MEDINFO 2004
M. Fieschi et al. (Eds)
Amsterdam: IOS Press


# On Parts and Holes: The Spatial Structure of the Human Body

**Maureen Donnelly**

*Institute for Formal Ontology and Medical Information Science, University of Leipzig, Germany*

**Abstract**

*Spatial representation and reasoning is a central component of medical informatics. The spatial concepts most often used in medicine are not the quantitative, point-based concepts of classical geometry, but rather qualitative relations among extended objects such as body parts. A mereotopology is a formal theory of qualitative spatial relations, such as parthood and connection. This paper considers how an extension of mereotopology which includes also location relations can be used to represent and reason about the spatial structure of the human body.*

***Keywords:***

Ontology, Knowledge Representation, Anatomy, Mereotopology.

## Introduction

A patient has an infection in the wall of his small intestine. His doctors need to monitor the progress of this infection to determine whether it spreads to (and interferes with the functioning of) nearby parts of the body. These parts may include material parts, such as the liver and kidneys, as well as body cavities and passageways such as the peritoneal cavity or the interior of the digestive tract. In addition, his doctors may look for a cause of the infection in the vicinity of the small intestines. The cause of the infection is likely to be some *foreign occupant* of the body (i.e. an object that is located in the body, but not a part of the body), such as bacteria or some other parasite.

This kind of reasoning about the spatial arrangement of organs, cavities, parasites and other inhabitants of the body is a commonplace, but crucial, component of medicine. It involves reasoning about parthood relations (that the infected cells are part of the wall of the small intestine), connection relations (that the wall of the intestine is connected to the interior of the digestive tract), and location relations (that a parasite is located in the digestive tract). Notice that such spatial reasoning does not involve quantitative information, for example distance or angular measures. Rather it is qualitative reasoning of the sort that has been modeled successfully in recent years by [1, 2, 3, 4]. This type of reasoning can be handled automatically by a computer only if the computer is able to draw inferences about parthood, connection, and location, and for this a formal theory is required.

A *mereology* is a formal theory of parthood and of relations--such as overlap (having a common part) and discreteness (having no common part)--defined in terms of parthood. A *mereotopology* is an extension of mereology that includes also topological relations, such as connection, interior, and boundary. Mereotopology treats these relations in abstraction from information about size, shape, and distance. Since it allows us to define topological relations in terms of parthood relations among qualitatively determined individuals, meretopology is a natural basis for spatial reasoning in medicine.

Existing work in mereotopology is restricted, however, by the fact that, for reasons of formal simplicity, it abstracts away from the individual objects (such as cells and molecules, bodies and body parts) and deals instead only with mereotopological relations between the spatial regions which these individuals occupy. This is not a harmless simplification. It means that we are prevented from dealing with those sorts of cases where objects have no parts in common even though their spatial regions overlap. Such cases are common in medicine. Consider again the relation between a parasite and the intestinal lumen in which it lives. Or consider (to take a spatio-temporal example) the relationship between those processes which constitute a disease and those associated processes which constitute the therapy applied to treat the disease. Here two processes overlap in their spatio-temporal locations, yet they share no common parts.

In [5], I present a mereotopology that is strong enough to comprehend the relations among objects whose spatial positions overlap even though the objects themselves have no parts in common. The purpose of this paper is to discuss the use of these relations in medical informatics as a basis for representing and reasoning about the spatial structures of the human body and of foreign occupants of the body such as parasites or medical implants.

## Mereotopological and Location Relations

Several different mereotopologies have been proposed in recent literature, for example [1, 2, 3, 4]. Mereotopologies have been extended to include also location relations [4, 5]. In this paper, I will not discuss the subtle differences in the parthood, connection, and location relations presented in these theories but will focus rather on the more general question of how these kinds of relations can be used to represent the spatial structure of the human body. In this section, I give a brief introduction to some important mereotopological and location relations.

**Mereotopological Relations**

**Parthood** (symbolized as "P") is the relation that holds between two objects, x and y, whenever x is part of y. In mereotopologies presented in [3, 4, 5, 6], parthood is treated as a primitive relation. This means that, instead of being defined, axioms fixing the logical properties of the parthood relaton are built into the theory. The parthood relation must be interpreted in applications in a way that conforms to these axioms. Rules for parthood that are included in nearly every mereotopology are:

(P1) Pxx (every object is part of itself)

(P2) Pxy & Pyx → x = y (if x is part of σy and y is part of x, then x and y are identical)

(P3) Pxy & Pyz → Pxz (if x is part of y and y is part of z, then x is part of z)

Most mereotopologies include additional axioms which further restrict the parthood relation [7]. These additional axioms are somewhat controversial and go beyond the scope of this paper.

