Mereological Considerations for Improving Semantic Ontology

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***Abstract*—This paper presents our experience in applying mereology in strenghtening ontologies for natural language processing. We show that to accurately reflect the actual parthood relations between semantic categories, introducing relations grounded in mereologies creates the semantic distinctions necessary to reflect the complex parthood relations occuring in natural language. We show how the applications of mereology increases expressive power of an ontology, helps to create more flexible, precise, consistent, and less redundant meaning representations.**

***Index Terms*—ontology, mereology, semantics, relationships, parthood relations.**

Introduction

Ontologies used for natural language processing must use the 'part of' relation because natural languages do. In ordinary language, however, the word *'part'* in English, as well as its counterparts in other natural languages, has several different meanings, not all of which correspond to the same relation [1]: for instance, the leg is a part of an animal body not in same sense as free elections are part of a democratic process nor as friendship is a part of a healthy marriage. Not accounting for these differences causes ambiguity, imprecision, and a number of problems, such as lack of expressive power, violations of integrity and consistency of an ontology, which will result in inapplicable inferences and faulty reasoning.

Mereology, a branch of mathematics, could be thought of as an "axiomatic theory of parthood". It provides the formal treatment of parthood relations, and summarizes them in terms of combinations of axioms that a parthood relation satisfies: these combinations are called the "mereology theories" or simply "mereologies." Each mereology then defines a different sense for the phrase *'part of'* depending on the combination of axioms satisfied.

The idea of applying mereology to the construction of ontologies is not new. It has been proposed by researchers such as Gangemi et al. [2] and Masolo et al. [3], and found its way to engineering applications as well modeling, simulating and designing physical systems [4], and other endeavors, such as the construction of a variety of pharmaceutical ontologies, as we find in [5].

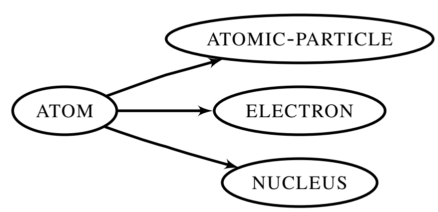
The closest we could find to applications of mereology in ontologies for natural language processing is an attempt to develop a semantic theory of plurals in natural language through mereological sums, hypothesizing that mereological sums are the semantic values of plurals) [6]. However, to the best of our knowledge, there have been no attempts to apply mereology to a full-fledged ontology for natural language processing.

This paper is organized as follows. We begin by introducing the problems that arise in the absence of formal treatment of parthood relations and give their examples in Section I (Problems). We then provide a short introduction to formal parthood definitions and the corollaries that follow in the Section II (Mereologies). We end with a Section III (Solutions) on how the application of mereology addresses the issues introduced in Section I.

I. Problems

A. Problem 1: Multitude of senses of 'part'

Ontologies used in natural language processing, especially if they are automatically generated, typically utilize a single parthood relation to denote a variety of essentially different parthood relations. Thus, in the Ontological Semantics ontology (OntoSem), acquired semi-automatically in [7], a single HAS-OBJECT-AS-PART relation is used to denote both the necessary[1] and the optional [2] parts of an object. For example:



Picture 1. Parts of ATOM in **OntoSem**.

However, it fails to represent the following possibilities: an ATOM in particle physics could still be an atom without a single ATOMIC-PARTICLE (e.g. without a NEUTRON) [3], or without a particular number of positive and negative particles, whereas it wouldn't be ATOM without all of them, or without a particular number of each of them, and, there is no way ATOM could be an ATOM without NUCLEUS [4]. From the example, it

[1]**necessary**: such that without it the object does not fit its definition.

[2]**optional**: such that without it the object does still fit its definition.

[3]Losing a neutron may destabilize an atom (when a nucleus has too many neutrons, it tends to beta decay), but formally, it still remains an atom.

