, it is also true that objects are more than mere sums of their properties: a descriptively adequate ontology has to explain the completeness, independence and spatio-temporal bulk that objects enjoy in contrast to arbitrary sums of attributes.

Attributes can be regarded either as *repeatables* or as *non-repeatables* (Armstrong 1997, p. 31). Repeatables, also called *universals*, apply to more than one case; by contrast, non-repeatables, commonly referred to as *property-instances* or *tropes* (Williams 1953; Campbell 1990), are single characteristics of individuals. OCHRE endorses the claim of Williams, Campbell, and Denkel that the atoms of mereology are all non-repeatables. So if two stones resemble each other with respect to mass or density, then they contain similar, but distinct mass- or density-instances. Note however, that not every non-repeatable has to be atomic: as we shall see, some non-repeatable properties (like colours) and in fact *all* non-repeatable relations (like family relationships) may be regarded as composite. In this paper, the term *trope* will denote atomic property-instances only.

Obviously, OCHRE has to acknowledge repeatable properties or relations, too, if only the *formal universals* that are the subject matter of every foundational ontology, such as *object*, *trope*, *parthood*, *dependence*, or *similarity.* References to formal properties and relations are made through (lambda-abstractions of) the respective predicates. Semantically, predicates can be interpreted as sets; ontologically, however, there is no need to regard a universal as something outside or above the entities that instantiate it. In point of fact, OCHRE embraces the stance of *Aristotelian realism*, according to which repeatable properties and relations are given or present in their very exemplifications (Aristotle, *Met.*: 1023b; Armstrong 1997, p. 22). For example, in order to know whether an individual is part of another, it suffices to inspect both of them.

Furthermore, formal universals apply to their exemplifications directly, without any further mediating relations. This is just a consequence of their being the top-level categories of reality. In other words, the nexus between a formal universal and its instances, in particular that between a formal relation and its relata, is ontologically unanalysable, lest there be an infinite regress. Nonetheless, the nexus of instantiation can be described on the level of model-theoretic semantics as the membership relation between a single instance or a tuple of relata and the class representing the extension of the universal. Set-theory, it should be noted, is not regarded here as a part of the ontology, which is assumed to deal with *urelemente* exclusively, but as belonging to the meta-ontological machinery of Tarskian semantics.

Intensity, Comparability and Similarity Tropes, as well as their mereological sums, constitute families whose members can be compared with each other and ordered in terms of their *intensity*. Qualities like mass or density, relations like being-in-love, and dispositions like intelligence or brittleness may vary according to degrees. And though individual marriages and tropes of magnetic polarity admit no such degrees, they are nonetheless comparable. But there is no way to collate hues and tastes, or masses and electrical charges.

The relation of *being more or equally intense* (in symbols: "Ixy") is a reflexive and transitive relation defined over tropes (atoms).

SA 1. $Ixy \rightarrow (\mathcal{A}x \wedge \mathcal{A}y)$ *(restriction)*

SA 2. $\mathcal{A}x \rightarrow Ixx$ *(reflexivity)*

SA 3. $(Ixy \wedge Iyz) \rightarrow Ixz$ *(transitivity)*

Multidimensional variability of intensity as in the case of colours indicates that the attribute in question is indeed composite; colours, for instance, can be resolved into tropes of saturation, brightness, and hue.

Two tropes are *comparable* iff they can be ordered in terms of their intensity.

SD 1. $CMxy \equiv_{df} Ixy \vee Iyx$ *(comparability)*

Two tropes x and y are *similar* iff x and y are equally intense. Note that similarity is to be understood as *exact*, not *approximative* similarity.

SD 2. $Sxy \equiv_{df} Ixy \wedge Iyx$ *(similarity)*

Two non-atomic individuals x and y are (exactly) similar iff their respective component tropes can be associated one-to-one such that to every trope of x there corresponds one (exactly) similar trope of y and vice-versa.

References to *material universals*, i.e. kinds of tropes (or trope-bundles), such as *Mass*, *Colour*, or *Humanity* are inevitable in every-day discourse and thus have to be allowed for by a descriptively adequate ontology. In particular, the *genus* of any conventionally chosen trope x is defined as the property of being comparable to x and its *species* as the property of being similar to x (cf. Campbell 1990, pp. 83–85). As similarity implies comparability, the genus of a trope (e.g. *Mass*) subsumes its species (e.g. *15 kg*).

