Midwinters, end games, and body parts: a classification of part-whole relations

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This paper deals with the conceptual part-whole relation as it occurs in language processing, visual perception, and general problem solving. One important long-term goal is to develop a naive or common sense theory of the mereological domain, that is the domain of parts and wholes and their relations. In this paper, we work towards such a theory by presenting a classification of part-whole relations that is suitable for different cognitive tasks and give proposals for the representation and processing of these relations. In order to be independent of specific tasks like language understanding or the recognition of objects, we use structural properties to develop our classification.

The paper starts with a brief overview of the mereological research in different disciplines and two examples of the role of part-whole relations in linguistics (possessive constructions) and knowledge processing (reasoning about objects). In the second section, we discuss two important approaches to mereological problems: the "Classical Extensional Mereology" as presented by Simons and the meronymic system of part-whole relations proposed by Winston, Chaffin and Hermann. Our own work is described in the third and last section. First, we discuss different kinds of wholes according to their inherent compositional structure: complexes, collections, and masses. Then partitions induced by or independent of the compositional structure of a whole are described, accompanied by proposals for their processing.
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1. Introduction

The *part-whole relation* plays an important role both in natural language semantics, e.g. the interpretation of possessive constructions, and in knowledge processing, e.g. reasoning about objects. In addition, since Greek philosophy this relation has been considered to be a fundamental ontological relation (cf. Burkhardt & Dufour, 1991). So it is rather surprising that there is so little actual work dealing with this kind of relation. A closer look at the part-whole relation shows that there is a broad range of rather complex phenomena associated with the relation which are far from being understood well (see Winston, Chaffin & Herrman, 1987). In order to develop a better understanding, the first step must be to further examine the part-whole

relation along the following lines:

- What kind of entities can be segmented into parts?
- What kind of part–whole relations can be distinguished?
- In what kinds of entities does the partition result?
- How are the different relations processed?

Our goal is to develop a cognitive theory of naive or common-sense mereology as it is used for different tasks like language processing, vision, or reasoning about objects. In this paper we present a task-independent classification of part–whole relations and make some initial proposals for processing these relations. The first section gives a brief overview of the mereological research in different disciplines and two examples for using part–whole relations in different tasks. The section ends with a call for the development of a naive or common-sense theory of part–whole relations. In the second section, we discuss two important approaches to mereological problems: logical/formal mereology and the most influential classification of part–whole relations. Our own work is described in the third and last section. First, we discuss different kinds of wholes according to their inherent compositional structure: complexes, collections and masses. Finally, partitions induced by or independent of the compositional structure of a whole are described, accompanied by proposals for their processing.

1.1. DIFFERENT VIEWS ON PART–WHOLE RELATIONS

The first to deal with the topic of parts and wholes were the "atomists" (500–370 BC) in ancient Greece. They and subsequent researchers (e.g. Plato, Aristotle, and the Scholastics) address all the fundamental questions that were important until today, like the characterization of the concepts of "whole" and "part", different relations between the two, or the inheritance of properties from parts to the whole and vice versa. In the last century, the research topics have been split up among the different disciplines. The logical/philosophical investigations are concerned with formal systems built around the "part-of" relation. They abstract from the concept of a whole. These formal mereologies are used for building up formal ontologies for time, space, events, and so on. Psychologists are interested in the interaction between the so-called partonomies (part–whole hierarchies for concrete objects;) and conceptual hierarchies.

Researchers in the field of visual perception propose that objects are recognized mainly with respect to the structure of their parts. Linguistic work focuses on different part–whole relations and their role as semantic primitives. In the following, we present an overview of relevant approaches in the different domains.

At the beginning of the 20th century, Husserl began the first logical/philosophical investigations of the part–whole relation. The first formal systems are the "Mereology" of Lésniewski (1929) and the "Calculus of Individuals" of Leonard and Goodman (1940). These systems are based on one simple "part-of" relation. They abstract from properties of the whole or different part–whole relations. Formal mereological systems are domain-independent in not making any assumptions about the entities they deal with. In his classic work on mereology, Simons presented the

"Classical Extensional Mereology" (CEM) as a basic system of the part-of relation. The systems of Lésniewski (1929) and Leonard and Goodman (1940) can be viewed as logical guises (Simons, 1987). The CEM-system is described in more details in Section 2.1, where we discuss the relation between the logical and the intuitive part(-whole) relation.

Today there are two different research topics concerning formal mereologies. The first topic includes further development of the formal system, e.g. the work of Simons (1987) on questions of time-dependence, on the essentiality of parts, or on the integrity of wholes. The second topic covers work on ontological modelling based on formal mereology. Included is work on the foundation of ontology, in which mereology is often used as substitute for set theory (e.g. Smith, 1982, 1993; Lewis, 1991; Eschenbach & Heydrich, 1993 on the mereological formalization of set theory, linear ordering, etc.) and approaches to formalizing specific domains of world knowledge like plural phenomena and collections (Link, 1983), continuants (Simons, 1987), or topological aspects of space (Egenhofer, 1989, Randell, Cui & Cohn, 1992).

The interaction between knowledge about part-whole relations and general conceptual knowledge is primarily studied by Tversky and Hemenway (1984). Their work is based on the results of Rosch and her fellow researchers (e.g. Rosch, 1977; Mervis & Rosch, 1981) on the human conceptual system. According to Rosch (1977), the conceptual taxonomy is a hierarchical system consisting of three levels—superordinate, basic, and subordinate—of which the basic level is fundamental for human cognition. Tversky and Hemenway (1984) ascertain that most of conceptual knowledge about parts belongs to basic level concepts. The information about the parts of an object and their spatial configuration enables inferences about form, structure, and functionality of the whole object. Thus part knowledge connects perception with behavioural tasks involving the object and builds the basis for causal reasoning about the function of objects. On the basis of this observation, Tversky and Hemenway (1984) suggest that informativeness and importance of the basic level are due to a good deal to part knowledge.

The parts associated with an object are organized in a *partonomy*, a structure which has much in common with taxonomies (Tversky, 1990). Partonomies form trees with no more than three levels: the whole, its parts, and parts of its parts. Analogous to the phenomenon of typicality of concept members, parts can be ranked according to their goodness where the best parts are those which are both perceptually salient and functionally important. Despite these similarities, there are also differences between partonomic and taxonomic knowledge. Preuß and Cavegn (1990) suggest that the taxonomic "is-a" relation and the partonomic "part-whole" relation are processed differently by humans. The former is tested by checking commonalities and differences while the latter involves a more complex processing of spatio-temporal and functional correlations.

Researchers in visual perception are interested in the role of parts in the recognition of objects. An object is primarily recognized by extracting its shape and comparing it with the characteristic shapes of object concepts. It is widely accepted that the shape of an object is induced by the part structure of this object (Marr & Nishihara, 1978; Biederman, 1987), an observation that fits perfectly into the conceptual theory of Tversky and Hemenway (1984).

