What's the Damage? Abnormality in Solid Physical Objects

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Abstract. The representation of damage to solid physical objects is complex in nature. Beginning with real world usecases of partially damaged used goods, we derive the description of damage through the approach of representing partial abnormality. We propose four predicates for partial abnormality corresponding to the fundamental characteristics and parthood relationships within solid physical objects: $ab\_portion, ab\_piece, ab\_component$, and $ab\_containment$. Such parthood relations and mereological pluralism concepts are drawn from the Ontology of Solid Physical Objects (SoPhOs), a general suite of upper ontology modules we proposed and axiomatized in First Order Logic. This paper reviews the SoPhOs ontologies that axiomatize parthood, spatial parthood and parthood connection theories and the foundational matter and shape characteristic ontologies that support them. We map the foundational solid physical object ontology to solving the problem of representing damaged goods in various domains including manufacture and e-commerce.

Keywords. Damage, Solid Physical Objects, Parthood, Mereology Pluralism, Ontology, Domain Application, Used Good

1. Introduction

An interesting challenge in conceptual modelling is the representation of some notion of ideal objects and their relationship to actual objects whose properties diverge from the specification of the ideal. Such a distinction plays a role in a wide range of applications, from manufacturing quality to commonsense reasoning with everyday objects. As such, the distinction between ideal and actual objects can refer to an object that is simply created in a way that violates the specification of the ideal, or it may refer to objects that have been changed in damaged through use. The notion of damage we present in this paper concretely arises from the representation of used goods in The Social Needs Marketplace (SNM)[9], which is an online marketplace exchange to offer and receive used goods for people who live under the poverty line. The match between supply and demand of used goods requires a detailed representation for damage of solid physical objects. However, the terminology people use for these descriptions is rife with ambiguity and always ad hoc and arbitrary. It is essential to derive an applicable approach for representing damaged goods for SNM.

From the motivating scenarios listed in the second section, we narrow our scope to the description of partially damaged goods. The specification of damage condition requires a comprehensive description to parthood relationships beyond mereological monism[1]. 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. In this paper we will focus on the representation of damage from the approach of pluralism to abnormality of solid physical objects, based on the multiple parthood relations raised from Ontology of Solid Physical Objects (SoPhOs). SoPhOs is 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 falls into what is often called the family of three-dimensional 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 [16] upper ontologies, although these upper ontologies are based on a time-indexed version of mereological monism.

2. Motivating Scenarios

Below are some scenarios that happened in SNM, and served as the motivation for the approach taken in this paper.

- Expectant parents are looking for children's furniture for their soon to arrive baby. They log into the SNM portal and search for a children's bed with complete safety measures. The supply of children's beds on the portal is limited returning only two partial matches to this family's needs. A family whose children are now of school age is offering a single child's bed with headboard missing, while another family is offering a bunk style bed for twins but it is convertible into a single bed.
- A furniture wholesale store is looking to relocate its warehouse due to the increasing rent, the store owner decides to mark down the selling prices heavily on most items stored in the warehouse to reduce the moving cost. However, some items are damaged because of improper storage or transportation, some tables have the corners cut out, some chairs have dents on the legs, and a sofa is also broken with filling coming out. For these items with minor damage, the store owner requests the warehouse manager to list them up on the SNM for donation.
- A retired couple is looking to clean up their garage and donate some of their old time favorite tablewares. Among them are a ceramic coffee mug with a handle broken but that has interesting pattern on it, a crystal wine decanter with the detachable stand missing, an emptied cookie can that could be used as a daily container, and a dish with a chipped corner. They log in the portal and listed these items with detailed description.

3. Ontological Commitments

The ontological commitments are semantic requirements we recognized from the motivating scenarios.

1. Damage to solid physical objects is determined comparing to the design.

[1] Mereological monism denotes that there is a single parthood relation. Approaches based on classical mereology [24] tend to use a single parthood relation to specify parthood relationships.