SD 3. $GE_x y \equiv_{df} \lambda y\, CMyx$ *(genus)*

SD 4. $SP_x y \equiv_{df} \lambda y\, Syx$ *(species)*

These definitions can be extended to aggregate comparability and similarity relations between trope-bundles. In practice, it is not necessary to define every type explicitly through a comparability or similarity relation. The mere *possibility* of such a definition should be sufficient for ontology engineering purposes.

4 Dependence

Though tropes are the basic building blocks of reality, they cannot be conceived of as separate from the objects they characterise. Each trope (e.g. a mass) is *dependent* on a specific object (e.g. a bullet). According to Strawson (1959, pp. 16–17), dependence can be understood in terms of *identification*. An individual x is identificationally dependent on an individual y – in symbols: "Dxy"– if, and only if, in order to identify x, one has to single out y first. In a certain sense, the entites on which something is dependent are part of its very definition or identity (Fine 1994/1995, p. 275).

The difference between objects (like cars, tables, body organs, persons, companies, constellations, and quarks) and dependent entities (i.e. tropes like masses, velocities, colours, flavours, or processes like orbital movements, heart contractions, and bank transfers) consists in the fact that the former can be singled out on their own, while the latter have to be individuated relatively to some object. Hence, objects can be defined as identificationally self-dependent entities; furthermore, I assume that no object is atomic, that is, a single trope:

DD 1. $\mathcal{O}x \equiv_{df} Dxx$ *(objects)*

DA 1. $\mathcal{O}x \rightarrow \neg \mathcal{A}x$ *(non-atomicity of objects)*

In the next section, these self-dependent trope-bundles will be identified with so-called *thin objects*, the mereological sums of the essential features of every-day *thick* objects. Being self-dependent, objects are not dependent on other entities.

DA 2. $\mathcal{O}x \rightarrow (\, Dxy \rightarrow x = y\,)$ *(objects are independent)*

Objects have ontological priority over other particulars since they constitute a framework of reference that serves as a basis for identification. It is an open question to which degree the ultimate framework of reference is based on convention, and hence involves vagueness, since conventions are usually only partially defined and are liable to compete with each other (cf. Heller 1990, pp. 47–49). But the conventionality and vagueness of divisions of reality are properly dealt with in the particular contexts of application and thus on the level of single *domain* ontologies.

Nothing can depend on an entity that is not self-dependent.

DA 3. $Dxy \rightarrow \mathcal{O}y$ *(everything depends on objects)*

Every trope that is part of an object is dependent on the latter.

DA 4. $(\mathcal{O}x \wedge \mathcal{A}y \wedge Pyx) \rightarrow Dyx$ *(dependent atomic parts of objects)*

If something is not self-dependent, then it depends on anything that one of its atomic parts is dependent on. Hence by dealing with the dependences of tropes, we determine the dependences of every entity that is not an object.

DA 5. $(\neg\mathcal{O}x \wedge \mathcal{A}y \wedge Pyx \wedge Dyz) \rightarrow Dxz$ *(dependence of non-objects)*

Now, every trope is assumed to depend on exactly one object (note that by **DA 2**, this holds for objects, too). In other words, each trope is a non-repeatable attribute of one single individual. Thus each physical object has its own mass, velocity, and so on.

DA 6. $\mathcal{A}x \rightarrow \exists! y\, Dxy$ *(a trope is dependent on one object)*

Non-repeatable relations (e.g. individual loves, kinships, and ownerships) have been defined as multiply dependent attributes in the literature on ontology (Simons 1995, Mulligan and Smith 1986). Since tropes as atomic attributes are dependent on one object, non-repeatable relations have to be mereological sums of tropes.

The theory according to which relations supervene on monadic properties of their relata, such that there are no relational differences without qualitative ones, is called *foundationism* (Campbell 1990, pp. 101, 113). OCHRE endorses foundationism only as far as non-repeatables are concerned. In fact, an individual marriage just amounts to the mereological sum of the particular rights and duties of the husband and the wife. Similarly, a biological kinship is based on the particular DNA of each member of a family. Foundationism is obviously false with respect to repeatable relations, i.e. formal relations as well as their combinations and restrictions. So, following a proposal by Mulligan (1998, p. 327), OCHRE adopts monadism for atomic non-repeatables, but assumes irreducible repeatable relations like the formal relations of parthood and dependence.

5 Connection

The Problem of Change; Thin and Thick Objects. The thesis that objects form the basic framework of reference seems to be undermined by the pervading character of change. Objects apparently lose and gain parts, move around, and exhibit uncompatible properties and relations over time. A solution favoured by many ontologists, e.g. Quine (1960, p. 171), Heller (1990), and Armstrong (1997, pp. 99–107), is to regard objects as space-time worms: incompatible facts just pertain to different phases of such fourdimensional entities. This approach is elegant, but rejects the intuitive distinction between objects and processes.