Mostly, the researchers who try to enlighten the nature of the (semantic/cognitive) part–whole relation are from the discipline of linguistics. The starting point for their investigations is the observation that the part-whole relation is not in general transitive as defined by the formal mereologies (see for example Miller & Johnson-Laird, 1976; Lyons, 1977; Cruse, 1979). Thus, for linguistic and conceptual tasks the simple "part-of" relation of formal mereology is replaced by a family of relations (see Winston et al. 1987, Iris, Litowitz & Evens 1988). The most famous work is that of Winston et al. (1987) which gives a classification of six different part–whole relations. We omit the description of their approach here because it will be discussed in more detail in Section 2.2. Associated with the classification are questions about the status of the family of part–whole relations as semantic primitives and their role in the lexicon. The developed classifications are used by other researchers, especially in AI, for the modelling of world knowledge (e.g. Markowitz, Nutter & Evens (1992) for a general ontology, Vieu (1991) for the French preposition "in").

What is missing in the list of disciplines concerned with the part–whole phenomenon is Artificial Intelligence. The part–whole relation, sometimes under the synonym of "has-part", plays an important role for modelling world knowledge in all kinds of semantic networks or terminological knowledge bases. However, the results regarding the transitivity problem and its solution by use of a family of relations are not adopted. Also there are nearly no attempts to develop representation formalisms specialized in processing part–whole information. Exceptions are the works of Markowitz et al. (1992) and Zadrotzny and Kim (1993).

Following Iris et al. (1988), Markowitz et al. (1992) view the part–whole relation as a family of (at least) four distinct relations: functional component, member of set, subset and piece. The distinction should avoid errors in reasoning, e.g. in transitive inferences, that could occur if only one single relation would be used. Zadrotzny and Kim (1993) employ the mereological "part-of" relation in interaction with the "member-of" relation from set theory for multimedia indexing. The relations should help to solve the problem of managing large amounts of data as it occurs in multimedia technologies.

1.2. TWO EXAMPLES

Adnominal prepositional phrases with "von", non-lexically assigned genitives, and non-auxiliary uses of "haben" are the major possessive constructions of German. Possessive constructions consist of two nominals referring to the possessor and to the possessee and of a linguistic element that is responsible for establishing a *possessive relation* between these two. It is widely assumed that possessive constructions may be used to express any relation whatsoever between two entities. There is, however, strong reason that there are two particularly prominent conceptual paradigms underlying the meaning of possessive constructions: the paradigm of "belonging-to" and "part–whole". While "belonging-to" covers cases of "being-at-one's-disposal", "(legal) possession" and "(legal) property", "part–whole" refers to a set of conceptual relations which may be stipulated in different ways and with varying degrees by the meanings of the expressions which identify the possessor and the possessee.

It is important to distinguish the linguistic notion of "possessor-possessee" from "part-whole" which is motivated by conceptual structure. The semantic processing of possessive constructions corresponds to a search for certain binary relations between entities. The only way to restrict the vast amount of possible results of this process in a reasonable manner is to provide a mean for filtering out certain relations that are in a sense preferred for the interpretation of the construction under consideration. For a broad range of possessive constructions this calls for a specific organizational level of conceptual knowledge that allows the computation of those relations between entities that may be regarded as instances of part-whole. This level may be extracted from the knowledge base by applying a certain scheme for splitting up entities into parts or pieces. This scheme can be used by a language generator to test whether a relation between two entities may be realized as a possessive construction. From the point of view of language analysis this scheme helps to reduce the search space for available interpretations of possessive constructions, especially in cases where contextual information is sparse.

Part-whole relations build up an important part of our knowledge about—among other things—the physical world. For example, to fix up a bookcase one must know from which other objects it is composed of and how these simpler objects are arranged with respect to each other to form the bookcase. So for handling objects, doing physical reasoning, and similar tasks, it is necessary to reason about the different parts of a complex object.

These examples illustrate why knowledge-based systems involving physical objects like expert systems for configuration or fault analysis rely on part-whole information. These systems use so-called partonomies which represent the partition of complex objects into simpler objects which themselves can be further broken down into their parts, and so on. For example, a car consists of the machinery and the body. The body can be decomposed into the internal parts, the windows, the metal parts, and so on. The result is a partition graph that describes the dismantling of a whole into its parts on different levels of granularity. Each level provides a partition into proper parts that are disjoint from each other and which together build up the whole original object. As the partition is complete and free of overlap for every level it forms a tree and not a graph.

A closer look at the problem shows that not all phenomena of the part-whole relation can be represented by a simple partonomy because there is more than one way of partitioning a whole into parts. The following text (T) together with three groups of questions, (Q1–Q3), shows the problem of common-sense reasoning about objects involving different kinds of part-whole relations.

(T)   Yesterday Babette and Matthias had a car accident when they tried to pass a truck. The whole right side of their car was smashed by an approaching car.

(Q1a)   Was the left side of the car damaged?
(Q1b)   Was the front of the car damaged?
(Q2a)   Was a door of the car damaged?
(Q2b)   Was the engine damaged?
(Q3a)   Was any glass broken?
(Q3b)   Was anything functionally relevant affected?

The text describes which part of the car was damaged in the accident. Because the phrase "right side" is used an external scheme is necessary to compute the relevant segment of the car. One has to know what a side is and how to use a reference system to determine what part of the object is referred to as "right side". One possible solution can be to use an abstract six-sided cube to refer to different sides, edges, and corners of an object. A remaining problem is how to relate this cube to the object, but that is not the topic of this paper.

To answer the first two questions Q1, the external scheme is used again. The reference system of the scheme provides the information that right and left sides are opposite to each other. Therefore, two parts of an object corresponding to these two directions are disjoint from each other. Following this line of argumentation, question Q1a can be answered with "no". The answer to question Q1b is not that easy. The right and the front side of an object are normally not disjoint but overlap as the abstract cube shows. The answer could be a restricted positive one like: "Yes, the right corner of the front is smashed".

The next two questions Q2 refer to components of the car, its doors and engine. Their relation to the car as the "whole" is given by the partonomy mentioned above. The problem is to relate these components to the right side selected by an external scheme. This task can only be carried out if the spatial structure of the components is known and the external scheme can be related to them too. If such a procedure exists it might compute that the right door, but not the left door is damaged and that—depending on the special construction of the car—possibly the engine is affected too.

The final questions Q3 refer to those parts of the car that have specific properties. To answer the first question, Q3a, it must be computed which pieces of the car are made of glass and if any of those pieces are related to the right side of the car. In our case the glass parts correspond to proper parts of the car, the windows and the lights. An answer to question Q3a can be that all windows and lights on the right side of the car are most probably broken. The second question involves functionally relevant parts, e.g. components that are necessary for the car to work or to be roadworthy. Conceptual knowledge is used to determine these components. In combination with spatial and functional knowledge, for every component is computed whether the damage of the right side may affect it.

1.3. A NAIVE THEORY OF PARTS AND WHOLES

The analysis of the existing work about part-whole relations shows that all approaches restrict themselves to isolated aspects of the phenomenon:

- Logical research centers upon mereological systems which are used to formalize ontological domains like plural phenomena or quantities but are—typically enough—not applied to the general part–whole phenomenon as it occurs in language, vision or other cognitive behaviour.
- Psychological research is concerned with the use of part information in recognizing objects and with partonomic knowledge in the conceptual system. In both

cases, one single kind of part, which we later call components, is considered.† All other variations of part–whole relations, e.g. arbitrary pieces or members of collections, and entities different from objects that can serve as wholes, e.g. situations or sets of objects, are not examined.