2. A partially damaged object can be presented in precise ways in terms of characteristics of solid physical objects.
3. There are multiple parthood relations of solid physical objects, and they are all distinct relations, each of which is synonymous with a mereology theory. Furthermore, there is no taxonomy of parthood relations.
4. There is different mereology for each part, and each mereology has different spatial ontology (radical pluralism).
5. In the scope of solid physical objects, each parthood relation is independently axiomatized with different characteristic module ontologies.
6. Each abnormality parthood relation is associated with a distinct parthood relation of solid physical object.

4. Ontology of Solid Physical Objects (SoPhOs)

The seminal work of Winston et al. [25] identified multiple relations that capture intuitions about parts and wholes, we follow this approach of mereological pluralism and propose each parthood relation corresponds to a generic module of upper ontologies. We adopt the sideways approach to upper ontologies [12], and focus on those modules that axiomatize intuitions about solid physical objects, which is organized into the Ontology of Solid Physical Objects (SoPhOs).

The design of the Ontology of Solid Physical Objects (SoPhOs) follows the principle that each module of SoPhOs axiomatizes necessary conditions for solid physical objects. We define a solid physical object as *an object that is made of some material, has some shape, and occupies some space*. SoPhOs is built to expand the definition with two modules: matter module and shape module. Each module features a characteristic ontology in the upper ontology and gives rise to corresponding parthood relations: [*portionOf*, *pieceOf*, *componentOf*] for parthood on solid physical objects, and [*confinedIn*, *containedIn*] for spatial parthood, respectively. The current design of the Ontology of Solid Physical Objects is shown below in Figure 1 and Figure 2. SoPhOs is fully axiomatized in First Order Logic[2].

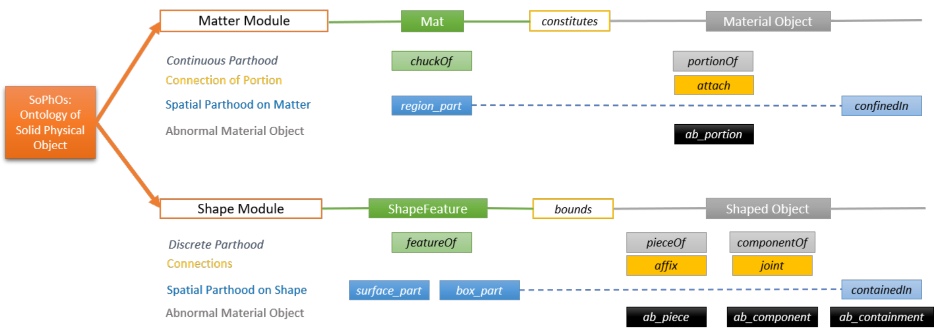

Figure 1. Structure of Relations within Ontology of Solid Physical Objects (SoPhOs)

[2] `colore.oor.net/sophos/sophos.clif`

	Characteristic	Parthood on Characteristic	Parthood on Characteristic with Spatial Relationship	Characteristic vs. Object	Defined Parthood on Characteristic Object	Parthood on Characteristic Object with Location	Connection on Characteristic	Damage Related
Ontologies	**Matter Module**	$T_{\text{Material Object}}$	T_{occupy} (adjusted)	$T_{\text{Material Object}}$	T_{Portion}	$T_{\text{confinement}}$	T_{Attach}	Removal of material
Relations	*Mat* (continuous)	*chunkOf*	*region_part*	*constitutes*	*portionOf* Damage: *ab_portion*	*confinedIn* Damage: *ab_confinement*	*attach*	
Ontologies	**Shape Module**	T_{Feature} (extended T_{BoxWorld})	$T_{\text{MT Multidimensional Object Mereotopology}}$	T_{Bounds}	T_{Piece}	$T_{\text{Containment}}$	T_{Affix}	Handle of mug; Dent in chair leg; Egg in box;
Relations	*ShapeFeature* (discrete, no metric)	*featureOf*	*surface_part* *box_part*	*bounds*	*pieceOf* Damage: *ab_piece* $T_{\text{component}}$ *componentOf* Damage: *ab_component*	*containedIn* (convex hull) Damage: *ab_containment*	*affix* $T_{\text{Mereotopology}}$ *joint*	

Figure 2. Module Ontologies in Ontology of Solid Physical Objects (SoPhOs)

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 4.1. 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[3].