Alternatively, one can stick to the intuition of objects as three-dimensional entities and temporalise the *assertions* about objects instead. Formal properties and relations, especially parthood, have to receive a time-stamp, an additional temporal parameter. This has been proposed, amongst others, by Thomson (1983, pp. 214–218), Johnston (1984, p. 129), Simons (1987, chap. 5) and

Haslanger (1989, pp. 120f). Temporalisation, however, makes reasoning about formal universals like parthood rather intricate.

The problem of change reveals an ambiguity of the ontological category of object. Varying the terminology of Armstrong (1997, pp. 123–126) and developing intuitions from Simons (1994) and Denkel (1996, p. 108), one has to distinguish between an evanescent whole, the *thick object* and a core of enduring characteristics, the *thin object.* Thick objects have spatio-temporal bulk and undergo change. Change consists in the succession of temporary aggregations of tropes shaped by relations of spatio-temporal connection. Thin objects, as the enduring cores of thick objects, constitute the ultimate referential framework of independent entities, the ontological backbone of reality. Thick objects, on the contrary, are dependent entities; successions of thick objects are held together by thin objects common to all elements in these chains, as for example by bundles of essential functions in the case of artifacts or organisms.

Our approach to the problem of change is akin to the stage theory proposed by Sider (2001, pp. 1–10, pp. 188–208), Hawley (2001, chap. 2), and Denkel (1996, pp. 101–109), with the main difference that thick objects as stages of thin objects are considered to be dependent entities. Successive incompatible states of affairs hold of distinct elements in a chain of succeeding thick objects that share the same thin object as a common core. The exchange of colour-tropes in a ripening tomato just pertains to different evanescent wholes centered around the bundle of core characteristics, amongst them the tomato's DNA. That one speaks of the same object through change is grounded in the existence of thin objects. Every seemingly temporal attribution of properties and relations to a thin object really is just the atemporal attribution of these attributes to succeeding thick objects that are stages of the thin object.

Connection As thin objects are nodes in a pervading network of dependences, thick objects are nodes in a comprehensive grid of spatio-temporal connections. The formal ontological theory of spatio-temporal connection is called *topology*; topology constraints mereology and both together constitute the formal-ontological framework of *mereotopology* (Casati and Varzi 1999, chap. 4).

The primitive of topology is *connection*, a symmetric and intransitive relation that is reflexive in all cases it applies at all. Its underlying intuition is that of immediate neighbourhood in space and time. E.g., France is connected to Germany and Germany to Poland, but France is not connected to Poland.

CA 1. $Cxy \rightarrow Cxx$ *(reflexivity)*

CA 2. $Cxy \rightarrow Cyx$ *(symmetry)*

Thick objects ("$\mathcal{O}^*x$") are bundles of tropes exhibiting spatio-temporal connections. No thick object is a self-dependent entity or *thin object* ("$\mathcal{O}x$").

CD 1. $\mathcal{O}^*x \equiv_{df} \exists y\, Cxy$ *(thick object)*

CA 3. $\mathcal{O}^*x \rightarrow \neg\mathcal{A}x \wedge \neg\mathcal{O}x$ *(thick objects are dependent trope-bundles)*

Parthood between thick objects is called *thick parthood.*

CD 2. $TPxy \equiv_{df} \mathcal{O}^*x \wedge \mathcal{O}^*y \wedge Pxy$ *(thick parthood)*

Thick parthood will be linked to connection through the topological relation of *enclosure.* A thick object is enclosed in another if, and only if, everything which is connected to the first is also connected to the second. A heart is contained in a chest, a fish in a lake, and so on.

CD 3. $Exy \equiv_{df} \forall z\,(\,Czx \rightarrow Czy\,)$ *(enclosure)*

Mutual enclosure implies identity. In other words: distinct thick objects cannot be co-located, they compete for space. Thus there is no need to distinguish between a thick object and the region in which it is located. Indeed, a thick object can be seen as a qualitatively enriched spatio-temporal region.

CA 4. $(\,Exy \wedge Eyx\,) \rightarrow x = y$ *(mutual enclosure entails identity)*

The formal link between mereology and topology is the axiom of monotonicity (Casati and Varzi 1999, p. 54): thick parthood entails enclosure, but not vice-versa. Since a heart is part of a chest, it is also enclosed in the latter. However, a fish is enclosed in, but is not part of a lake.