[4]In case of "positronium" - an exotic atom made of only an electron and a positron - we could think of positron as its degenerate nucleus.

is easy to see that there are at least 3 qualitatively different possibilities, not accounted for by the current implementation of the parthood relation:

1) X **is part of** Y ⇔ “Y *must* be a part of X” (necessary, like in case of nucleus)
2) X **is part of** Y ⇔ “Y *conditionally must*[5] be a part of X” (conditionally optional, like in case of different numbers of different particles)
3) X **is part of** Y ⇔ “Y *mustn't* be a part of X” (optional, like in case of a neutron)

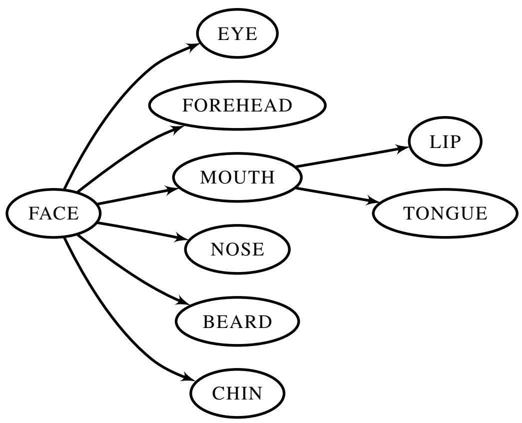
The failure to differentiate between the necessary and optional parts leads to a problem of inherent ambiguity in the knowledge representations using such an ontology.

As we shall see later, there are practical implications of considering these distinctions, and a mereology-theoretic ground for introducing the distinction between the (1) and (3), and ultimately (2).

B. Problem 2: Transitivity violations

In order to make correct logical inferences from the knowledge represented in an ontology, it is crucial to have accurate transitivity relations. So that, for example, if we have information that ROOM is part of BUILDING, and that a WINDOW is a part of ROOM, we could correctly deduce that WINDOW is a part of a BUILDING.

However, it is because of lack of forethought and formal treatment of parthood relations, the ontologies created for natural language processing that we are aware of suffer from numerous violations of the transitivity principle. Consider the following example from **OntoSem**.



Picture 2. Parts of a FACE in **OntoSem**.

The example is trying to depict the objects that are supposed to be *'parts of'* a primate's FACE. However, relying on the representation, we would inadvertantly enable an intelligent agent to incorrectly conclude that anything that will be a part of EYE, FOREHEAD, MOUTH, NOSE, BEARD and CHIN must (by transitivity) be also a part of FACE, which is clearly not the case. For instance, an eye's retina would be a part of an eye, but not a part of face; a mouth's palate would be a part of a mouth, but not part of a face; a nasal cavity and a olfactory bulb would be parts of a nose, but not parts of face. (Tongue is a part of mouth, but rarely does it show as a part of a face.)

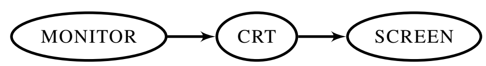
As we shall see in the later sections, the application of knowledge about about the mereological granularity can help to resolve this issue.

C. Problem 3: Multiple alternative combinations of parts

Ontologies in general, as well as those designed for natural language processing, are not just composed of concepts, which are the nodes in their graph representations, but the relations (graph vertices) also play a key role in conforming with the definitions of the concepts used. They are, effectively, trying to formalize the definitions. For example, when a certain essential part of an object is missing, the object may not fit its definition anymore.

The problem is that in many cases an object may have more than one combination of parts that qualify. For instance, the concept of a clock may require either of the two alternative combinations of parts: HOUR ARM or LCD-DISPLAY for it to be a clock. The more abstract a concept the more alternative combinations of parts may be associated with it. For example, a concept as broad as LIFE-FORM would have a combinatorically large, possibly infinite number of part combinations that fit.

However, the existing ontologies in natural language processing do not account for the ranges of different alternatives. Below is an example from **OntoSem**.



Picture 3. Parts of MONITOR in **OntoSem**.