- Research from a linguistic viewpoint no doubt offers the most extensive analysis of different part–whole relations. But there are two problems. First, the research clings too close to the word "part" and its cognates to result in a general cognitive theory of parts and wholes (cf. the analysis of Winston et al. (1987) below). Second, there seem to be no attempts to formalize the research or to develop mechanisms for processing the relations.

What we are looking for is a comprehensive theory about the—cognitive— phenomenon of parts and wholes and their relations. This theory should view the phenomenon as a complex one by providing a classification of different part–whole relations. The classification should not be restricted to linguistic problems but should also take into account other domains in which the segmentation into parts is important, like visual perception, object partonomies and language. The theory should include mechanisms for representing and reasoning about different relations. We do not want to restrict reasoning to transitivity; other inferences like the combination of relations or the inheritance of properties from parts to wholes and vice versa are by far more important. It is also necessary to provide a formal basis for dealing with the different part–whole relations. This formalization will show in which way a mereological system must be modified or supplemented to result in an adequate formal basis for the part–whole phenomenon. It is obvious that the development of such a theory can not be done in a single paper but needs more time and effort. We want to offer one first step towards the theory by presenting a classification of part–whole relations that is suitable for different cognitive tasks and give proposals for the representation and processing of these relations.

For our classification of relations, we assume a conceptual system underlying different cognitive tasks, like perception, language processing, or problem solving, realized by different modules (cf. Fodor's (1983) theory of the "modularity of mind"). Applied to the part–whole phenomenon, this assumption proposes a conceptual subsystem for handling part–whole relations. Each specific module that involves part–whole problems as the language or the vision module has access to the conceptual part–whole subsystem. Typically each module uses only a share of the relevant conceptual subsystem. An overlap of the used shares of different cognitive modules facilitates the interaction of the modules. By using the same knowledge about part–whole relations, the vision system could help to determine the color of those parts of a car the linguistic module refers to with the word "door".

Each conceptual subsystem might be described by a naive or commonsense theory of the represented domain in the sense of Hayes (1979, 1985). According to Hayes, it is one main goal of Artificial Intelligence to develop such naive or commonsense theories for all important domains of our everyday life, like time, space, folk

† In visual perception, a shape is segmented into its parts by the principle of transversability (Hoffmann & Richards, 1984). Nobody seems to have carried out examinations about whether the segmented parts always correspond to components, even though they normally do.

physics, and—last but not least—phenomena like subsumption or mereology. Our purpose is to work towards such a *naive theory of part-whole knowledge*. To be independent of specific cognitive modules we use structural properties to develop our classification of part-whole relations.

2. What inferential capabilities do current theories of part-whole offer?

As has been illustrated in Section 1.3, the notion of part-whole plays an important role in many different scientific disciplines. Consequently, theories about parts and their relations to wholes are subject to investigation with different motivations in mind. In the following we briefly examine two theories and discuss their potential contribution to a *common-sense theory* of part-whole relations. First, we draw our attention to *classical extensional mereology* (*CEM*), a familiar approach to formal mereology, which is probably the most fundamental account towards a formalization of parts. Our criticism of classical extensional mereology mainly concerns expressivity, which is too strong from one point of view and too weak from another. In contrast to formal mereology, we then discuss a proposal by Winston *et al.* (1987). As a theory motivated by the use of the expression "is ... part of" it comes closer to our goal of a commonsense theory of part-whole relations. At any rate, it falls short of providing a satisfactory account due to the dubious nature of some classes of part-whole relations proposed by the authors.

2.1. CLASSICAL EXTENSIONAL MEREOLOGY

Mereology as a formal theory of the relation "part-of" is most accurately represented by the work of the Polish logician Stanislaw Lésniewski (1929) and by the Calculus of Individuals of H. S. Leonard and Nelson Goodman (1940). Classical extensional mereology offers an axiomatic system that has been proposed as an alternative to set theory providing the expressibility of a complete Boolean algebra without zero. An important Property of classical extensional mereology that makes it ideally suited for the description of plural entities is its lack of a distinction between a single element and the "whole" comprising only this element.

The "part-of" relation as defined by formal mereology usually is a partial order subject to the axiom of antisymmetry. However, since under the perspective of a commonsense theory "part-of" clearly refers to the notion of "proper part", we follow the axiomatization of (Simons, 1991) which includes the axiom of asymmetry and thus characterizes "part-of" as a strict partial ordering relation:

EXIST: If A is part of B, both A and B exist
ASYMM: If A is part of B, B is not part of A
SUPPL: If A is part of B, B has a part C such that there is no X which is both part of A and part of C [i.e. B has a part C disjoint from A].
TRANS: If A is part of B and B is part of C, then A is part of C

Whereas the validity of EXIST, ASYMM and SUPPL as basic properties of the "part-of" relation is fairly uncontroversial, it may be argued that TRANS does not generally hold. Particularly work in the domain of lexical semantics has continually pointed out that there are restrictions to the application of transitivity in reasoning

about part–whole relations (Lyons, 1977, Cruse, 1979). (1) and (2) below show a classic example by Lyons that contrasts a case where transitivity holds (1) with a case where this seems not to be true (2).

(1) the jacket has sleeves +
   the sleeves have cuffs
   the jacket has cuffs

(2) the house has a door +
   the door has a handle
   ?the house has a handle

Clearly there may be a view (call it the assembly–view) under which "handle" is part of a "house" but this seems not to cover the notion of part–whole prevalent in common-sense reasoning. Cruse explains the divergence between (1) and (2) by stipulating the notion of a functional domain (FD) implicit in the meaining of lexical items such as "finger" or "handle" (Cruse, 1979). Since we do not share Cruse's view of part–whole as a lexical relation, we do not consider this suggestion as intriguing. However, Cruse's idea emphasizes an important aspect of part–whole relations which the mereological account is totally unaware of, namely the importance of the way in which certain well-defined parts contribute to the function of the whole. In the following, these parts will be called *components*. Since formal mereology is a theory of *the* "part-of" relation, it does not offer any means to distinguish between the roles, two different entites play with respect to an entity they both are part of. Though not a property of lexical meanings, the functions of parts within wholes may help to explain why certain deductions based on transitivity seem to be better than others. Since transitivity is at the core of a spatial account of part–whole relations, it may be considered valid if functionality is disregarded (viz. the assembly–view). However, if functionality is an issue, there should be a way to block the application of transitivity since it may hold only in a restricted sense as illustrated by (1) and (2) above.

Adding the axioms EXT (extensionality) and SUM (existence of mereological sums) to the four core axioms yields classical extensional mereology (Simons, 1991; p. 674). Mereological extensionality as given by the axiom EXT implies that objects with the same parts are identical. It can be regarded as an analogy to the extensionality of set theory where sets with the same members are identical. The axiom SUM postulates that there exists a *unique* mereological sum S for any non-empty class of existing individuals.

The axiom of extensionality claims that any two individuals which consist of the same parts need to be identical. The classical example which shows that this assumption may be too strong refers to a committee A and a committee B consisting of the same members. In this case it is possible that the proposition "committee A is meeting" is true while "committee B is meeting" is not. Again, the difference has something to do with structure beyond pure membership. This may be made visible by focusing on the functionality of parts with respect to the whole, i.e. the chairman of committee A might, for instance, be the same person as the secretary of committee B.