All of the parthood relations are given conservative definitions in their respective generic ontology modules, and hence are treated as defined relations. Real world physical examples of some parthood relation are shown below in Figure 3.

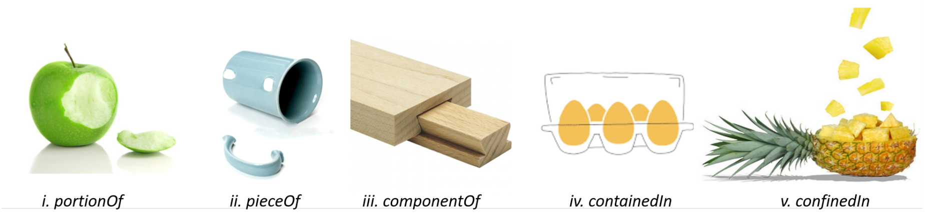

Figure 3. Physical Examples of Parthood Relations of Objects

4.1. Matter Module

A solid physical object is a material object. Matter constitutes solid physical objects and is one of the prime characteristics we determine for solid physical objects. Under the matter module we have The Material Object Ontology, which axiomatizes the constitution relation *constitutes* between *Mat* (matter) and *MaterialObject*, and defines *chunkOf* as the parthood relation within matter. The Portion Ontology contains the corresponding continuous parthood relation *portionOf* for the material objects. An example of *portionOf* a material object is a one person portion of pizza in a whole pizza, or a bite of

[3] colore.oor.net/mereology

an apple is a portion of the apple. The Attach Ontology features the connection relation *attach* between material objects. Incorporating the spatial parthood relation *region_part* from Occupy Ontology[2], the Confinement Ontology defines *confinedIn* to denote the parthood relationship between two material objects that the space occupied by one material object is in the region of the space occupied by the other material object (e.g. a chunk of pineapple is confined in the whole pineapple).

4.2. Shape Module

The shape module of SoPhOs starts from the Feature Ontology which is an extension to the BoxWorld[10] with *ShapeFeature* and *featureOf*. *ShapeFeature* is a primitive class, it can be individual non-enclosed basic shape in BoxWorld (point/edge/surface) or the union of any adjacent non-enclosed shape or the box. Adjacent non-enclosed shapes are defined to be connected by at least one lower dimensional shape, as from examples in Figure 4, (i.e. two edges that meets at a point/vertex in i, two surfaces that meet at one edge and two points in ii, one edge and one surface that meet at one point in iv). *featureOf* is primitive parthood relation for *ShapeFeature*, it is a predicate between one *ShapeFeature* and another *ShapeFeature* at a higher dimension or the same dimension. Every *ShapeFeature* is a *featureOf* itself (including points).