A monitor may be composed of a CRT (Cathode Ray Tube), but it may alternatively be composed of LCD (Liquid Crystal Display), or PDP (Plasma Display Panel), or have some other component realizing its function. In the current implementation of ontologies for natural language processing, these possibilities are not accounted for.

As we shall see later, the mereological sum principle and unrestricted mereological composition creates the basis, and suggests the ways of incorporating such alternatives.

II. MEREOLOGIES

Denote expression “x is part of y” as binary relation Pxy. Taking different assumptions into account, different parthood relations are defined. [8] [5]

A. Axioms of parthood relation

According to the theory of mereology, there are the three properties that *any* “is part of” relation has to satisfy, to be called a parthood relation: *reflexivity*, *transitivity* and *antisymmetry*. Let's call them 'Primary Axioms'.

[5]**conditionally must**: there are conditions, when it must.

1) Primary Axioms:

(P.1) **Reflexivity**

$$Pxx$$

(P.2) **Transitivity**

$$(Pxy \wedge Pyz) \rightarrow Pxz$$

(P.3) **Antisymmetry**

$$(Pxy \wedge Pyx) \rightarrow x = y$$

The relation Pxy that satisfies these axioms is said to satisfy 'Ground Mereology' (M-theory).

Using the parthood relation Pxy defined in M-theory, the *proper parthood*, *overlap* and *underlap* relations are defined, and further, secondary axioms formulated.

2) Definitions:

(D.1) **Proper parthood**

$$PPxy \Leftrightarrow Pxy \wedge \neg Pyx$$

(D.2) **Overlap**

$$Oxy \Leftrightarrow \exists z(Pzx \wedge Pzy)$$

(D.3) **Underlap**

$$Uxy \Leftrightarrow \exists z(Pxz \wedge Pyz)$$

3) Secondary Axioms:

(P.4) **Weak supplementation principle**

$$PPxy \rightarrow \exists z(Pzy \wedge \neg Ozx),$$

(P.5) **Strong supplementation principle**

$$\neg Pyx \rightarrow \exists z(Pzy \wedge \neg Ozx)$$

(P.6) **Sum principle**

$$Uxy \exists z(\forall w:\ Owz \leftrightarrow Owx \vee Owy)$$

(P.7) **Product principle**

$$Oxy \exists z(\forall w:\ Pwz \leftrightarrow Pwx \vee Pwz)$$

(P.8) **Unrestricted sum**

$$\exists y \varphi y \exists z : \forall y\ (Oyz \leftrightarrow \exists x\ (\varphi x \wedge Oxy))$$

Depending on the combinations of the above axioms that are satisfied, parthood relation is said to follow a different theory, each of which has a name: *Ground Mereology* (M-theory) - when Pxy satisfies the (P.1), (P.2), (P.3); *Minimal Mereology* (MM-theory) - when Pxy satisfies the M and (P.4); *Extensional Mereology* (EM-theory) - when Pxy satisfies MM and (P.5); *Closure mereologies* (CM-theories) - when Pxy satisfies M, (P.6) and (P.7); *Closure Minimal Mereology* (CMM-theory) - when Pxy satisfies MM, (P.6) and (P.7); *Closure Extensional Mereology* (CEM-theory) - when Pxy satisfies EM, (P.6) and (P.7); *General mereologies* (GM-theories) - when Pxy satisfies M and (P.8); *General Minimal Mereology* (GMM-theory) - when Pxy satisfies MM and (P.8); *General Extensional Mereology* (GEM-theory) - when Pxy satisfies EM and (P.8).