There is another problem with extensionality caused by the fact that entities such

as living organisms typically have different parts at different instants of time. Such a mereologically variable entity can not be identical with the sum of its parts at any time, for then it would be different from itself (Simons, 1987).

Simons (1987) contains a summary of solutions that try to overcome the limitations of CEM. These solutions have in common that they add substantial complexity to the system by introducing additional parameters such as a dimension of time.

The axiom SUM that claims the existence of arbitrary sums of individuals makes it obvious that formal mereology does not offer a theory of "wholes". However, for the description of plural expressions the assumption of SUM is plausible since coordinate conjunctions pose no restrictions on the entities they combine, neither on major conceptual categories nor on relatedness along the spatial or temporal axes. As an approach towards the meaning of coordinate expressions, it may be assumed that expressions such as "Harry and Fermat's second theorem" or "Henry Ford and Michael Jackson" refer to some abstract aggregate motivated solely by the use of the coordinative construction. For a commonsense theory of part–whole relations one would, however, expect some degree of autonomy from the linguistic means that may be used to refer to these relations. It seems that restrictions on the appropriate conceptual categories as well as on spatial or temporal relatedness are crucial for stipulating the existence of a part–whole relation between individuals.

Summing up, classical extensional mereology provide a formal axiomatic theory of the core of part-whole relations but suffers from a lack of ability to express additional structure as in the case of components. They are thus too weak since they lack a notion of additional structure and too strong since the axioms TRANS, EXT and SUM lead to predictions which, under a commonsense perspective, do not generally hold. With the exception of the problems caused by the axiom of transitivity, the above mentioned problems are due to the fact that formal mereology as a theory of the relation "part-of" does not offer an answer to the question of what it means for some entity to be an *integral whole*. For a commonsense theory of "part–whole", however, the notion of integrity is at least as important as the formal properties of parts. The approach discussed in the following section comes closest to our aims since it is based on properties of parts, wholes and of the possible relations between these two.

2.2. THE APPROACH OF WINSTON, CHAFFIN, AND HERRMANN

Winston *et al.* (1987), henceforth WCH, have proposed an account of the notion of part–whole which is based on a distinction of six types of *meronymic relations*. Instead of focussing on a single relation "part-of" this classification helps to account for the fact that parts might relate to wholes in different ways. The taxonomy proposed by WCH is based on the use of the linguistic term "part of" and its cognates.

In WCH's classification, the class a particular part-whole relation belongs to depends on whether a relation is *functional, homeomerous,* or *separable.* These properties are characterized as follows:

> Functional parts are restricted, by their function, in their spatial or temporal location. For example, the handle of a cup can only be placed in a limited number of positions if it is

to function as a handle. Homeomerous parts are of the same kind of thing as their wholes, for example (slice–pie), while nonhomeomerous parts are different from their wholes, for example, (tree–forest). Separable parts can, in principle, be separated from the whole, for example, (handle–cup), while inseparable parts cannot, for example (steel–bike). (Winston *et al.* 1987, p. 420)

On the basis of these functional properties WCH define six types of meronymic relations as illustrated by the table below. An entry is marked by " + " if the corresponding property is characteristic for the relation at issue and by " – " if it is not.

Of the eight possible combinations of positively or negatively specified criteria, only six are listed. The authors do not explain why +Func, +Hom, +Sep and +Func, +Hom, –Sep do not show up in the list although one might suspect that +Func implies –Hom and +Hom implies –Func, i.e. Func and Hom are not independent. In order to get an idea of what might be wrong with WCH's account we shall draw our attention to the motivations the authors provide for their classification.

Relation	Examples	Func	Hom	Sep
Component/ Integral–Object	handle–cup	+	–	+
Member/Collection	punchline–joke tree–forest	–	–	+
Portion/Mass	card–deck slice–pie	–	+	+
Stuff/Object	grain–salt gin–martini	–	–	–
Feature/Activity	steel–bike paying–shopping	+	–	–
Place/Area	dating–adolescence Everglades–Florida oasis–desert	–	+	–

(Winston *et al.*, 1987, p. 421)

Since separablity is based on the decision whether "parts can/cannot be physically disconnected, in principle, from the whole to which they are connected" (Winston *et al.*, 1987: p. 421) this criterion should be applicable only to those cases where both the part and the whole are physical objects. With the exception of "punchline–joke" this is valid for the examples of the first three types of meronymic relations: COMPONENT/INTEGRAL–OBJECT, MEMBER/COLLECTION and PORTION/MASS. However, there is no reason in principle why a distinction based on the conceptual category of parts and wholes should motivate a distinction of part–whole relations. As we want to abstract from different conceptual categories separability is not regarded as an appropriate criterion for our classification of part–whole relations.

What examples such as "handle–cup" and "punchline–joke" have in common is a certain role the part plays with respect to the whole. This role is typically characterized by some notion of functionality which might pose certain requirements on the spatial and temporal location of the part within the whole. This holds both for relations of type COMPONENT/INTEGRAL–OBJECT and of type

FEATURE/ACTIVITY, rendering the distinction between these types superfluous. Therefore, we subsume the two relations under the class of COMPONENT–COMPLEX (cf. Section 3.1) because they show the same pattern regarding the criterion of functionality.

For a relation to be homeomerous means that "parts are similar/dissimilar to each other and to the whole to which they belong" (Winston *et al.*, 1987; p. 421). According to WCH's classification, relations of the type PLACE/AREA have the property of being homeomerous. However, this is only valid if one takes a very general notion of similarity. After all, "Florida" is a state of the US associated with certain geographical and political characteristics. Nobody would expect "the Everglades" to be similar to Florida under any meaningful measure of similarity. At any rate, "Florida" and the "Everglades" share certain properties according to the aspect of defining a geographical region. The same line of argument holds even more convincingly for "oasis–desert", the second example of the class PLACE/AREA. However, on this level of abstraction even those instances of COMPONENT/INTEGRAL–OBJECT may be considered as homomereous in which the part and the whole are physical objects and thus similar in the sense of both defining some three dimensional region of space. What seems to be characteristic for the examples of type PLACE/AREA is the specific spatial position the part occupies with respect to the whole and some property of the part not available for the whole, such as providing water in the case of "oasis–desert". This line of argument provides evidence for the fact that the examples of PLACE/AREA are not in any important sense different from the examples of type COMPONENT/INTEGRAL–OBJECT which has been conflated with FEATURE/ACTIVITY as argued above.

The remaining types are COMPONENT/INTEGRAL–OBJECT (including the former examples of FEATURE/ACTIVITY and PLACE/AREA), MEMBER/COLLECTION, PORTION/MASS and STUFF/OBJECT. This distinction still has its problems as a consequence of WCH's linguistic test. The problems follow from a misconception of the phenomena, the type STUFF/OBJECT represents, and from the lack of a type of meronymic relation which WCH's classification does not cover (SEGMENTS).

According to the type STUFF/OBJECT the authors refer to a contrast between examples based on the expression "be partly" as in (3)/(4) and examples using the term "made of" as in (5). They do not mention examples of the use of "be partly" as in (6) which obviously do not fit their classification.

(3) A martini is partly alcohol

(4) the bike is partly steel.

(5) the lens is made of glass (*the lens is partly glass)
    (Winston *et al.*, 1987; p. 425)

(6) the bike is partly soiled.