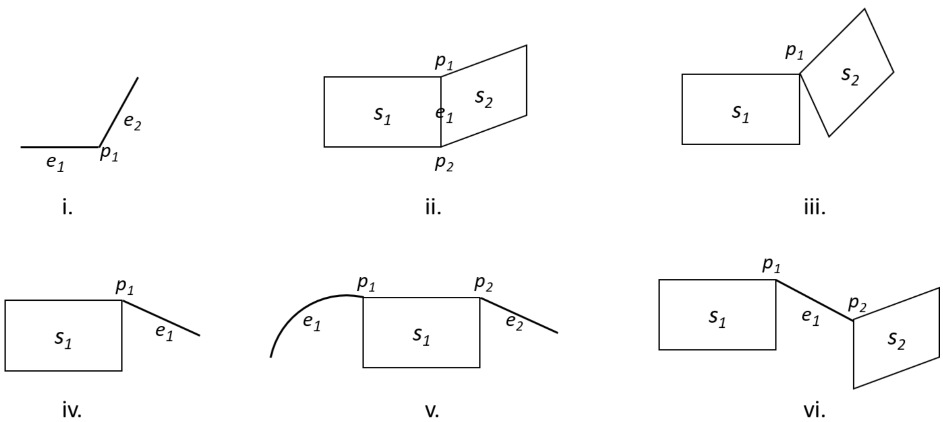

Figure 4. Examples of *ShapeFeature*

The Bounds Ontology describes the relationship between the shaped object and the shape feature that bounds it. For the multidimensional parthood of solid physical objects regarding shape, we have Piece Ontology and Component Ontology based on dimensionality. We use *pieceOf* for shaped objects in different dimensions below or at three-dimension, and *componentOf* between three-dimensional shaped objects and a set of three-dimensional shaped objects. For instance the mug example in Figure 5, if we say the shape feature that bounds a non-detachable handle of a mug is the two dimensional cylinder surface s_1 and the whole mug is bounded by a three dimensional box b_1, then the handle of the mug is a piece of the mug in terms of shape. However, if we are talking about the three dimensional box b_2 bounded cap and the whole mug with cap which is bounded by a poly[4] p_1, we use *componentOf* to define the parthood between the cap and the whole mug with cap. The cube in Figure 5 shows three instances of *featureOf*: $featureOf(f_1,b_1) \wedge featureOf(f_2,b_1) \wedge featureOf(f_3,b_1)$.

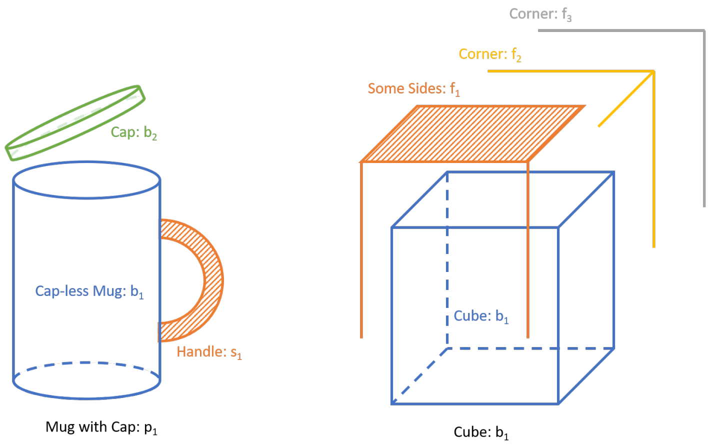

Figure 5. Distinguishing *featureOf* and *componentOf*

We use *affix* to denote the connection between pieces, and components are *joint* together, where *joint* is synonymous with *ec* (external connection) from classic mereotopology. Last but not least, we also have *containedIn* to describe the spatial parthood when the space occupied by the shape of one solid physical object is fully enclosed in the convex space occupied by the shape of another solid physical object (e.g. an egg is contained in the lunch box).

5. Abnormality of Solid Physical Objects

We find it is ambiguous to take ”ideal object” as the standard for determining abnormality. In real world, a chair can be designed in multiple different styles, it can have four legs, three legs, no legs like sofa, or one leg with four to six wheeled arms like an office chair; it is difficult and inaccurate to determine one specific design as a general ”ideal chair”. In contrast, we define the abnormality in terms of the intended properties instead of type or class, and differentiate abnormality with characteristics of the object.

Reiter [22] used *AB* to distinguish normal and abnormal conditions in diagnosis reasoning systems with examples of faulty circuits. We follow this approach and extend its use to abnormal conditions on solid physical objects. We propose four predicates in correspondence with four of our parthood relations for solid physical objects, *ab_portion*, *ab_piece*, *ab_component* and *ab_containment*, to denote an abnormal portion/piece/component/containment of the whole in terms of standard design. We don't represent an abnormal confinement since the definitive nature that confinement describes the relationship that some matter M_1 located inside the space occupied by another matter

[4]Poly is defined as the shape of a set of three dimensional physical objects, and is considered as one dimension higher than a three dimensional box.