Important additional relations can be defined in terms of parthood.

**Proper Parthood:** x is a *proper part* of y, if x is any part of y other than y itself. Symbolically: PPxy =: Pxy & x ≠ y. For example, my hand is a proper part of my body. My body is a part of itself, but it is not a proper part of itself.

**Overlap:** x and y *overlap*, if there is some object, z, that is part of both x and y. Symbolically: Oxy =: ∃z (Pzx & Pzy). My pelvis and my vertebral column overlap: my sacrum and my coccyx are part of both. Notice that, because parthood is reflexive, any part of an object overlaps that object: the part is a common part of both objects. Thus, my hand and my body overlap: my hand is part of both itself and my body.

**Connection** (symbolized as "C") is the relation that holds between two objects when they touch. For example, my head is connected to my neck. Connection is typically treated as a primitive relation. The following axioms for the connection relation are included in nearly every mereotopology.

(C1) Cxx (everything is connected to itself)

(C2) Cxy → Cyx (if x is connected to y, then y is connected to x)

(C3) Pxy → ∀z(Czx → Czy) (if x is part of y, everything connected to x is connected to y)

As with parthood, additional axioms for the connection relation are usually included in a mereotopology. See, for example, [4] for a survey of different ways of axiomatizing connection.

Several useful relations can be defined using parthood, overlap, and connection:

**External Connection:** x and y are *externally connected* if they are connected, but do not overlap. Symbolically: ECxy =: Cxy & ~Oxy. My head and my neck are externally connected. My torso and my body are connected but not externally connected.

**Tangential Parthood:** x is a *tangential part* of y if x is a part of y that is connected to y's exterior. Symbolically: TPxy =: Pxy & ∃z(Czx & ~Ozy). My hand is a tangential part of my body: it is connected to the portion of space surrounding my body.

**Interior Parthood:** x is an *interior part* of y if x is a part of y that is not connected to y's exterior (i.e. x is a part of y, but not a tangential part of y). Symbolically: IPxy =: Pxy & ~TPxy. For example, my heart is an interior part of my body.

**Location Relations**

A mereotopology can be further extended to include location relations. We can already say something about the relative location of objects using parthood and connection: If x is a part of y, then x is located in y in the sense that x's spatial region is part of y's spatial region. If x and y are connected, then the objects' spatial regions are connected. The location relations enable us to describe the relative location of objects that may coincide wholly or partially without overlapping. For instance, a parasite in the interior of a person's intestines is located in the intestinal lumen, but it is not part of the intestinal lumen. Nor does the parasite have any parts in common with (i.e. overlap) the intestinal lumen.

In both [4] and [5], location relations are defined in terms of each object's relation to the unique spatial region at which it is exactly located at a given time. (To simplify the presentation, I abstract here from the temporal dimension.) In [5] this is done by introducing a primitive function, r, which maps every object to its unique spatial region. Axioms for this function include the following.

(R1) ∀x∃y(y = r(x)) (every object is located at some region)

(R2) Pxy → Pr(x)r(y) (if x is part of y, then x's region is part of y's region)

Two important location relations are then defined as follows:

**Partial Coincidence:** x and y *partially coincide* if x's region overlaps y's region. Symbolically: PCoin(x, y) =: O(r(x), r(y)). For example, a portion of food that is beginning to enter the stomach cavity partially coincides with the stomach cavity. Some (but perhaps not all) of the food is located in the stomach cavity. Notice, however, that the food and the stomach cavity do not themselves overlap -- only their spatial regions overlap.

**Located-In:** x is *located- in* y if x's region is part of y's region. Symbolically: Loc-In(x, y) =: P(r(x), r(y)). For example, a bullet inside a patient's body is located-in (but not part of) the patient's body. Notice that the located-in relation does not correspond exactly to the English expression 'is in'. We would say that the bullet *is in* the patient's body. But we would also say that a portion of water *is in* a glass even though the water's spatial region is not part of the spatial region of the glass. (The corresponding spatial regions do not even overlap.) The water is merely contained by the glass. It is located-in the interior of the glass (i.e. the hole determined by the glass which enables the glass to contain liquids) but not located-in the glass itself. For clarity, I will always use the hyphenated expression, 'located-in' to refer to the relation defined in the formal theory.