A closer inspection of these examples shows that (3)/(4) are special cases of a use of "be partly" which includes examples like (6). On the other hand, (5) shows that there is a systematic correspondence between WCH's examples (3)/(4), the use of the expression "to be partly ...," and the referencial meaning of the term "part" as in (7).

(7) A part of the bike is (made of) steel.

Obviously, the meanings of (3), (4) and (6) decompose into two propositions. One of these refers to a part–whole relation, the other characterizes a property of the part at issue. Thus, WCH have correctly attested the role of a part–whole relation in these examples. They are, however, wrong in restricting this relation to cases of material constituency.

Another serious problem with WCH's classification is that it altogether refuses to characterize the type of relation underlying examples (8)–(10).

(8) the end of the story
(9) the uppermost half of the apples in the basket
(10) a corner of the table.

Turning our attention to WCH's linguistic test makes clear why the authors do not take into consideration examples as in (8)–(10). The reason is that constructions of this type may not easily be transformed into the form of an expression containing "is part of". The corresponding constructions would be as in (8')–(10') where the part–whole relation does not result from the use of "is part of" but from the genitive construction to the left of "is part of".

(8') the end of the story is part of the story
(9') half of the apples in the basket is part of the apples in the basket
(10') a corner of the table is part of the table.

The meaning of a noun such as "end", "half" or "corner" in a construction of the type represented by (8)–(10) presupposes the existence of a part–whole relation between the individual referred to by the NP embedded in the "of"-PP with the referential meaning of the entire construction. The part–whole relations which are presupposed by the meaning of these nouns can thus never be established by an expression of the type WCH have used in their exploration. It can however be confirmed by an expression of this type as the examples (8')–(10') illustrate. WCH are right in excluding the type of part–whole relations exemplified by (8)–(10) (later called SEGMENTS) since it does not belong to the meaning of "part of" and its cognates. This makes clear that WCH's findings may best be characterized as an empirically based investigation of the meaning of "part" and "partly" but not as an account towards a commonsense theory of part–whole relations.

3. A common-sense theory of part–whole relations

The following considerations depart from a distinction between the above-mentioned generalization of WCH's type STUFF/OBJECT and the type illustrated by (8)–(10) (SEGMENTSs) on the one hand and the three remaining types COMPONENT/INTEGRAL–OBJECT, MEMBER/COLLECTION AND PORTION/MASS on the other. The latter three types share an important communality which WCH's account is totally unaware of, namely the dependence on a certain *point of view* onto the *compositional structure* of the whole. The core idea of our common-sense theory of part–whole relation is a distinction between those part–whole relations that are motivated by the compositional structure of the

whole, and part–whole relations which result from the application of external criteria independent of the compositional structure of the whole.

Since our approach makes use of linguistic examples, even though they are not central as in WCH's account, it is important to emphasize a potential source of confusion caused by disregarding certain aspects of linguistic structure. This may be illustrated by the contrast between the nominal construction in (11)/(12) on the one hand an (11′)/(12′) on the other.

(11) Hundred grams of rice . . .
(12) Two apples . . .
(13) The tail of an ox . . .

(11′) Hundred grams of the rice in the saucepan . . .
(12′) Two of the apples on this table . . .
(13′) The tail of Mephisto . . . (where Mephisto is the name of an ox)

The definite or demonstrative article together with a prepositional specification in (11′)/(12′) and the proper name in (13′) strongly motivate a reading where the referent of the "off"-expression (i.e. the "whole") is considered as an *individual*, i.e. connected and separable from its environment. In these cases the "part" is necessarily indivudated as well.

On the other hand, the expressions "of rice", "apples" and "of an ox" in (11)–(13) refer to a *kind*. Constructions of type (11) which have been called "pseudo-partitive" constructions (Selkirk, 1977) in contrast to "partitive constructions" as exemplified by (11′), do not refer to a part–whole relation but refer to a relation of type INSTANCE/KIND. The same holds for the noun phrase consisting of a numeral together with a plural noun in (12). Example (13), however, refers to a part–whole relation, though at the level of kinds, i.e. of general conceptual knowledge. This matches the observation that the part–whole relation which underlies the meaning of (13) constitutes the semantic core of the corresponding compound "oxtail".

This observation shows that in order for a linguistic example to refer to a part–whole relation it is essential that the expressions referring to the part and to the whole are interpreted as referring either both to individuals or both to kinds. The problematic cases are those in which these modes of reference are mixed up, i.e. one expression refers to a kind and the other to an individual.

3.1. PART-WHOLE RELATIONS INDUCED BY THE COMPOSITIONAL STRUCTURE OF THE WHOLE

Some entity, independent of its categorical status as a physical object, a situation, or an abstract entity, may in general be viewed as having parts by means of a potentially inherent *compositional structure*. Depending on what aspects of this structure one focuses on, different types of part–whole relations are possible. However, in many cases there is a primary or prototypical view.

Without any compositional structure an entity is considered as *homogeneous* like, for example, a certain amount of rice. Taking the single grains of rice into consideration, it may also be viewed as a *collection* having a *uniform* compositional structure. The contrast between mass nouns like "rice" and plurals like "peas"
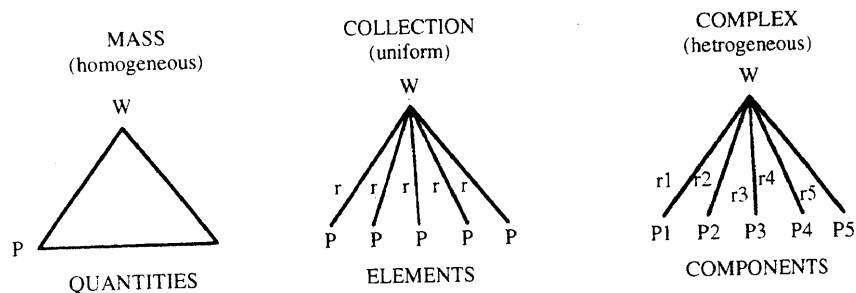
FIGURE 1. The types of wholes induced by compositional structure.

might be considered a linguistic reflex of the fact that in the former case the primary view is that of a homogeneous entity while in the latter case the primary view is that of a collection. If parts are distinguished on the basis of their spatiotemporal arrangement with respect to the whole and/or on the basis of their contribution to some function of the whole (the engine of a car), the entity may be viewed as a *heterogeneously* structured *complex* comprising different sorts of *components*. The three types of wholes induced by compositional structure are illustrated by Figure 1.

It is important to notice that MASS, COLLECTION, and COMPLEX in a sense represent three extreme cases on a scale leading from a total lack of compositional structure to entities with a complex internal organization. As the example of "rice" versus "peas" with respect to the distinction between MASS and COLLECTION shows, the primary view critically depends on the level of granularity which is assumed for classifying an entity. The same holds for the transition between COLLECTION and COMPLEX since configurations such as "a pile of books" are on one hand similar to COLLECTIONS and on the other hand similar to COMPLEXES. This will be discussed in more detail in Section 3.1.2.