CA 5. $TPxy \rightarrow Exy$ *(monotonicity)*

There is no commitment to regions of space and time as a distinct category of particulars in OCHRE. Space and time are considered as universals, namely as (formal) spatio-temporal relations that are exemplified by thick objects.

6 Inherence

Direct Parthood and Essence. The formal relation between (thin or thick) objects and their attributes that has traditionally been called *inherence* can be accounted for in terms of dependence and parthood. Since a thick object may have other thick objects as parts, one has to specify whether a trope or a thin object is associated with that thick object or one of its thick parts. For example, one would like to distinguish the weight of a body and the weight of its heart.

Such distinctions can be done through the relation of *direct parthood.* An individual x is a direct part of an entity y iff x is a proper part of y, y is a thick object, and there is no thick proper part z of y such that x overlaps with z.

ID 1. $DPxy \equiv_{df} PPxy \wedge \mathcal{O}^*y \wedge \neg\exists z\,(\,TPzy \wedge \neg\, z = y \wedge Oxz\,)$ *(direct parthood)*

Direct parts cannot be thick objects. In the words of Williams (1953, p. 6), they are *fine* or *abstract* parts, as opposed to *gross* or *concrete* parts, of thick objects.

Every trope is a direct part of some thick object; there are no homeless tropes.

IA 1. $\mathcal{A}x \rightarrow \exists y\, DPxy$ *(no homeless tropes)*

No two comparable tropes may be both direct parts of the same thick object. E.g. a thick object cannot have more than one mass or kinetic energy.

IA 2. $(DPyx \wedge DPzx \wedge CMyz) \rightarrow y = z$ *(comparability and direct parthood)*

A thin object x that is a direct part of a thick object y is an *essence* of y.

ID 2. $ESxy \equiv_{df} \mathcal{O}x \wedge DPxy$ *(essence)*

Each thick object has at least one essence. It seems counterintuitive that a thick object may have more than one essence, but this is the case for most every-day objects such as artifacts (or organisms) and the amount of material they are made of.

IA 3. $\mathcal{O}^{*}x \rightarrow \exists y\, ESyx$ *(existence of essences)*

In order to fully specify the dependence of entities that are not self-dependent, one further constraint on the dependence of tropes is needed (cf. **DA 5**). Indeed, the so-called *inherence principle* links atomic direct parthood and dependence by stipulating that, for any trope x, thin object y, and thick object z, if x depends on y and is a direct part of z, then y is an essence of z.

IA 4. $(\mathcal{A}x \wedge Dxy \wedge DPxz) \rightarrow ESyz$ *(inherence principle)*

Since a) each thin object has tropes as parts (by **DA 1**), b) each atomic part of a thin object is dependent on the latter (by **DA 4**), and c) each trope is a direct part of some thick object (by **IA 1**), it follows that every thin object is an essence of some thick object (by **IA 4**; see also **TA 16**). The presence of a thin object in a thick object does not imply the presence of *all* its dependent tropes.

Coincidence and Guises. Common-sense allows for numerically distinct objects to be spatio-temporally co-located, or *coincident*, e.g., a terracotta statue and the clay it is made of, or a person and her body. Some ontologists, like Simons (1987, chap. 6), assume such entities to be distinct physical objects of which one (e.g. the clay) *constitutes* the other (e.g. the statue). In OCHRE, there is no need to allow for *constitution* as an additional non-extensional composition.

Thick objects cannot be co-located, since they have spatio-temporal bulk and thus compete for space. Instead, I consider coincident entities to be *direct parts* of the same thick object. Thick objects may have more than one essence, each of which has its own periphery of dependent tropes. The mereological sum of a thin object and all the tropes dependent on it represents a qualitative aspect of the thick object, which I call a *guise*, after Castañeda (1985/1986). Formally, some x is a guise of a thick object y with respect to some essence z of y iff x is the mereological sum of all atomic direct parts of y which are dependent on z.

ID 3. $G_{z}xy \equiv_{df} ESzy \wedge SM(x, \lambda w\,(\mathcal{A}w \wedge DPwy \wedge Dwz))$ *(guise)*

A particular thick object that we identify as a terracotta statue made of clay contains two sub-bundles of tropes, namely the statue and the amount of clay, each centered on a particular thin object: the functions of the artifact and the chemical characteristics of the material. These trope bundles are *fine* or *abstract* parts of the same thick object and represent different aspects of the latter.