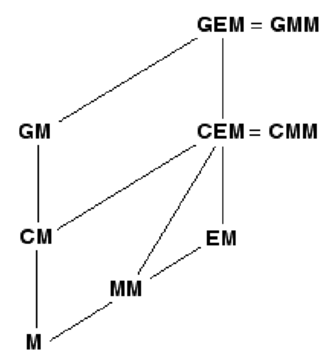
For further details and examples about the mereologies, we refer the reader to [1] and [5]. However, it is worth mentioning the following corollaries that follow from the axioms, definitions and naming:

1) Axiom (P.4) implies (P.1), (P.2), (P.3).
2) Axiom (P.5) implies (P.4).
3) From axiom (P.5), follows the following theorem:

(T.1) *For all x's and y's, such that x has proper parts or y has proper parts, x and y are identical if and only if x and y have the same proper parts.*

4) Theories CMM and CEM are equivalent, because (P.4) and (P.7) implies (P.5).
5) Theories GMM and GEM are equivalent, because (P.8) implies (P.7), and (P.7) with (P.4) implies (P.5).
6) GM is an extension of CM, and GEM is an extension of CEM, because (P.6) can be deduced from (P.8).

Taking the corollaries into account, the following summarizing diagram can be drawn.



Picture 4. All the theories presented in this section.

B. Mereological Granularity

Except for these 8 axioms, there are more assumptions that are discussed in [1]. These are: *atomicity*, *atomlessness*, and the concept of mereological *granularity*.

(P.9) **Atomicity**

$$\exists y(Ay \wedge Pyx)$$

(P.10) **Atomlessness**

$$\exists y : PPyx$$

The idea of mereological granularity in [1], is mentioned as the position available for an atomless mereology, but not for a mereology with an assumption of atomicity. However, the intermediate position between atomicity and atomlessness is also suggested, which represents the position where we hold that "there are atoms, though not everything need have a complete atomic decomposition, or [...] there is atomless gunk, though not everhything need be gunky," which "formally amounts to endorsing a restricted version of either (P.9) or

(P.10) in which variables are suitably restricted so as to range over entities of certain sort:" (axiom numbering different from originally in [1])

(P.9$_\varphi$)

$$\varphi x \rightarrow \exists y(Ay \wedge Pyx)$$

(P.10$_\varphi$)

$$\varphi x \rightarrow \exists y : PPyx$$

Here, the assumptions are introduced analogously to atomicity and atomlessness, albeit replacing either the assumption of atomicity or the assumption of atomlessness with their analogues dependent of the choice of the condition φ in (P.8).

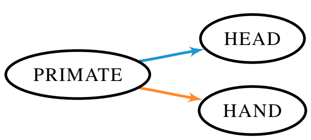
Although, according to [1], "at present, no thorough formal investigation of such options has been entertained," the idea of such extremely flexible "granularity" can be useful in dealing conceptually with transitivity violations, and it is defined precisely in a case of atomless mereology – the choice of the base then depends each time on the level of "granularity" set by the relevant specification of 'φ'. [1]

III. SOLUTIONS

A. Solution 1: The more senses of the 'part of'

Considering the fact that **(T.1)** [6] follows from **(P.5)** (Extensional Mereology), but does not follow from **(P.4)** (Minimal Mereology), there are two distinct parthood relations - one that denotes proper parts that are optional, and one that denotes proper parts that are necessary to keep the identity of a concept.

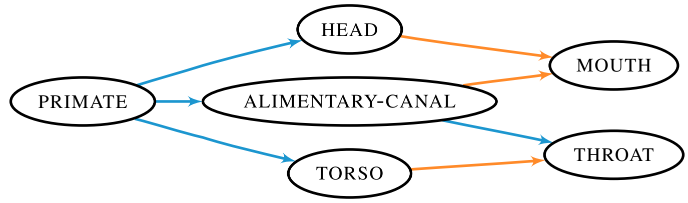
To illustrate how this distinction is helpful in making an ontology less ambiguous, here is an example. In **OntoSem**, we have HAND and HEAD as parts of PRIMATE. However, there was no distinction as to which part is necessary, and which is optional for something to be a primate. Decapitating PRIMATE would effectively turn it into a non-living primate, and we would have no primate anymore, but removing a hand would keep the primate alive, and we would still have a primate. So we would denote this difference in parthood as satisfaction of different axioms, namely, (P.1) through (P.5) for necessary, and (P.1) through (P.4) for optional proper parts. In the illustration below, we color-code the relations with blue and orange lines respectively.