The importance of our relativized notion of the distinction between QUANTITY–MASS, ELEMENT–COLLECTION, and COMPONENT–COMPLEX may be illustrated by WCH's example "ship–fleet" which the authors quote as an instance of the type COLLECTION/ELEMENT. This decision, however, depends on the information available about how ships and fleets relate to each other, i.e. about the compositional structure assigned to a fleet. The contribution of this structure depends on the view one takes on the entity referred to by "fleet". The view assumed by WCH obviously concentrates on the aspect of plurality by equating the meaning of the group expression "fleet" with the meaning of the plural expression "ships". A different view, probably more in spirit with the use of the group expression, focuses on a less uniform compositional structure that takes differences between the functions elements perform with respect to the whole into consideration. According to this perspective a fleet is a COMPLEX consisting of various parts of COMPONENTS (ships) with different tasks according to the internal organization of the fleet.

We now turn to a discussion of the three types of wholes in detail. For each type we present three linguistic examples referring to a relation of this type. These examples illustrate the independence of our classification from conceptual categories by referring to "wholes" that belong to the domain of physical objects, situations and abstract entities, respectively.

3.1.1. Masses

An entity classified as MASS is assumed not to have any compositional structure. It may, however, be separated into QUANTITIES by applying a certain kind of quantitative measure. This operation carves out a part of the original mass, the extension of which is specified by the dimension together with the value of the measure. The phrases in (14)–(16) refer to a relation of the type QUANTITY–MASS.

(14) Hundred grams of the rice in the saucepan ...

(15) Five minutes of a soccer game ...

(16) The majority of the votes ...

An important property of masses, due to their lack of compositional structure, is that quantities are in a sense arbitrary pieces of the whole as long as they are properly characterized by the quantitative measure. According to our examples, this means that any part of "the rice in the saucepan" fits the referential meaning of (14) as long as its weight is correctly specified by "hundred grams". Since the use of a measure phrase as in (14)–(15) guarantees that the referent corresponding to the "part" is an individual, the referent of the "of"-construction needs to be an individual too. This excludes pseudo-partitive constructions as exemplified by (11) and examples like "a glass of water" (Winston et al., 1987; p. 424). Even "a glass of this water" may only then be considered as referring to a relation of type QUANTITY–MASS if "glass" is interpreted in a purely quantitative sense as in "?there is a glass of (this) wine spilled all over the table". If the meaning of "glass" contributes some non-quantitative aspect to the meaning of the entire construction, i.e. "a physical object of sort "glass" filled with this wine", the relation of type QUANTITY–MASS is supplemented by the notion of containment.

Instances of QUANTITY-MASS may be represented as a pair (A, B) consisting of a quantitative measure A and some representation B of the entity classified as a whole. The quantitative measure is, again, a pair (D, N) consisting of a dimension D and a numerical value N. The numerical value may, of course, be underspecified as in example (16). An equivalence relation between quantitative measures may be used as a means for inferences based on mappings between different (D, N) pairs, i.e. "thousand grams of rice" equals "one kilogram of rice". Let (DA, NA) be the quantitative measure associated with A and (DB, NB) the quantitative measure associated with B. In this case a linear order $<$ between equivalence classes allows the inference that for a relation of type QUANTITY–MASS to hold between A and B requires (DQ, NQ) $<$ (DM, NM), i.e. "some quantity taken from one kilogram of rice is necessary less than one kilogram". Due to their lack of compositional structure, the primary view on an entity that is part of another entity by means of a relation of type QUANTITY–MASS, is typically again that of a MASS.

3.1.2. Collections

In case an entity is considered as a COLLECTION the compositional structure provides one single relation "part-of" which allows the separation of parts from the whole. These parts are not distinguished according to the way in which they relate

to the whole, although they may be distinguished with respect to each other. The phrases in (17)–(19) refer to a relation of type ELEMENT–COLLECTION.

(17) Two of the three apples in the basket...
(18) One of Mary's three visits to Paris...
(19) One of the "Bundesländer" of the Federal Republic of Germany...

By use of the plural, the three examples suggest that no structure is present in addition to the relation "part-of". This strongly motivates an interpretation of ELEMENT–COLLECTION as the primary type of relation referred to by the entire partitive construction.

Because of the existence of a single type of "part-of" relation between a COLLECTION and its ELEMENTS, the axiomatic system of classical extensional mereology seems to be ideally suited as a means for representing this type of part–whole relation. As should be obvious from the discussion in Section 2.1, the objections which have been put forward to the use of formal mereology as a common-sense theory of *part–whole* relations do not apply to those relations which are restricted to the type ELEMENT–COLLECTION. There is one exception, however, namely the criticism concerning the axiom (SUM). There is still good reason to exclude examples of arbitrary coordination of nominals as in (20).

(20) Boris Becker and Mary's anger about her brother...

What seems to be needed is some notion of an *integral whole* which CEM does not offer. This notion must make explicit the intuition about entities "being compatible" or even "belonging together" such that their (mereological) sum forms an integral whole. Considering entities, the primary view of which is that of a COMPLEX, as COLLECTIONS (in Section 2.1 called the "assembly-view") obviously is in accordance with the criterion of integrity. In addition, referring to the whole with a (morphological) plural as in (17)–(19) seems to make sure that the criterion of integrity is guaranteed.

An ELEMENT of a COLLECTION may be considered as either non-atomic (17) or as atomic (18)/(19) depending on whether its primary view is again that of a COLLECTION or not. Formal mereology is neutral with respect to this distinction, which corresponds to the set-theoretic notions of set-inclusion (non-atomic) versus membership (atomic). This fits the principles of our classification since the decision whether an ELEMENT is atomic or not depends on the view one has on the ELEMENT if it is in turn considered as a whole.

Configurations such as stacks, piles, heaps, etc., come close to COLLECTIONS in that their compositional structure is based on instances of a single relation which, hwoever, allows the unique selection of certain elements with respect to the whole, such as "the top of a stack", "the first/last element of a chain", "the uppermost three books on a heap of books", etc. Obviously, configurations offer additional structure not available in collections. This additional structure, which in the case of stacks, piles, and heaps is based on spatial arrangement, allows certain elements to be distinguished from others. From the point of view of representation, this forces us to classify configurations as generic instances of complexes, since the uniform structure corresponding to the type ELEMENT–COLLECTION prevents configurations from being specific instances of collections.

3.1.3. Complexes

Complexes differ both from masses and from collections in that their compositional structure is based on different relations of the type COMPONENT–COMPLEX. These relations typically depend on the contribution of the part to the function of the whole. In case the entity considered as a complex is a physical object or a situation, this function may presuppose a certain spatiotemporal arrangement between part and whole which might be required in order to support this function. The phrases in (21)–(23) refer to a relation of type COMPONENT–COMPLEX.

(21) The engine of the car...

(22) The plenary session of a conference...

(23) The head of the department...

Relations of type COMPLEX–COMPONENT are typically based on general conceptual knowledge with a varying degree of specificity ranging from highly specific instances as in "the reset button of a computer" to less specific instances such as "the cover of a book, umbrella, tape,...". The least specific instances are generic components such as the configurations we mentioned at the end of the previous subsection. As discussed in Section 3.1.2 in the context of ELEMENT–COLLECTION, components may be atomic or non-atomic depending on whether they reflect some of the compositional structure of the whole. There are two possible ways in which this may happen. If the component is not connected as in "the lights of the car", the primary view on the component considered as a whole is most probably that of a collection. If the component is connected and it corresponds to a non-terminal node of the partonomy, the primary view mòst probably is again that of a complex. In the remaining cases the partition does not provide a primary view and the component must be considered as atomic.