M_2, but in terms of solid physical objects, the spatial relationship between M_1 and M_2 cannot be changed unless the shape of M_2 is altered. We use the notion $\neg Ab$ to describe the condition when an object coincides with its design, that is, it is not abnormal, or "ideal".

Of course, some change/abnormality of characteristics will lead to inevitable change of other characteristics. The correlation between different characteristics are shown in Table 1. From the table we can conclude that the occurrence of *ab_portion*, *ab_component* or *ab_containment* would all result in one or more *ab_piece*, but an occurrence of *ab_piece* might not cause any other partial abnormalities. The occurrence of either *ab_component* or *ab_containment* would result in both some *ab_portion* and *ab_piece*, but the former two are isolated from any subsequent occurrences.

Table 1. Relativeness Chart of Change for Solid Physical Objects

Resulting Abnormality	new *ab_portion*	new *ab_piece*	new *ab_component*	new *ab_containment*	Examples
ab_portion	-	Y	N	N	Add/Remove Material
ab_piece	N	-	N	N	Bent, Dent
ab_component	Y	Y	-	N	Replaced Component
	Y	Y	-	N	Add/Remove Component
ab_containment	Y	Y	N	-	Add/Remove Containment

It is important to distinguish our use of abnormality predicates from their earlier use in nonmonotonic reasoning. We are *not* using abnormality to represent typicality (e.g. a typical chair has four legs, a typical dining room table is made of wood, a typical bookshelf does not have wheels). Instead, we are using abnormality predicates to specify the intended properties of an (ideal) object, so that any divergence from the specification of these properties (e.g. missing or spurious parts) are indications of damage. If a particular class of chairs is designed to have three legs, then it is not considered to be damaged when an instance of this class has three legs, even if a typical chair has four legs. On the other hand, if a class of chairs is designed to have four legs, then an instance of this class is indeed damaged if it is missing a leg.

6. Damage of Solid Physical Objects

In the motivating scenarios from SNM specified in Section 2, 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 damaged" here might have different meanings: partially missing, partially broken, or material partially removed. We apply abnormality to scenarios of damages. A standard design of My Chair with three legs is represented in Axiom (1)-(3) as in Figure 6 below, showing the intended properties of components, pieces and portions respectively.

Axiom (4)-(8) in Figure 7 below showed example representations of damaged chairs. C_1 denotes an replaced leg resulting an abnormal component; C_2 denotes a dent in one leg of a three-leg chair resulting an abnormal piece; C_3 denotes one leg missing; C_4 denotes when there is an extra leg; last but not least, C_5 denotes some additional matter is added to the chair.

Each class of solid physical objects is axiomatized by sentences of the form seen in Figure 6. By using the abnormality predicate Ab, we allow the existence of objects

$$MyChair(x) \supset (\neg Ab(x)$$
$$\equiv (\exists y_1, y_2, y_3) Leg(y_1) \wedge Leg(y_2) \wedge Leg(y_3) \wedge (y_1 \neq y_2) \wedge (y_1 \neq y_3) \wedge (y_2 \neq y_3)$$
$$\wedge componentOf(y_1, x) \wedge componentOf(y_2, x) \wedge componentOf(y_3, x)$$
$$\wedge ((\forall z) componentOf(z, x) \supset z = y_1 \vee z = y_2 \vee z = y_3)) \quad (1)$$
$$Leg(x) \supset (\neg Ab(x)$$
$$\equiv (\exists y_1, y_2, y_3) bottom(y_1) \wedge side(y_2) \wedge top(y_3) \wedge (y_1 \neq y_2) \wedge (y_1 \neq y_3) \wedge (y_2 \neq y_3)$$
$$\wedge pieceOf(y_1, x) \wedge pieceOf(y_2, x) \wedge pieceOf(y_3, x)$$
$$\wedge ((\forall z) pieceOf(z, x) \supset z = y_1 \vee z = y_2 \vee z = y_3)) \quad (2)$$
$$MyChair(x) \supset (\neg Ab(x)$$
$$\equiv (\exists y) Mat(y) \wedge constitutes(y, x) \wedge ((\forall z) portionOf(z, x) \equiv chunkOf(z, y))) \quad (3)$$