Picture 5. Parts of PRIMATE; blue indicates necessary, orange indicates optional proper parthood relations.

We looked at how this distinction works for the relations found in the publicly available semantic ontology **OntoSem**[7], which utilizes only a single HAS-OBJECT-AS-PART parthood relation. Among all the relations, we counted 156 relations that - in our opinion - should fall into the "optional", and 177 relations that should fall into the "necessary" class, and a small remainder that does not fall into any of the classes. The approximately similar numbers of each of the two classes indicate that, by providing the distinction, we significantly reduce the uncertainty around the relation.

Here is another example showing how making this distinction provides important information.

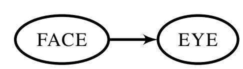


Picture 6. Parts of PRIMATE.

B. Solution 2: Preserving the transitivity

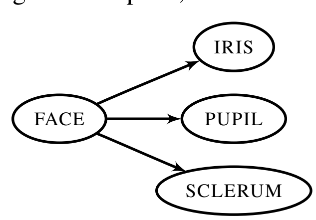
As it is clear from the Section II, transitivity is an essential property of parthood relations, but as demonstrated in Section I, it can be violated, which - in effect - disqualifies the relations from being called and treated as parthood relations. For instance, if in the Picture 6, we were to introduce a ALIMENTARY-CANAL as a part of TORSO, it would create such violation, because MOUTH, as a part of ALIMENTARY-CANAL, would have then also be a part of TORSO, while it clearly isn't (it is a part of HEAD). Another example of such a violation is provided in Section I, B: if an eye is part of face, an eye's retina would have to be a part of face, but it isn't.

The solution to the problem lies in optionally increasing or decreasing the grain-size (level of smallest parts considered), and introducing smaller parts of an objects as necessary to preserve transitivity relation in each situation. For instance, suppose we are talking again about the parts of face. First, we say that EYE is part of FACE, and then realize that it's not the case, because by transitivity, EYE's RETINA would then also have to be a part of FACE. So, we refine the granularity: look at the smaller parts of EYE, and identify those parts, which *are* parts of FACE, for example: IRIS, PUPIL, SCLERUM (eye's white). We then sever the parthood relation FACE–EYE, and create relations FACE–IRIS, FACE–PUPIL, FACE–SCLERUM, as seen below.



Picture 7. EYE is incorrectly part of FACE.

After severing the relation, and creating new relations between smaller grain-size parts, and the whole, we get:



Picture 8. Smaller grain-size parts of FACE.

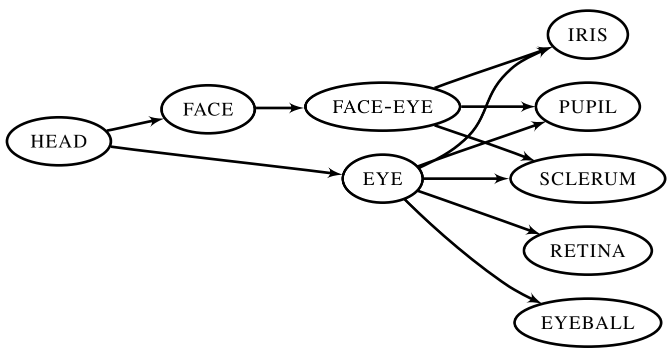
[6](T.1): x and y are identical if and only if x and y have the same proper parts.

[7]http://www.csee.umbc.edu/ aks1/ontosem.owl

This way, decreasing the grain-size allows us to preserve the transitivity, and thus have correct parthood relations.