The compositional structure of complexes may be represented by frames or scripts (Abelson, 1981; Schank, 1975; Minsky, 1975). Non-atomic components lead to a nested representation which corresponds to the partonomies used in psychological research (Section 1.1). Figure 2 shows a partonomy representing the different levels of components and subcomponents representing the primary compositional structure of a thermos bottle.

A partonomy obviously is a substructure of the complete Boolean algebra generated by the mereological "part-of" relation. There is, for example, no node combining only the nodes gasket and handle. As the existence of "gaps" shows, the compositional structure of complexes adds restrictions to the symmetric and well-balanced mereological structure underlying ELEMENT–COLLECTION. Though the application of partonomies is usually restricted to material objects, they may also be used to represent the primary compositional structure of situations and artifacts.

3.2. PARTITIONS INDEPENDENT OF THE COMPOSITIONAL STRUCTURE OF THE WHOLE

Parts of type SEGMENT or PORTION are independent of an inherent compositional structure of the entity considered as whole. Since a partition into segments or portions relies on principles other than compositional structure, it is suitable for
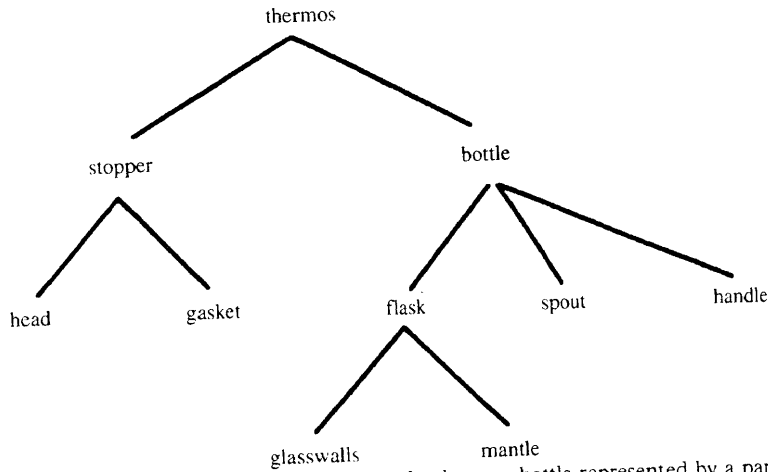
FIGURE 2. The primary compositional structure of a thermos bottle represented by a partonomy.

entities conceptualized as being heterogeneously or uniformly structured as well as for those which are conceptualized as being homogeneous masses. The processing of segments and portions is also independent of any actual or possible conceptualization of the whole. Therefore, in the following, we do not differentiate between different kinds of wholes with respect to their compositional structure. Nevertheless, segments or portions might more or less arbitrarily coincide with results of a structure dependent partition, as we will show below.

At first glance, segments and portions have much in common. Nevertheless, the two variants differ from each other by the extent to which the principles for partitioning are inherent to the whole or external. The construction of SEGMENTS involves primarily external structure, whereas the internal structure of the whole is only used for excluding inappropriate external structures. The construction of PORTIONS relies on internal structure induced by properties of the whole and must be consistent with the—external—structure of the property domain. Therefore, in both cases, one structure (internal or external) is used as the primary principle for partitioning while the other serves as a constraint for the application of the former.

3.2.1. Segments

As stated above, a SEGMENT is a part that results from the application of an *external scheme*. In order to be applicable, it presupposes certain attributes of the internal structure of the whole. For example, the most simple external scheme is the topological scheme of segmenting an entity into exterior/boundary/interior parts. The only requirement on the internal structure of the whole is its one-dimensional boundedness, which is even provided by some masses. One characteristic of segments is that they may have vague boundaries with respect to one or more dimensions. A vague boundary may be contextually or prototypically fixed if the segment coincides with a part induced by the compositional structure of the whole, e.g. the segment (24) of a house typically coincides with the component (24').

(24) the upper part of a house
(24') the roof of a house

Beginning point   Middle point   End point
        BP   BP   BP

●━━━━━━━━━━━━━━━━━━━━━━━━━━●━━━━━━━━━━━━━━━━━━━━━━━━━━━●

├───────)   (─────────────────────────────────)   (──────┤
        B   M   E
Beginning phase   Middle phase   End phase
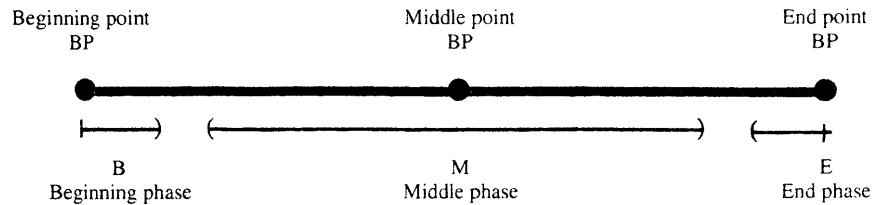
FIGURE 3. One-dimensional scheme.

In general, the external schemes used for a segmentation are spatial. They are only applicable if the whole is a spatial object or can be projected on a spatial entity. Examples for such projections are the time span of situations viewed as a sector on a one dimensional scale or the organization of an institution represented as diagram. Normally, such projections result in some kind of—mental or physical—picture like a drawing or a diagram.

Perhaps the most versatile external structure is the one-dimensional scheme depicted in Figure 3. It provides the segments "beginning" or "starting", "middle", and "end" which can occur as points or as extended phases. The three parts, which occur as points, are referred to in the figure as the "beginning point" BP, the "centre" or "middle point" MP and the "end point" EP. The corresponding phases are the "beginning (phase)" B, the "middle (phase)" M, and the "ending (phase)" E. The middle phase has two vague boundaries. The beginning and the end phase both have one vague and one fixed boundary where the fixed one coincides with the beginning or ending point respectively. Modifications of the discussed scheme are one-dimensional structures which are undirected ("beginning" and "end" are not distinguished) or supplemented with a scale.

The original scheme and its modifications are applicable to every entity which can be conceptualized as or projected onto a one-dimensional entity. It can be used to segment a street, a rope, a queue of people, or, after projection, a story, a cinema play, or even an abstract entity like a career into the parts presented above. Each segment might in principle coincide with a component. For example, the segment described by expression (25) may be identical with the component (25').

(25) the beginning phase of a story
(25') the introduction of a story

In this case, the vague boundary of the segment gets anchored in the strict boundary of the component it coincides with. Possibly, there is a special rule in the domain knowledge that the beginning part of a story typically is identical with the introductory chapter, thus providing a general means for fixing the vague boundary of story beginnings.