7 Temporal Order

Temporal Anteriority and Essential Succession. As stages of thin objects, thick objects are not only spatio-temporally connected, but also succeed each other in time. Since any computer representation of time has to be granular, time may be regarded as a *discrete* series of atomic intervals.

The theory of temporal order is based on two primitive relations: *direct anteriority* and *simultaneity*, both defined over thick objects. Direct anteriority is irreflexive, asymmetric and intransitive.

TA 1. $DAxy \rightarrow (\mathcal{O}^*x \wedge \mathcal{O}^*y)$ *(restriction)*

TA 2. $\neg DAxx$ *(irreflexivity)*

TA 3. $DAxy \rightarrow \neg DAyx$ *(asymmetry)*

Simultaneity is, of course, an equivalence relation.

TA 4. $SIxy \rightarrow (\mathcal{O}^*x \wedge \mathcal{O}^*y)$ *(restriction)*

TA 5. $\mathcal{O}^*x \rightarrow SIxx$ *(reflexivity)*

TA 6. $SIxy \rightarrow SIyx$ *(symmetry)*

TA 7. $(SIxy \wedge SIyz) \rightarrow SIxz$ *(transitivity)*

Thick parthood only holds between simultaneous thick objects.

TA 8. $TPxy \rightarrow SIxy$ *(thick parthood implies simultaneity)*

Thick objects do not temporally overlap, but form discrete and synchronised series of stages that are instantaneous with respect to a certain granularity of time. This is ensured by postulating that all direct temporal antecessors, as well as all direct temporal successors, of a thick object are simultaneous.

TA 9. $(DAyx \wedge DAzx) \rightarrow SIyz$ *(simultaneity of direct temporal antecessors)*

TA 10. $(DAxy \wedge DAxz) \rightarrow SIyz$ *(simultaneity of direct temporal successors)*

The temporal relation of *(indirect) anteriority* is defined by recursion:

TA 11. $DAxy \rightarrow Axy$ *(indirect anteriority: base case)*

TA 12. $(DAxy \wedge Ayz) \rightarrow Axz$ *(indirect anteriority: recursive step)*

Any two thick objects x and y can be temporally compared in the sense that either x is an indirect temporal antecessor of y, or y is an indirect temporal antecessor of x, or x and y are simultaneous:

TA 13. $(\mathcal{O}^*x \wedge \mathcal{O}^*y) \rightarrow (Axy \vee Ayx \vee SIxy)$ *(temporal comparability)*

Successive thick objects that are stages of the same thin object stand in a peculiar relation of loose identity: they are not identical, but everything that is true of them is also true, in a temporal sense, of the common thin object. In the following I develop the idea of stage-successions, which is related to Chisholm's (1976, pp. 97–104) account of change in terms of consecutive entities.

A thick object x is the *direct essential successor* of some thick object y *with respect to a thin object* z iff y is directly anterior to x, x and y are spatio-temporally connected, and z is a common essence of x and y.

TD 1. $DS_z xy \equiv_{df} DAyx \wedge Cxy \wedge ESzx \wedge ESzy$ *(direct essential succession)*

Direct essential succession is linear. In other words, distinct thick objects cannot be direct essential successors of the same thick object, nor may they share the same direct essential successor.

TA 14. $(DS_z yx \wedge DS_z wx) \rightarrow y = w$ *(unicity on the left)*

TA 15. $(DS_z xy \wedge DS_z xw) \rightarrow y = w$ *(unicity on the right)*

In order to exclude that thin objects have instantaneous lives, I postulate for each thin object x there are at least two thick objects that are in direct essential succession with respect to x.

TA 16. $\mathcal{O}x \rightarrow \exists yz\, DS_x yz$ *(non-instantaneity of thin objects)*

Finally, the relation of indirect essential succession with respect to a thin object can be characterised recursively in terms of direct essential succession:

TA 17. $DS_z xy \rightarrow SC_z xy$ *(indirect essential succession: 1)*

TA 18. $(DS_z xy \wedge SC_z yw) \rightarrow SC_z xw$ *(indirect essential succession: 2)*

Note that, by extensionality of parthood, there must be at least one atomic part that is not shared between distinct stages of a thin object. Hence there cannot be successive stages with exactly the same proper parts: things change constantly.

Endurants and Perdurants. In everyday discourse, we distinguish between objects and processes, or, as the philosophical jargon has it, between *endurants* and *perdurants*. Perdurants consist of different *phases*, or *temporal parts*, at different times. Endurants, on the contrary, have no temporal parts, but are present as a whole at each instant they are present at all. (Lewis 1986, p. 202).