A note on preserving high level of abstraction

Decreasing the granularity size increases the number of relations between the nodes. In our above example, instead of having one relation between an eye and a face, we inevitably created three relations necessary to preserve transitivity. It may be inconvenient to have many high-degree nodes in a graph. To reduce that number, we are always free to introduce new concepts. For example, introducing a concept FACE-EYE, made up of only 3 parts (IRIS, PUPIL, SCLERUM) in parallel to the general concept of an EYE composed of (IRIS, PUPIL, SCLERUM, EYEBALL, RETINA, etc.), we would be able to reduce the degree of the node FACE. The below is an illustration of what this would look like.



Picture 9. Preserving transitivity and high level of abstraction.

So, by trying to resolve the transitivity issues, we arived to clearly distinct notions (eye and face-eye), which are not readily disambiguated in natural text, because they appear as homonyms: an eye as a part of face, and an eye as an distinct biological organ.

C. Solution 3: The multiple alternative combinations of parts

As mentioned in the Section I, an object may have more than one combination of parts that qualify the object to be of a particular kind. Let's go to the example of the concept CLOCK.

Depending on the kind of clock it is (digital or analogue), it may have two equally qualifying combinations parts: either CLOCK-ARMS and PENDULUM, or LCD-DISPLAY and QUARTZ. Let's focus on the parts PENDULUM and QUARTZ. In order to avoid the disparate qualifying conditions, we could resort to calling these parts using a more abstract term OSCILLATOR. However, an OSCILLATOR itself would now have two different parts under different conditions, that qualify it to be called an oscilator. We could go further, and more abstractly say that it could be any parts that satisfy certain mathematical properties (such as periodic recurrence). Although properties are not generally considered parts of physical objects, but according to GEM (General Extensional Mereology) there exists an object, which is exactly the sum of all objects that satisfy certain condition φ, and these conditions can be any mathematical properties, too (although the actual parts that satisfy those properties are combinations are physical objects). For instance, in case of a solar clock, the cellestial bodies satisfy this property of an oscillator, and in that sense, the Sun and another cellestial body, on which the solar clock works, are essential parts of a solar clock, without which it would not be a clock. It is worth noticing that this is where the functional and concrete compositional definitions come together. The below are examples of the compositional definition contrasted with the functional.

```
CLOCK (
  HAS-OBJECT-AS-PART (
    (CLOCK-ARMS or LCD-DISPLAY)
    (PENDULUM or QUARTZ)
  )
```

Picture 10. Concrete compositional definition.

The below is an example of providing a list * of combinations of parts, that implement a functional oscillatory property, and time-displaying property for a CLOCK.

```
CLOCK (
  HAS-OBJECT-AS-PART (
    ( * | HAS(OSCILLATION-PROPERTY))
    ( * | HAS(TIME-DISPLAY-PROPERTY))
  )
)
```

Picture 10. Definition of CLOCK using using unrestricted sums as parts.

The OSCILLATION-PROPERTY here is defined as those combinations of things occuring in real life, like QUARTZ, PENDULUM, EARTH-SUN-SYSTEM, etc. which satisfy a certain condition: $\varphi_1 = $ HAS(OSCILLATION-PROPERTY). The TIME-DISPLAY-PROPERTY is similarly defined as those combinations of things occuring in real life, like CLOCK-ARMS, LCD-DISPLAY, etc., which satisfy another condition: $\varphi_2 = $ HAS(TIME-DISPLAY-PROPERTY).

However, not all the combinations that satisfy a chosen condition frequently occur, and there certainly is dependence accross the conditions. For example, if OSCILLATION-PROPERTY is realized by PENDULUM, it is much more likely that TIME-DISPLAY-PROPERTY by clock-arms. To reflect that, we may want to define a conditional probability distributions for each of the conditions, however we won't go into details about it, because it is outside the scope of this paper.

Important observation

Regarless of usability of parthood relations defined in MM-theory (axioms up to **(P.4)**) and EM-theory (axioms up to **(P.5)**), we observe that in case of the just described parthood representation in terms of GEM, the information about the necessary and optional parts can be obtained by inheriance through IS-A relations.