Theorems stating important properties of the defined relations can be derived from the axioms. For example, we can derive the following theorems concerning the located-in relation.

(Theorem 1) If x is located-in y and y is located-in z, then x is located-in z.

(Theorem 2) If x is part of y and y is located-in z, then x is located-in z.

(Theorem 3) If x is located-in y and y is part of z, then x is located-in z.

## Parts of the Human Body

The relations presented in the previous section can now be used to describe the spatial arrangement of parts of the human body. Examples of body parts include organs (heart, kidney), limbs (arms, legs), and portions of bodily tissue. These parts are all on a mesoscopic granularity level: they can be identified without the use of a microscope or other instrument. A body system (the circulatory system) is a somewhat more complicated mesoscopic body part which has organs and tissues as proper parts. Examples of microscopic body parts are cells and (at an even finer granularity level) the molecules (DNA, RNA, proteins) of which the cells are composed.

It is an important and somewhat more controversial assumption of this work that the body also includes immaterial parts, such as cavities and passageways. Body cavities include both bona fide cavities (i.e. cavities with complete material boundaries) such as the peritoneal cavity and fiat cavities (i.e. cavities whose boundary is partly fixed by medical convention) such as the chest cavity and the abdominal cavity. (For more on the distinction between fiat and bona fide objects, see [8, 9].) Body passageways are, for example, the interiors of blood vessels.

All of these immaterial parts can be considered holes in the sense of [10]. My treatment of holes differs from that of e.g. [2, 11] in the assumption that at least some holes in the body are parts of the body. [2, 11] treat holes as spatial regions exterior to the material objects, such as human bodies, which are their hosts. This approach is not appropriate for body cavities and passageways because it requires that, whenever a body moves from one spatial region to another, it loses its old cavities and passageways and acquires new ones. On the approach defended here, body cavities and passageways move through space with the body and retain their identity throughout the life of the body or the body part in they are lodged. This is important for medical informatics. For example, it would severely complicate procedures for tracking information on diseases affecting body cavities if these cavities were treated, not as enduring body parts, but as portions of space external to the body which function as body cavities only at random times.

Another advantage of my approach is that it allows us to represent foreign objects such as parasites or bullets as located-in the body. We will say that an object is *completely material* if has no immaterial parts (i.e. no holes as parts). It is an assumption of the approach of [2, 11] that physical objects are completely material. Distinct completely material objects cannot occupy the same spatial region at the same time. Thus, if bodies are completely material, objects such as parasites may be surrounded by the body, but they will always be exterior to the body. If, on the other hand, cavities and passageways are admitted as parts of the body, then a foreign object that is housed in one of these immaterial body parts can be seen as being located-in the body. See [12] for a similar treatment of immaterial body parts.

Finally, note that proper parts of the body may have as parts holes of their own. For example, the heart has cavities as parts: the ventricles and the atriums. On a lower level of granularity, the interiors of mitochondria are cavities which are parts of cells. It follows from the transitivity of parthood (axiom P3) that these holes are also parts of the body.

We will now consider how the relations of section 2 can be used for representing and reasoning about the spatial structure of body parts. The parthood relation allows us to describe inclusion orderings among body parts. For example, we may say that a given clump of tissue is part of the left gyrus frontalis medius, which, in turn, is part of the brain, which is part of the nervous system, which is part of the body. The ordering may be extended to lower levels of granularity to include cells or molecules that are parts of the clump of tissue. We can also add additional middle terms such as the left hemisphere of the brain Parthood orderings are important for formalizing anatomical knowledge as in the Foundational Model of Anatomy [13]. This anatomical knowledge can then be used, for example, in automated reasoning about parts of the body affected by disease and other irregularities. For example, if the clump of brain tissue is damaged, then we can infer that the gyrus frontalis medius and, more generally, the brain and nervous system are damaged.

Body systems may overlap. For example, in males, the urinary system and the reproductive system overlap -- the urethra is a part of both systems. Knowledge about overlapping systems is useful in monitoring diseases -- a disruption in the function of one system may be tied to a disruption in the function of an overlapping system.

Parthood relations alone do not tell us which parts of the body are next to one another. The stomach and the small intestine are connected but they have no parts in common. The capacity to represent connection relations is important for reasoning about the spread of substances (bacteria, nutrients, drugs, etc) throughout the body. Substances in one part of the body, say the liver, can spread *directly* only into body parts that are connected to the liver. If, for example, the proteins synthesized in the liver find their way into muscles in the legs, then they must have passed through intermediary body parts, for example, blood vessels leading from the liver to the legs, on their way to these muscles.

