Parts Unknown: Mereologies for Solid Physical Objects

Yi RU and Michael GRUNINGER
Mechanical and Industrial Engineering, University of Toronto, Canada

Abstract. When describing a mereological relationship, the use of the word *"part" to whole* hides the intended semantics of the parthood relations. Existing studies in mereology usually present *part of* as a general top level mereology relation, and all other mereological relations are sub-relations under it. We present an alternative approach of mereological pluralism, in which each mereological relation corresponds to one characteristic of the solid physical object, and the characteristics are formalized in different modules within an upper ontology. A general suite of upper ontology modules is proposed in this paper to support the specification of the parthood relations for solid physical objects. We name the union of these modules Ontology of Solid Physical Objects (OPO).

Keywords. Upper Ontology, Parthood, Mereology, Solid Physical Objects

1. Introduction

The seminal work of Winston et al. [21] identified multiple relations that capture intuitions about parts and wholes, we follow this approach of mereological pluralism[1] to suggest a new relationship among the mereological relations. Our claim is that there is no super-relation of the mereological relations, but each mereological relation is comprehensive by its own. In addition, we propose that each parthood relation corresponds to a generic module of the Ontology of Solid Physical Objects (OPO). We adopt the sideways approach to upper ontologies [12], and focus on those modules that axiomatize intuitions about solid physical objects (although we will briefly discuss parthood relations for other upper ontology modules such as time and activity). In our ontology of the representation to the parthood of solid physical objects, our objective focuses on the correctness and completeness of the ontologies with respect to the semantic requirements.

The Social Needs Marketplace (SNM), as the motivation of this paper, is an online marketplace for the population who live under the poverty line to exchange, offer and receive used goods. The match between supply and demand of goods requires a detailed representation of physical objects. [8] Such a representation faces several daunting challenges. First, the terminology that people use for these descriptions is rife with ambiguity. Second, it is often unclear whether or not the terminology used is adequate to provide complete descriptions of a given range of goods. A third challenge is that many of the terms that people use to describe physical objects are ad hoc and arbitrary. It is thus essential to develop an ontology for the SNM.

[1] Mereological pluralism denotes that there are multiple distinct parthood relations.

In some scenarios of SNM, we need to describe partially damaged object (i.e. a bed with the headboard missing, a mug with the handle broken or a chipped dish), where the "partially" here might have different meanings: partially missing, partially broken, or material partially removed. To represent these different relationships of the part to the whole, the specification of damage condition requires a comprehensive description to parthood relationships beyond mereological monism. In this paper we will focus on the different notions of parthood of physical objects that have arisen within SNM, but which are really within the scope of an upper ontology. In particular, we propose Ontology of Solid Physical Objects (OPO), a general suite of upper ontology modules that support the specification of the parthood relations for solid physical objects and used goods within the scope of SNM.

Our approach can be seen as a development along the lines mentioned in Artale's work [3]: "The particular behaviour of the different part-whole relations may lie, among other things, in the ontological nature of both the whole and the part", namely, the ontological nature of the whole and part are captured by the generic modules of the upper ontology.

Definition 1.1. Let $\mathbf{R}$ be a binary relation, and let $\mathfrak{M}^{\mathbf{R}}$ be a class of structures with signature $\langle \mathbf{R} \rangle$.

The relation $\mathbf{R}$ is a parthood relation iff $Th(\mathfrak{M}^{\mathbf{R}})$ is synonymous with a theory in the $\mathbb{H}^{mereology}$ Hierarchy[2].

2. Previous Work

Existing studies in mereology usually either have a single *part-of* relation to summarize all parthood relations, or adopt a taxonomy of parthood relations that all other parthood relations are specializations or sub-relations of a general top level *part-of* relation.

2.1. Mereological Monism

Approaches based on classical mereology [20] tend to use a single parthood relation to specify parthood relationships, an approach known as mereological monism. This is not a viable approach if we are to support application domains such as SNM. The relationship between the detachable leg of a table and the table itself is fundamentally distinct from the relationship between the table and a portion of the table that has been chipped off.