Figure 6. $T_{mychair}$: Representation of Standard MyChair Design

$$MyChair(C_1) \wedge Leg(L_1) \wedge Leg(L_2) \wedge Leg(L_3)$$
$$\wedge ab\_component(L_1, C_1) \wedge componentOf(L_2, C_1) \wedge componentOf(L_3, C_1) \supset Ab(C_1) \quad (4)$$
$$MyChair(C_2) \wedge Leg(L_4) \wedge Leg(L_5) \wedge Leg(L_6)$$
$$\wedge component(L_4, C_2) \wedge componentOf(L_5, C_2) \wedge componentOf(L_6, C_2)$$
$$\wedge Dent(P_1) \wedge Bottom(P_2) \wedge Side(P_3) \wedge Top(P_4)$$
$$\wedge ab\_piece(P_1, L_4) \wedge pieceOf(P_2, L_4) \wedge pieceOf(P_3, L_4) \wedge pieceOf(P_4, L_4) \supset Ab(C_2) \quad (5)$$
$$MyChair(C_3) \wedge Leg(L_7) \wedge Leg(L_8) \wedge componentOf(L_7, C_3) \wedge componentOf(L_8, C_3)$$
$$\supset Ab(C_3) \quad (6)$$
$$MyChair(C_4) \wedge Leg(L_9) \wedge Leg(L_{10}) \wedge Leg(L_{11}) \wedge Leg(L_{12})$$
$$\wedge ab\_component(L_9, C_4) \wedge componentOf(L_{10}, C_4) \wedge componentOf(L_{11}, C_4) \wedge componentOf(L_{12}, C_4)$$
$$\supset Ab(C_4) \quad (7)$$
$$MyChair(C_5) \wedge constitutes(M_1, C_5) \wedge chunkOf(M_2, M_1) \wedge ab\_portion(M_2, C_5) \supset Ab(C_5) \quad (8)$$

Figure 7. $T_{chairexample}$: Representation of Damaged MyChair Examples

in a class even if they do not satisfy the conditions for the ideal object in that class; inconsistency is avoided since such an object is simply an abnormal instance of the class. Furthermore, we can use the parthood relations in SoPhOs to identify the nature of the abnormality – missing matter vs. spurious matter, missing shape feature vs. unintended shape features, missing components vs. extra components.

Recall the motivating scenarios mentioned in Section 2, we can now help the SNM users to describe the damages in used goods (the actual terminology can be more userfriendly and easier to interpret by daily users, depends on the wording selection of the application designer):

- The expectant parents can eliminate the single children's bed with missing headboard by adding a filter to their request that map into the category with $\neg ab\_components$.
- The warehouse manager can list the tables with corners cut out and the chairs with dents on the legs in the category of *ab_piece*, and the sofa is broken with some *ab_portion* forms came out.
- The kind retired couple can donate the ceramic coffee mug with a handle broken as an entry with *ab_piece*, the crystal wine decanter with the detachable stand missing as with *ab_component*, the emptied cookie can as having *ab_containment*, and the dish with a chipped corner as havng either *ab_portion* or *ab_piece*.

7. Relationship between Previous Work and Our Work

Our representation of damage follows Reiter's[22] approach of abnormality and applies it to solid physical objects. There are limited previous studies that proposed a complete representation of damage for solid physical objects, but there are a few approaches for constructing an ontology of physical objects.