Especially interesting for solid physical objects is the three-dimensional scheme of a cube shown in Figure 4(a). The structure of a cube is used to select specific halves,

(a) Upper right corners
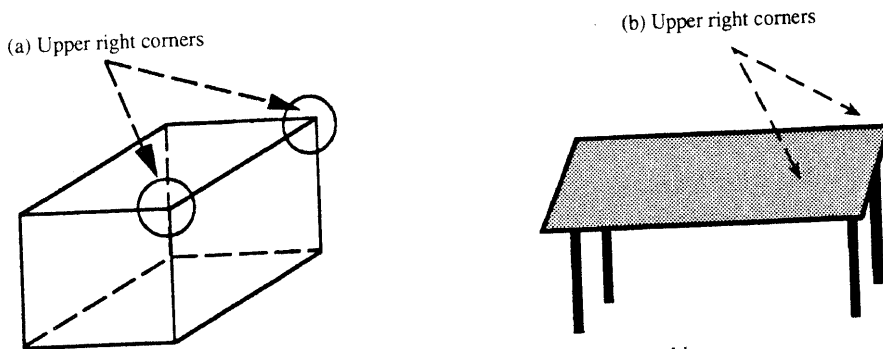
(b) Upper right corners

FIGURE 4. (a) Cube scheme, (b) segments of a table.

sides, edges, etc. of an entity. The object or the spatial projection of the whole must provide a three-dimensional form not too far away from a cube.†

In the following, we propose one alternative for the processing of cube segments. This alternative implements the external scheme of the six-sided cube by procedures. Each procedure computes a different kind of segment, e.g. sides, edges, and so on. The selection of one special side or corner out of the possible extensions of that kind of segment is done by parameters associated with the six directions. For specifying a corner, three parameters are necessary for the vertical and the two horizontal dimensions. (26) shows the procedure "corner" and the possible parameter values.

(26) corner($x1, x2, x3$) $x1 =$ top/bottom, $x2 =$ front/back, $x3 =$ left/right

In order for the segmentation procedures to be applied, a spatial representation, e.g. a diagram, of the whole is needed. An instantiated procedure selects one part of the spatial representation as the required segment. If a parameter is not specified, the procedure computes one segment for every possible instantiation of the underdetermined parater. Figure 4(b) shows the result of the evaluation of the expression (27).

(27) the upper right corners of the table

3.2.2. Portions

A PORTION is constructed by using a *property dimension* to select parts out of the whole, e.g. the dimension of color to select the portion corresponding to the expression (28) or the dimension of valuation for (29).

(28) the red parts of a painting
(29) the annoying parts of the evening television program

The resulting portions are those parts of the whole that provide the requested value

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† The meaning of "not too far away from a cube" needs to be explored, either by psychological experiments or by computer simulations of segmenting objects of irregular shapes.

of the relevant property. This kind of processing is not restricted to a single property dimension. Any combination of properties is possible as example (30) shows.

(30) all people in the population who are female, over fifty, and working in industry

A construction with respect to material properties such as (31) or (32) should not be confused with the STUFF–OBJECT relation of Winston *et al.* (1987) as described in Section 2.2.

(31) the wooden parts of a table
(32) the metal parts of a car

The STUFF–OBJECT relation refers to the material itself and provides metal, chrome, plastic, cloth, or leather, etc. as "parts" of a car. Our PORTION–ENTITY relation selects those parts of a car which are made of one specific material. Here the material is used as a property dimension and not as a part domain.

A PORTION can only be constructed with respect to a certain property if this property is applicable to the whole. For example, using colors for partitioning situations does not make sense. Which properties are adequate for wholes of a certain category belongs to our world knowledge and must be checked prior to the construction of a portion. Even if the property is applicable to the whole under consideration, the construction process can result in an empty portion. This happens if no part of the whole provides the given value, e.g. if one tries to select the red parts of a totally blue picture (Monochrome bleu 1956, Yves Klein).

The construction of portions with respect to a specific property is supported by the *structure of the value domain* of that property. This aspect is especially interesting for domains that are not only sets of discrete values like names, but which provide more internal structure such as orderings (numerical value domains like "age" and "height", or circular domains like colour frequencies) or hierarchies (geometric shapes or colour terms). For example, to evaluate the expressions in (33) or (34) knowledge is needed about which simple colors are subsumed under the color terms referred to.

(33) reddish parts of an object
(34) dark (colored) parts of an object

One property of portions is that they are not necessarily connected, even if the whole is connected. Other parts selected from connected wholes, such as components, quantities, or segments are normally also connected or even convex entities.† However, the portion referred to by expression (28), here repeated as (35), can—but must not necessarily—consist of hundreds of tiny (connected) pieces spread all over the painting.

(35) the red parts of a painting

As shown for segments, it is also possible for a portion to coincide with parts depending on the compositional structure of the whole. For example, the portion

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† However, even if connectedness is the normal case for parts of connected wholes, there are exceptions, such as the lights of a car (the primary view of which is that of a COLLECTION).

described by the expression (36) might in some cases be identical to (36'), which can be viewed as a component of knives.

(36) the wooden parts of a knife
(36') the handle of a knife

A processing mechanism for portions must primarily provide means for handling the value domain of the property under consideration and to determine parts with a certain value. As the different properties involve very different structures of their value domains and different mechanisms for detecting the property values it is not possible to propose one general processing mechanism for portions. For example, color is a visual property that needs a visual perception mechanism to detect different colors and thus provide a basis for selecting parts of a certain color. The value also involves an ordering according to frequency on the finest level of granularity, which builds the basis of a hierarchy of color terms as described above. A visual mechanism for processing the property color must be able to take into account that hierarchy.

4. Conclusion

This paper is concerned with the conceptual part–whole relation, a ubiquitous phenomenon underlying various kinds of cognitive behavior like language processing or vision. As we show in the first section, there are a lot of different views from different disciplines on the part–whole phenomenon. But these views all concentrate on isolated topics. What is missing is a naive or commonsense theory of the mereological domain in the sense of Hayes. Our work is a first step towards such a naive mereology, but until now it is work in progress and does not yet represent final results tested for various tasks.

In this paper, we develop a (language-independent) classification of part–whole relations and give some initial proposals for associated processing mechanisms. Our classification is domain-independent in that it does not differentiate between physical objects, situations or abstract entities making up a whole. Here we adopt the domain-independent view of formal mereology and do not follow Winston et al. (1987) which introduce different relations for physical objects, spatial areas and activities. Our classification subsumes part–whole relations that are induced by the inherent compositional structure of a whole and those that are independent of it. We distinguish three different kinds of wholes with respect to their compositional structure:

- COMPLEXES with a heterogeneous compositional structure of COMPONENTS based on various spatio-temporal and/or functional relations between part and whole,
- COLLECTIONS based on a uniform compositional structure of atomic or non-atomic ELEMENTS all related in the same way to the whole,
- homogeneous MASSES which can be divided into QUANTITIES by external measures.

By looking at the compositional structure of a whole, our approach differs from

formal mereology by not abstracting from the whole and its possible properties.†
Instead it allows for different views on an entity considered as whole with respect to
the compositional structure: a fleet can be viewed as a collection of ships
(ELEMENT–COLLECTION) if there are no distinguished members that play a
specific role with respect to the fleet or as a complex if each ship has a special
function or location with respect to the fleet (COMPONENT–COMPLEX). In
addition to relations depending on compositional structure, there are part–whole
relations that induced by properties (PORTIONS) or by external schemes
(SEGMENTS). These kinds of part–whole relations could not be found in the
classifications of Winston *et al.* (1987) or Iris *et al.* (1988) which restrict themselves
to a linguistic perspective. As our case study on knowledge processing in the
"smashes car" example shows, relations of this type are crucial for a common-sense
theory of part–whole relations.

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† An exception to the ignorance of the whole and its properties is provided by Simons (1987) who focuses on the importance of revealing the notion of an "integral whole".

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