One possible way of maintaining mereological monism while also allowing multiple parthood relations is to say that all other parthood relations are definable with respect to a single primitive parthood relation. For example, one can define the restriction of *part* to specific classes of elements within the domain. For example, in DOLCE [14] one can restrict the parthood relation P to the class of time intervals to define a notion of temporal parthood, as distinct from arbitrary elements.

McDaniel [15] used this approach to define causally integrated parthood, functional parthood and immediate parthood. Causally integrated parthood applies to cases in which each of the object's parts is robustly related to every other part of the object; functional parthood indicates the functional role of the part in the production of the whole, and im-

[2] `colore.oor.net/mereology`

mediate parthood defines the largest part of the whole. However, all of these approaches require the new parthood relations to be definable using the single *part-of* relation, and we will see that in the case of SNM, this is not possible, that is, the different parthood relations are not definable with respect to each other.

2.2. Taxonomy of Parthood Relations

Mereological pluralism [15] is based on the idea that there are indeed multiple distinct parthood relations. The earliest work in this area was by Winston [21], who presented a taxonomy of part-whole relations as specializations of a general *part-of* relation. Winston's approach was informal, and was based on a series of examples that motivated the types of parthood relationships: phonology-linguistics as *component-integral object*; tree-forest as *member-collection*; slice-pie as *portion-mass*; steel-bike as *stuff-object*; grasping-stacking as *feature-activity* and oasis-desert as *place-area*.

Later, Odell [18] proposed six kinds of aggregation relationships: component – integral object; material – object; portion – object; place – area; member – bunch; and member – partnership. They are determined by the combination of three basic properties: *configuration* (the parts bear a particular functional or structural relationship to one another or to the object they constitute), *homeomerous* (the parts are the same kinds of things as the whole), and *invariance* (the parts can be separated from the whole).

However, neither Winston nor Odell provided axiomatizations of their different parthood relations. For axioms, we need to look at actual parthood ontologies. The upper ontology SUMO [17] contains the relation *part* as a spatial relation and a set of other relations that specialize it. In more recent work, Keet [13] introduced a taxonomy as summarization of Odell's approach to types of part-whole relations [18], and also provided OWL axiomatizations of the taxonomy.

One of our primary claims is that the notion of a taxonomy of parthood relations is not correct[3]. We will see that each distinct parthood relation has its own axiomatization, and hence is synonymous with a different mereology ontology within the set of possible mereologies. The taxonomy approach cannot adequately capture the relationships between the different axiomatizations.

3. Ontology of Solid Physical Objects (OPO)

The design of the Ontology of Solid Physical Objects (OPO)[4] follows the principle that each module of OPO axiomatizes necessary conditions for solid physical objects. We define a solid physical object as *an object that is self-connected*[5]*, has some shape, is made of some material, and occupies some space*. OPO is built to expand the definition with four modules: structure module, shape module, constitution module and spatial module. Each module features a characteristic ontology in the upper ontology, and gives rise to a corresponding parthood relation: *componentOf*, *pieceOf*, *portionOf*, and *containedIn*, re-

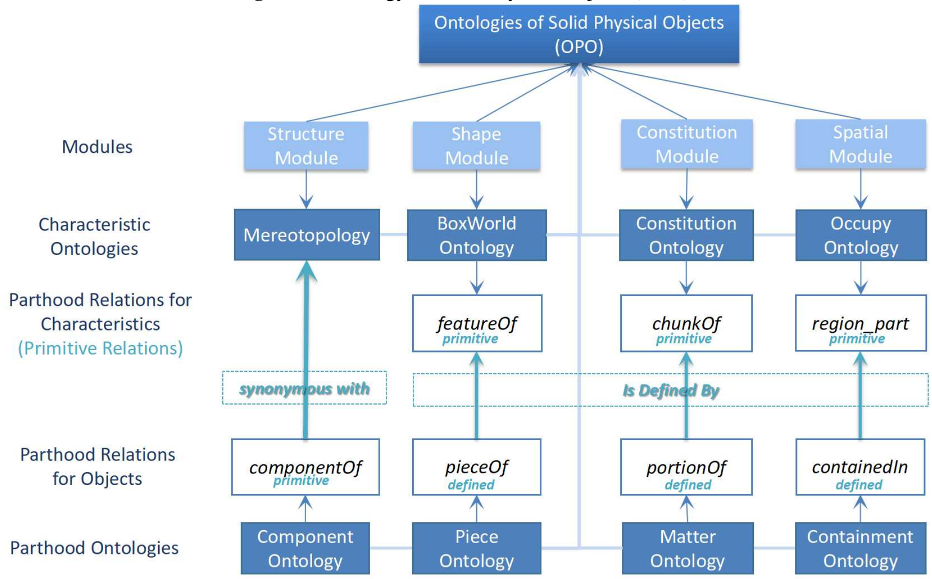
[3]Of course, one can always define a trivial taxonomy by the disjunction of other relations, but the question is about the relationships between the various parthood relations themselves.