For example, according to MM-theory and EM-theory, we may wish to make the following distinctions:

```
CLOCK (
  5-HAS-OBJECT-AS-PART (
    ( * | HAS(OSCILLATION-PROPERTY))
```

```
    ( * | HAS(TIME-DISPLAY-PROPERTY))
  )
  4-HAS-OBJECT-AS-PART (
    ( * | HAS(MOUNTING-DEVICE))
  )
```

Picture 11. Definition of CLOCK combining unrestricted sum principle with minimal and extensional mereologies.

By making these distinctions we want to say that a clock can be anything that has an object that has OSCILLATION-PROPERTY, and optionally has MOUNTING-DEVICE. For instance, a wall clock may have a hook.

However, when parthood relations are defined in GEM, and are all of the "necessary" kind (i.e., satisfy at least **(P.5)**), it is easy to induce, which relations are optional. For example:

Having the more specific examples of concepts (e.g., DIGITAL-CLOCK, WRIST-WATCH are more specific examples of a CLOCK), we can automatically find all the parts that do not occur in all the child concepts, and conclude that they are optional for the general concept (CLOCK).

```
CLOCK (
  5-HAS-OBJECT-AS-PART (
    ( * | HAS(OSCILLATION-PROPERTY))
    ( * | HAS(TIME-DISPLAY-PROPERTY))
  )
)

DIGITAL-CLOCK (
  IS-A (CLOCK)
  5-HAS-OBJECT-AS-PART (
    (FOR OSCILLATION-PROPERTY: QUARTZ),
    (FOR TIME-DISPLAY-PROPERTY: LCD-DISPLAY),
  )
)

ANALOGUE-CLOCK (
  IS-A (CLOCK)
  5-HAS-OBJECT-AS-PART (
    (FOR OSCILLATION-PROPERTY: PENDULUM),
    (FOR TIME-DISPLAY-PROPERTY: TIME-ARROW),
  )
)

WRIST-WATCH (
  IS-A (CLOCK)
  5-HAS-OBJECT-AS-PART (
    (FOR MOUNTING-DEVICE: BRACE)
  )
)
```

Picture 12. An example of a structure, where optional parts of CLOCK can be induced from more specific examples connected through IS-A relation: parts not mentioned in the definition of CLOCK, but appearing in its children, are optional.

Since eliminating the property (for mounting-device: brace) does not rule out all of the clocks (we still have DIGITAL-CLOCK and ANALOGUE-CLOCK, which do not necessarily have MOUNTING-DEVICE, it implies that MOUNTING-DEVICE is an optional feature of a clock, i.e., satisfies (P.4), but not (P.5), and makes the knowledge about these (P.4) and (P.5) relations redundant.

So, having more specific examples connected by IS-A relation with necessary (P.5) relations, us to find the implied parthood relations that satisfy (P.4) automatically.

CONCLUSION

Having more informative parthood relations grounded in MM-theory and EM-theory can be useful, especially if an ontology is being created by an expert, and there is no sufficient number of more specific concept examples to conclude about the status of a relation through inductive reasoning automatically.

Reducing mereological granularity and creating new abstractions is an effective way of preserving transitivity (and thus parthood relations), and keeping the degrees of vertices in an ontology low.

Defining parthood relations in terms of GEM-theory (General Extensional Mereology), through using unrestricted sum principle with specific conditions (φ), allows to overcome the difficulty of multiple possible combinations of parts that are possible for a concept.

A deep philosophical and methodological issue that we are skirting here is whether the existence of a well-defined mathematical or scientific theory should immediately affect an ontology underlying natural language. The argument can go both ways. On the one hand, a more correct picture of reality will preserve the validity of logical inferencing and reasoning. On the other, a native speaker reasoning in natural language may deviate from a well-defined theory. This paper automatically assumes the former and marshals some supporting examples.

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