It is crucial for a descriptively adequate ontology to acknowledge this distinction. However, this does not mean that both categories have to be considered as primitive. According to the informal definition of endurants, tropes, as well as thin and thick objects, turn out to be endurants. Thin objects are wholly present in each of the thick objects they are part of, and the same holds for tropes, i.e. for atoms. And since a thick object as well as its thick parts are only present in one instant, they are trivially endurants. Perdurants can be regarded as successions of thick objects, i.e. endurants.

The basic perdurants are events as changes or state-transitions: the change of a tomato's colour from green to red amounts to the succession of a red tomato-stage to a green tomato-stage. The change of a memory cell from 0 to 1 is the succession of a charged cell-stage to an uncharged one. Some x is an *event in* a thin object y iff x is the sum of two thick objects that are directly essentially succeeding with respect to y; we also say that y is the *substrate* of x.

TD 2. $EVxy \equiv_{df} \exists wz\,(\,SM(x,w,z) \wedge DS_y wz\,)$ *(event in)*

TD 3. $\mathcal{E}x \equiv_{df} \exists y\, EVxy$ *(event)*

The definition implies that there are no instantaneous events, which is consistent with the doctrine that perdurants have at least two distinct temporal parts. The instantaneous left and right boundaries of perdurants are endurants, namely thick objects. Hence the *events* that represent the beginning and the ending of a perdurant cannot be instantaneous and always have to involve at least two object-stages.

Perdurants are arbitrary mereological sums of events; they can be recursively characterised with single events as a base case.

TA 19. $\mathcal{E}x \rightarrow \mathcal{P}x$ *(perdurant: base case)*

TA 20. $(\,\mathcal{E}x \wedge \mathcal{P}y \wedge SM(z,x,y)\,) \rightarrow \mathcal{P}z$ *(perdurant: recursive step)*

In particular, the life of a thin object is the perdurant that is the sum of all events in this thin object:

TD 4. $Lxy \equiv_{df} SM(x, \lambda z\, EVzy\,)$ *(life)*

The relation between perdurants and the (thin) objects involved in them is called *participation*. OCHRE's particular account of perdurants in terms of endurants allows for participation to be defined as a special case of parthood. Indeed, a thin object x *participates in* a process y, iff x is the substrate of an event that is part of y.

TD 5. $PCxy \equiv_{df} \mathcal{O}x \wedge \mathcal{P}y \wedge \exists z\,(\,EVzx \wedge Pzy\,)$ *(participation)*

Thus OCHRE acknowledges the distinction between endurants and perdurants without assuming two separate domains of objects and processes organised by two different parthood and dependence relations.

8 Conclusions

Building a foundational ontology involves challenges that are unusual to common knowledge representation practice. On the one hand, the need for descriptive adequacy requires a considerable subtlety of conceptual analysis based on a solid philosophical background. On the other hand, the usability of foundational ontologies depends on the greatest possible formal simplicity and transparency.

This paper places a strong emphasis on a clear and elegant mereological framework that gives a straightforward account of parthood relations between individuals. I have tried to illustrate this point by sketching the formalisation of the ontology OCHRE and by elucidating its underlying ontological choices.

Part-whole reasoning in Atomistic General Extensional Mereology, the basis of OCHRE, is quite simple, since the parthood structure is considered to be a Boolean algebra (without a null element). The problem of the identity of objects through change motivates many ontologists to reject extensional mereology and to recur to an opaque temporalisation of properties and relations, amongst them parthood itself. Furthermore, the apparent coincidence of objects is often tackled by introducing a non-mereological relation of constitution between objects. All in all, these modeling choices involve many superfluous complications.

OCHRE maintains the descriptively correct distinctions of common-sense while avoiding formal intricacies. To account for change in objects, OCHRE emphasises the ambiguity of references to objects and distinguishes between thin objects and thick objects as their evanescent stages. Temporal statements about thin objects are translated into atemporal statements about their stages. Events are accounted for in terms of succeeding object-stages. And co-located distinct entities are reconstructed as qualitative aspects or guises of the same thick object. Classical extensional mereology can be preserved throughout, assuming attributes as atoms out of which thick and thin objects are ultimately composed, leaving no space for propertyless substrates.

This essay should be considered a case study which attempts to highlight the particularities of building a foundational ontology. Once these particularities are better understood, more theoretical investigations into measuring the quality of the design of top-level ontologies will be possible.

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