[4]`colore.oor.net/opo/opo.clif`

[5]Self-connected is axiomatized in mereology as $(\forall x) SC(x) \equiv (\forall y,z)((\forall w) \supset (overlaps(w,x) \equiv (overlaps(w,y) \vee overlaps(w,z))) \supset C(y,z))$

spectively. The current design of the Ontology of Solid Physical Objects is shown below in Figure 1.

Figure 1. Ontology of Solid Physical Objects (OPO)



With respect to the modules of OPO, the *componentOf* relation is axiomatized as a primitive relation within a theory that is synonymous with *MT* in mereotopology. On the other hand, *pieceOf*, *portionOf* and *containedIn* relations are given conservative definitions in their respective generic ontology modules, and hence are treated as defined relations. Examples of each parthood relation are shown in Figure 2.

Figure 2. Physical Examples of Parthood Relations of Objects

i. componentOf *ii. pieceOf* *iii. portionOf* *iv. containedIn*

3.1. Structure Module

The Structure Module identifies the external connections of an integrated physical object and the criteria for the atomicity of a solid physical object. The basic intuition here is that a physical object is self-connected, the external connection axioms and corresponding parthood ontology are axiomatized by an ontology that is synonymous with the mereotopology MT[6] [7]. Future extensions on the Structure Module will incorporate process ontology PSL [9] to represent the assembly and disassembly activities for furnitures and other integrated objects.

3.1.1. componentOf

If the physical object whole is an integrated object, and can be broken down into smaller disconnected integrated or atomic self-connected solid physical objects by only breaking the external connections from the whole, we use *atomic component* to describe the components that cannot be further broken down by only breaking the external connections. The primitive *componentOf* relation is synonymous with MT in mereotopology as:

$$(\forall x,y) componentOf(x,y) \supset (\forall z)(EC(x,z) \supset EC(z,y))$$

where *EC* is the external-connected relation defined with the primitive *C* (connected) in mereotopology. A typical example that will use *componentOf* to describe its parthood relationships is a furniture with all components assembled together (i.e. wooden children bed in Figure 2).

3.2. Shape Module

The Shape Module needs an extension to the BoxWorld[7] ([10], [11]), which is an ontology for shapes composed of surfaces and edges. As such, it can represent aspects of an object that have different dimensionality, for example the 2D surfaces of a 3D object and one-dimensional features (i.e. edges and ridges). We extend it with a *featureOf* parthood relation to represent the parthood relationship between a shape feature and the whole. A shape feature is defined as an individual or sum of adjacent ridges in the whole shape. Ultimately, we want to categorize sufficient types of shape to identify common atomic shapes (i.e. cylinder, box, curved cylinder, ball) and differentiate the pieces of one object and some pieces as atomic shapes.

3.2.1. pieceOf

The *pieceOf* relation describes the shape-related parthood relationship and is a defined relation:

$$(\forall x,y) pieceOf(x,y) \equiv (\exists f_1,f_2) boundedBy(x,f_1) \wedge boundedBy(y,f_2) \wedge featureOf(f_1,f_2)$$

where *boundedBy* means that the object is partially or fully bounded by the shape feature, and *featureOf* is a reflexive parthood relation in the extended BoxWorld Ontology. The corresponding example in Figure 2 shows the handle of a coffee mug can be identified as a piece by its distinct shape from the mug cylinder body, as there are two ridges of the piece. Of course, the *pieceOf* relation is able to describe the shape identified parthood beyond atomic but also integrated self-connected objects, for instance, the back piece of the chair could include the upper piece of the frame and the whole back cushion (the cushion is a component to the whole chair) with multiple specific ridges.