In some contexts, it may be useful to distinguish between interior and tangential parts of the body or between interior and tangential parts of a given organ. For example, a tumor on the exterior of an organ or, especially, on the exterior of the body is easier to examine and remove than a tumor in the interior of an organ.

Finally, the location relations can be used to locate material and immaterial body parts within body cavities. The heart, lungs, trachea, and pericardial cavity are located-in the chest cavity. The small intestines, liver, and kidneys are located-in the abdominal cavity. Body parts that run through the middle of the torso, for example the esophagus and the aorta, partially coincide with both the chest cavity and the abdominal cavity. Notice that in all of these cases the stronger mereological relations, parthood and overlap, do not hold. The heart is not part of the chest cavity. No part of the aorta is also part of either the chest cavity or the abdominal cavity. Thus, the location relations are an important addition to our vocabulary for describing the spatial layout of the body. The interior of the body can be divided into smaller fiat cavities in which body parts can be more precisely located. For example, the abdominal cavity can be divided into the subcostal, umbilical, and hypogastric zones. This array of more precise locations is useful for pinpointing the source of a disease or the site of an abnormality (e.g. a tumor) in the body.

## Foreign Occupants of the Body

The location relations can be used, not only to describe the location of body parts within the body, but also to describe the location of foreign occupants in the body, i.e. of objects that are located-in but not part of the body. A foreign occupant of the body is always located-in some immaterial body part, since it cannot share the same space with a completely material body part. For example, a myocardial parasite (a worm that inhabits the heart muscle) cannot occupy the exact same spatial region as any portion of the heart tissue. Rather, the worm is located-in a hole in the heart tissue that the worm itself has created. More generally, as was pointed out in section 2, foreign occupants can be located-in the body only if the body contains some immaterial parts.

It follows from Theorem 1of section 2 that, if the worm is located-in the heart, the worm is also located-in any part of the body in which the heart is located. Thus, given the relatively specific information: there is a worm in patient x's heart, a computer programmed to handle mereotopological and location relations can deduce that there is a worm in patient x's chest cavity (or in patient x's torso or in patient x's body). Moving in the opposite direction, we can more precisely pinpoint the location of the worm in the heart by specifying proper parts of the heart in which the worm is located. For example: the worm is located-in the myocardium. Or, we can say which body parts worm in connected to. For example: the worm is connected to the aorta.

We might wonder what exactly are the foreign occupants of a given body. Some objects located-in the body are parts of the body which have been constructed by the body itself. I will call these *innate* occupants of the body. The heart, brain, arms, and legs are innate occupants: they were constructed by the body in its embryonic stage and are continually developing with the support of body processes. Other innate body occupants, for example red blood cells, are continually being created by the body. Some objects located-in the body were not constructed by the body itself. We will call these *acquired* occupants of the body. Examples of acquired occupants include parasites, bacteria, viruses, bullets, surgical implants (breast implants, artificial valves, pacemakers, transplanted organs), drugs, and digested food (sugar or protein molecules). All of the smallest parts of the body, the sub-atomic particles of which the molecules in the body are composed, are also acquired occupants. Acquired occupants may be organic (bacteria, parasites, transplanted organs) or inorganic (bullets, breast implants). Some acquired occupants contribute to the functioning of the body (artificial valve) and others either do nothing or interfere with the functioning of the body (bullet, viruses, breast implants). Some entered the body with the permission of the owner of the body (surgical implants, digested food) and others did not (viruses, bullets).

Clearly, some acquired occupants, for example, a worm or a bullet, are not parts of the body, but are merely located-in the body. In other words, they are foreign occupants of the body. But other acquired occupants seem to become parts of the body, either immediately upon entering the body or at some later point during their stay in the body. For example, we might hold that food molecules become parts of the body either when they are first absorbed into the body or when they take on a functional role in the body, e.g. as a component of a cell. We might wonder whether other acquired occupants, for example an artificial valve, should be considered in some sense parts of the body when they take on functional roles in the body. But note that a virus may also take on a functional role in cells, directing the cell to construct certain proteins that the virus needs for reproduction. Should we then say that a virus is at this point a part of the body? Perhaps not, because the direction given by the virus to the cell interferes with the proper functioning of the body.