Many representations of solid physical objects involve time as a fourth dimension. Bennett[5] founds the representation to physical objects on a theory of the spatio-temporal distribution of matter types and proposes a characterization of various degrees of physical damage based on this theory. In the book that proposed his Four-dimensional Ontology of Physical Objects[14], Heller argues that physical objects are four-dimensional hunks of matter and that objects like chairs do not exist. To realize the application in SNM however, we need the existence of such physical entities of tables and chairs to describe the motivation scenarios. We do not consider time as a characteristic or dimension in SoPhOs at this stage, and consider all of an object's parts exist at any point in time. Other upper ontologies BFO [4] and DOLCE [16] also follow this approach but they are based on a time-indexed version of mereological monism.

Some three-dimensional representations to physical objects define by matter and space. 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. [7] One could say that SoPhOs is following the definition of *stratified ontology*[5] Borgo adopted, where the distinct classes of parthood relations correspond to different identity criteria of characteristics of solid physical objects, 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.

Existing studies in mereology usually either have a single *part-of* relation to summarize all parthood relations as mereological monism following the classical mereology[24], 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. This is

[5] 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." [7]

not a viable approach if we are to support application domains such as damage representation in SNM. The earliest work in this area was by Winston [25], 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. Later, Odell[20] also proposes six parthood relationships. Despite the lack of axiomatization, these taxonomies are not specific to physical objects and not suitable for our practice for SNM. Upper ontology SUMO [19] contains the relation *part* as a spatial relation and a set of other relations that specialize it. In more recent work, Keet [15] introduced a taxonomy as summarization of Odell's approach to types of part-whole relations, and also provided OWL axiomatizations of the taxonomy. However, to solve our problem in SNM, the taxonomy approach cannot adequately capture the relationships between the different axiomatizations. Bittner and Donnelly [6] have also presented an axiomatization that follows mereological pluralism, and which does not strictly adhere to a taxonomy of parthood relations. 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.

This paper continues the approach of characteristic upper ontologies modules supported multiple distinct parthood relations from Ru and Grüninger[23].

8. Future Research

Ideally, we want to incorporate the Process Specification Language[13] to describe the process from before to after of a damage, and map the occurrence of damage to the repairing process. Some further topics that would be interesting to look at is the determination of whether a damaged physical object is still functional at a certain degree, and if it regains its full functionality after repair. One potential solution to this problem is a scale of condition of damage in terms of functionality. Another direction of future research would be water damage. Different types of water damage can lead to varies results, just to name a few, matter can be changed due to chemical reaction, shape can be altered due to resolving and liquidizing, or neither matter or shape is changed but the water damage creates electronically malfunction from short circuit. Damages due to both environment and time are also on future research. Hardening and color changing of form are mostly due to wear out over time, rust on metallic items are also typically resulting from exposure of oxygen and moisturizing environment over time. Future work on SoPhOs will include a surface module ontology to capture color and surface damage such as stains and scratches.

9. Conclusion

What's the damage? We can now represent both the chair with a dent in one leg and the mug with a handle broken with having abnormal pieces comparing to their intended properties. Starting from the motivating scenarios of partially damaged furnitures from Social Needs Marketplace, we have proposed a representation of damage deriving from partial abnormality. We have described the abnormality of solid physical objects based on the Ontology of Solid Physical Objects (SoPhOs), a general suite of upper ontology modules we proposed and axiomatized in First Order Logic. SoPhOs is a complete system of ontologies featuring the characteristic parthood, spatial parthood, parthood connection theories, and the foundational matter and shape characteristic ontologies that support them. We employ the 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. Damage of used goods can be represented in terms of the partial abnormal characteristics. We have introduced four predicates for partial abnormality corresponding to the fundamental characteristics and parthood relationships within solid physical objects: $ab\_portion, ab\_piece, ab\_component$, and $ab\_containment$.

The current framework presented in this paper is able to represent different conditions of partially damaged objects and solve the scenarios raised in SNM. This domain will also serve as a testbed for identifying new concepts in upper ontologies required for the representation of damages in everyday objects.

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