[6] colore.oor.net/combined_mereotopology/mt.clif
[7] colore.oor.net/boxworld/boxworld.clif

3.3. *Constitution Module*

The Constitution Ontology[8] defines the constitution between matter and material objects, independent of types of materials. And the Matter Ontology[9] contains the corresponding parthood ontology for the Constitution Module.

3.3.1. *portionOf*

Portions of a solid physical object and the whole are all material objects, the boundary between them is arbitrary. The whole here can be an atomic self-connected object, a component, or an integrated object. An example is a portion of a broken dish as shown in Figure 2, or more deliciously, a slice of a pizza. One can divide a pizza in arbitrary ways; there is no physical boundary or visible standard on how the pizza can be divided. The *portionOf* relation is the parthood relation in the Matter Module of the ontology, and it is defined with the *constitutes* relation in Constitution Ontology:

$$
\begin{aligned}
&(\forall x, y) \\
&\qquad portionOf(x, y) \\
&\qquad \equiv (\exists m_1, m_2) constitutes(m_1, x) \wedge constitutes(m_2, y) \wedge chunkOf(m_1, m_2)
\end{aligned}
$$

where *chunkOf* here is the parthood relation in Constitution Ontology. Borgo [6] distinguished physical boundary for matter discontinuity, and imaginary boundary for adjacent parts of a body. Following the approach, we indicate that physical boundary lies for components to the whole and imaginary boundary lies for piece or portion to the whole; while the boundaries for pieces are explicit and identifiable in shape, boundaries for portions have some arbitrariness.

3.4. *Spatial Module*

The Spatial Module represents the location of physical objects within abstract space together with the spatial relationship between the regions occupied by objects. Incorporating with the representation of enclosure in the Occupy Ontology[10] [2], the Containment Ontology defines the containment parthood relation.

3.4.1. *containedIn*

The *containedIn* relation is defined as the containment relation between the occupied regions of two self-connected physical objects: the space occupied by one solid physical object is enclosed by the space occupied by another solid physical object. It is given by the following conservative definition:

$$(\forall x, y)\, containedIn(x, y) \equiv (\exists r_1, r_2)\, occupies(x, r_1) \wedge occupies(y, r_2) \wedge region\_part(r_1, r_2)$$

where *region_part* is the parthood relation over regions of abstract space within the location ontology T_{occupy}. As the example in Figure 2, the space an individual egg occupied

[8] colore.oor.net/constitution/constitution.clif
[9] colore.oor.net/matter/matter.clif
[10] colore.oor.net/occupy/occupy_root.clif

is a region of the enclosed space occupied by the outer container, therefore we can say the *containedIn* relationship holds between an egg and the container.

4. Relationship between Previous Work and Our Work

Looking at each of the parthood relations, the *component-integral object* and *portion-object* parthood relations in Odell [18] are similar with our proposals of *componentOf* and *portionOf* as relationships for integration and mass. The *portion-mass* in Winston et al. [21] also shares the definition with our *portionOf* relation. Despite the lack of axiomatization, the three basic properties that these relations were built upon (as discussed in Section 1) are not specific to physical objects and not suitable for our practice for SNM.

In Borgo's approach, the concrete existence of physical object is determined by the material object that is a piece of matter and occupies a region of space. [6] He defined a notion of *contingent part* for physical objects with location, he also restricted a binary predicate P to hold between the substrate matter and another P to hold between the other substrate region. One could say that OPO is following the definition of *stratified ontology*[11] Borgo adopted, where the classes of parthood relations correspond to different identity criteria of characteristics of solid physical objects, such classes of parthood relations are disjoint and the ontological dependencies among the criteria of characteristics are explicit. However, resulting from the difference in scope, SNM requires further mereological pluralism beyond matter and location.

Bittner and Donnelly [5] have also presented an axiomatization that follows mereological pluralism, and which does not strictly adhere to a taxonomy of parthood relations. In particular, their axiomatization of *CmpOf* (component of), and *CntIn* (contained in) are similar to what we presented in Section 3. Nevertheless, they still use a general *PP* relation which does not itself correspond to any generic ontology for objects, and the other two parthood relations are not grounded in a generic ontology.