These questions lead us beyond the scope of this paper. For now, I merely suggest that an account of the distinction between body parts and foreign occupants will depend in a complicated way upon the kinds of considerations (innate or acquired? organic or inorganic? functional or non-functional?) raised above. Moreover, these considerations are important in their own right. A new acquired occupant of the body may elicit an allergic reaction in the body. Damage to a functional occupant (whether innate or acquired) may require medical intervention. The formal theory of mereotopology and location can be supplemented with additional terminology for describing these distinctions among body occupants. The predicates *Innate*, *Organic*, and *Functional* can be introduced along with axioms governing their behavior with respect to the mereotopological and location relations. For example: If x is *Functional* and x is part of y, then y is *Functional*. Information about the location of different types of occupants in the body can be used in automated reasoning. For example, suppose patient X has an infection is his peritoneal cavity and there is a record that patient X has an implanted prosthesis of the abdominal part of the aorta. A computer can automatically infer that there is an acquired occupant in patient x's retroperitoneal space and report this information so the retroperitoneal space can be checked as a possible source of infection.

## Conclusion and Related Work

Throughout this paper, I have given simple examples of how the various mereotopological and location relations can be used for automated reasoning about the body. Human beings perform such reasoning without thinking about it, but computers need to call upon the resources of a formal theory. Support from automated reasoning systems will be crucial where researchers must keep track of and utilize information about hundreds of patients. For example, researchers experimenting with new treatments for cancer could use computers to keep track of and reason about the location the cancer in the patients' bodies. Data about the location of other abnormalities can be added and used to better evaluate the effectiveness of given treatments.

Other work which investigates the use of mereotopological and location relations in medical and bio informatics includes [11, 12]. Unlike [11] the approach of this paper is to represent the human body as having immaterial parts in which foreign occupants, such as bullets or parasites, may be located. Unlike [12], I do not require that *all* holes formed by an object are part of that object. Thus, in my treatment, as opposed to that of [12], the cranial cavity is not a part of the skull just as the interior of a glass is not part of the glass.

**Acknowledgments**

I am grateful for the helpful comments of Barry Smith, Igor Papakin, and Mariana Casella dos Santos. This work was supported by the Alexander von Humbolt Foundation under the auspices of its Wolfgang Paul Program.

## References

[1] Asher N, and Vieu L. Towards a geometry of commonsense: a semantics and a complete axiomatization of mereotopology. In: *Proceedings of IJCAI'95*; San Francisco (CA): Morgan Kaufmann; 1995. 846-852.

[2] Cohn AG, Bennett B, Gooday J, and Gotts N. Qualitative spatial representation and reasoning with the region connection calculus. *Geoinformatica* 1997; 1: 1-44.

[3] Smith B. Mereotopology: a theory of parts and boundaries. *Data & Knowledge Engineering* 1996; 20: 287-303.

[4] Casati R, and Varzi AC. *Parts and places: the structures of spatial representation*. Cambridge (MA): MIT Press; 1999.

[5] Donnelly M. Layered mereotopology. In: *Proceedings of IJCAI'03* San Francisco (CA): Morgan Kaufmann; 2003. 1268-1274.

[6] Smith B, and Rosse C. The Role of Foundational Relations in the Alignment of Biomedical Ontologies. *Proceedings of Medinfo2004*.

[7] Simons P. *Parts, a study in ontology*. Oxford: Oxford University Press; 1987.

[8] Smith B. Fiat objects. *Topoi* 2001; 20:131–148.

[9] Smith B and Varzi AC. Fiat and bona fide boundaries. *Philosophy and Phenomenological Research* 2000; 60: 401–420.

[10]Casati R and Varzi AC. *Holes and other superficialities*. Cambridge (MA): MIT Press; 1994.

[11]Cohn AG. Formalizing bio-spatial knowledge. In: *Proceedings of FOIS´01*; New York: ACM Press; 2001. 198-209.

[12]Schulz S and Hahn U. Mereotopological reasoning about parts and (w)holes in bio-ontologies. In: *Proceedings of FOIS´01*; New York: ACM Press; 2001. 210-221.

[13][13]Rosse C, and Mejino JLV. A Reference Ontology for Bioinformatics: The Foundational Model of Anatomy. *Journal of Biomedical Informatics* 2004.

**Address for correspondence**

Maureen Donnelly, IFOMIS, HärtelStr aße 16-18, 04107 Leipzig Germany. email: maureen.donnelly@ifomis.uni-leipzig.de