Our approach falls into what is often called the family of 3D representation of physical objects, in which all of an object's parts exist at any point in time. This approach can also be seen in the BFO [4] and DOLCE [14] upper ontologies, although these upper ontologies are based on a time-indexed version of mereological monism.

5. Beyond Physical Objects

Recall that the original paper of Winston et al. [21] identified parthood relations that did not apply to physical objects, such as the relationship between feature and activity. Within the PSL Ontology [9], there are three relations of interest – the $subactivity$ relation over arbitrary activities, the $atomic\_subactivity$ relation over concurrent activities, and the $subactivity\_occurrence$ relation over occurrences of activities. Each of these relations corresponds to a different module of the PSL Ontology – $T_{subactivity}$, T_{atomic}, and T_{actocc}, respectively. Furthermore, the axiomatization of each of these relations is synonymous with a different ontology in the $\mathbb{H}^{mereology}$ Hierarchy, and hence is a parthood relation.

[11] Stratified Ontology is denoted as "an ontology where classes corresponding to different identity criteria are kept carefully disjoint and represent the roots of separate hierarchies called strata, and where the ontological dependencies among strata are made explicit." [6]

Another distinct parthood relation corresponds to generic time ontologies that include time intervals within the domain. As shown in [16], the $temporalPart$ relation of SUMO can be axiomatized as a definitional extension of the time module within SUMO, and since this extension faithfully interprets the ontology T_{cem_G} within the $\mathbb{H}^{mereology}$ Hierarchy, the $temporalPart$ relation is also a parthood relation.

6. Conclusion and Future Research

We have proposed a novel approach to the identification and axiomatization of parthood relations for physical objects as they arise from the generic ontologies required to formalize the intuitive definition of a physical object – an object that is self-connected, has some shape, is made of some material, and occupies some space. We use structure, shape, constitution, and spatial modules to capture four characteristics of physical objects to support the definition of proposed parthood relations. The four parthood relations we identified are *componentOf*, *pieceOf*, *portionOf* and *containedIn*. Each parthood relation corresponds to one characteristic module in the Ontology of Solid Physical Objects (OPO). In this sense, the characteristic ontologies in OPO are modules of an upper ontology that is strong enough to represent any solid physical object.

Given the axiomatizations of these parthood relations shown in Section 3, it is clear that they are all distinct relations and that there is no priori subproperty taxonomy among these relations. Furthermore, given the correspondence between these relations and the generic ontology modules of an upper ontology, we anticipate that new parthood relations will be recognized as additional modules of upper ontologies are considered. We have covered structure, geometric and material characteristic in this version of OPO.[12] The current framework is able to represent different conditions of partially damaged objects, especially the examples from SNM shown in Figure 2: children's bed with missing component indicates an incomplete structure, mug with fractured handle piece indicates broken shape, and the dish fragmented into portions indicates some matter is divided. Future work on OPO will include a surface module ontology to capture color and surface damage such as stains and scratches, as well as a function ontology to represent functional characteristic of physical object.

A generic ontology of state and change is also needed to be incorporated into parthood relations. As it stands, the upper ontologies BFO and DOLCE axiomatize the notion of temporary parthood, in which a physical object (perdurant in BFO and physical endurant in DOLCE) can have different parts at different times. Using the methodology from Aameri [1], we can specify particular ontology as the domain state ontology for corresponding module in OPO. Thus, an ontology for assembly and disassembly specifies how the components of an object change, an ontology of production/consumption specifies how portions of the matter that constitutes an object can change, and an ontology for kinematics would specify how the location of parts within an object can change.

Given the motivation comes from the Social Needs Marketplace (SNM) project, the OPO supports the description of any solid physical objects and will be used to represent damages and to automatically categorize household goods such as furniture and home

[12] As Sanfilippo stated in [19], features of physical objects can be categorized into functional, geometric, material, structure and other types.

appliances. This domain will also serve as a testbed for identifying new concepts in upper ontologies required for the representation of everyday objects.

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