Bones, Holes, and Scales – on the Need for a Spatial Ontology for Anatomy

Rainer Schubert

Institute of Mathematics and Computer Science in Medicine, University Hospital Eppendorf, Hamburg, Germany

schubert@uke.uni-hamburg.de

Abstract

Objectives

This paper focusses on the special demands on those computer-based anatomical models, which are suited for visualization, navigation and simulation, e.g. for surgical simulation or computer aided image analysis. These demands go beyond those imposed by existing approaches used in documentation and information systems. Analysis of this situation shows that anatomy has to be considered in a more general and autonomous way to obtain operationally viable spatial models.

Concept

Based on a survey of characteristic features and entities studied by anatomy, essential elements and requirements of a suitable ontology of spatial anatomy are set forth. The domain of anatomy is structured by multiple orthogonal and overlapping partitions of different motivation, scale and granularity. Different types of spatial objects have to be considered and the consideration of their topological relations is then essential. Existing anatomical and medical terminologies are not well-suited from this strictly spatial point of view, but their constituent terms and concepts can be mapped to spatial objects or locations for communication purposes.

Results

An ontology is outlined and partly formalized. It supplies mechanism oriented towards common sense for representing multiple partitions - a classification of physical spatial objects - and it shows the possibilities for integrating existing methods for classifying non-physical objects such as holes and boundaries, mereotopological calculi and a suitable handling of terminologies.

Conclusions

The proposed ontology at first considers anatomy from a strict spatial point of view. It provides comprehensive structures and mechanisms which can help in the construction of concrete models for 3d-applications. Besides including the typical characteristics of the anatomical domain needed for any 3d-navigation or spatial reasoning, it can also easily be extended, without changing the basic concepts, to additional needs for instance by clinical or functional partitions. Future work has to concentrate on formalizing the whole ontology and to proving its suitability for concrete implementation and application.

Introduction

Anatomy is not only one of the oldest disciplines in medicine, it is also still the backbone of any medical process. From this it follows that some kind of a formal representation of anatomy is a prerequisite of a wide range of applications in medical informatics too. This range of applications can be divided into two groups, according to the different ways anatomy is used.

The first group contains applications such as clinical documentation- and information-systems, electronic patient records, databases of different kind, e.g. genomic, cancer, epidemiologic, biometric, and so on. In these applications anatomy is not within the primary view of the represented domain. Anatomical terms are used to identify the location of the primary domain entities such as symptoms, findings, or deseases. This use of anatomical terms is then analogous to the use of street addresses in databases of persons or institutions. Addresses in such systems are links to the location of the entity of interest, but no geographical model or digital map is integrated within the system itself. Therefore addresses as well as anatomical terms are implicit links which need to be resolved via additional resources: a mental image in someone's brain, an atlas, a map etc. This mechanism can be successful only if the terms are unambiguous, which means that New York must be New York on any map, just as the right femur must be the right femur in all domain-related sources. Consequently, standardised anatomical terminology is a mandatory but also nearly the only requirement for this first group of applications.

A completely different situation appears whenever an anatomical model is to be used not only for localisation purposes, but also for purposes of navigation, simulation, and identification. This is true for applications like CAS, CAR, or as a prerequisite for computer-based interpretation and segmentation of medical images. Such models have to include more infomation than a standardised naming of anatomical objects. At least, information about the geometry/shape of a single object and knowledge about the structural relations between objects is required. For most applications additional knowledge about topology, function and modes of dynamic change is needed. Up to now, two general approaches have been advanced to fulfill these requirements:

1. Extended terminologies. Standardized anatomical terminologies are extended by semantic relations to model structural, mainly part-whole knowledge.
2. Formal Ontologies. An abstract formal description of the relevant classes, relations, functions, and properties of the anatomical domain supplies a general frame to derive a consistent theory and modeling scheme in which terminology is one property among others.

Based on a qualitative survey of the entities and properties studied by the discipline of anatomy, we will discuss both approaches. We will argue that the first approach cannot succeed. Our preference for the second approach will be motivated and advocated by analysis of current contributions to common-sense ontologies in philosophy and computer science which supply some (but not all) essential elements required for a powerful modeling scheme in anatomy. Finally, a concept for such a formal anatomical ontology will be outlined and its benefits as well as remaining problems will be discussed. The paper is restricted to problems of modeling static 3d-anatomy – complex dynamics like growth, motor behavior, or pathologies are not focussed upon, but will be discussed in an outline of future work.

Entities and characteristics of the anatomical domain

Since anatomy describes the human body - that part of the world which hosts our sensorium and determines the range of our common experiences - it is not surprising that multiple parallels between anatomy and the study of the wider common-sense domain can be found. This is especially true for two typical characteristics:

1. Anatomy is a mesoscopic domain. It focusses on the description of objects within a scale between micrometers to meters. It is divided into three typical ranges of magnitude (macroscopy, histology, cytology), each historically associated with a certain instrument of investigation: eyes, magnifying glass, and microscope. Therefore, and in contrast to other typical natural sciences, extreme microscopic (e.g. quantum physics) and macroscopic (e.g. cosmology) objects and effects do not play a role.
2. Anatomy describes a „normal“ world in the sense of describing prototypes of structures first and only then, in a second step, outlining typical variations from this prototype. Although it is very improbable that we would find exact prototypes in reality, anatomy nonetheless *describes* reality by appeal to the notion of correspondences to or differences from these prototypes. Up to now, there is no formalism allowing us to predict one individual anatomy.

Therefore modeling 3d-anatomy first has to take into account our common-sense world of visible, touchable, and spatially organized objects. With the exception of touchability, this is even true for microscopic anatomy.

Partitions

Parts and Wholes

The anatomist's usual procedure is to imagine the human body as being divided into parts. In general, two types of parts can be distinguished: Genuine parts, like the femur as a part of my leg, and abstracted parts, like the shaft of my femur. These two categories of objects are explained by the theory of *bona fide* (genuine) and *fiat* (thought) objects [1, 2]. The kind of an object depends on its boundaries. In the first case the femur has only bona fide boundaries defined by a substantial change of material (joints, periosteum). Parts of the second sort at least have one fiat boundary, which is to say a boundary not determined by a substantial change (although it may correspond to material landmarks). From a geometrical point of view, 3d-applications do not need to consider these differences. But for any kind of semantic interaction like navigation or spatial reasoning, the distinction of bona fide and fiat objects and boundaries is mandatory - crossing a bona fide boundary means to exit a substance, whereas crossing a fiat boundary means to enter another section of the same substance.

Figure 1 illustrates the process of anatomical division by means of the example of the cerebral cortex. It shows that there are different ways to divide the cortex which are orthogonal to each other and which result in parts that are not congruent. Obviously, all these parts involve the same real underlying matter. Their motivations differ (e.g. functional, morphological, scale or granularity of concern) and due to their practical usefulness they are all allowable and true. They can be considered as different interpretations of spatial reality resulting in a suitable „partition" for the point of view in question. From an abstract standpoint, they are all equivalent to each other – for a concrete application one of them might be more useful t han the other, e.g. when talking about brain morphology, partition a in figure 1 will be more suitable than b.
Although the complexity of the cerebral cortex implies more partitions than other parts of the body, this principle of multiple partitions can be found all over anatomy.

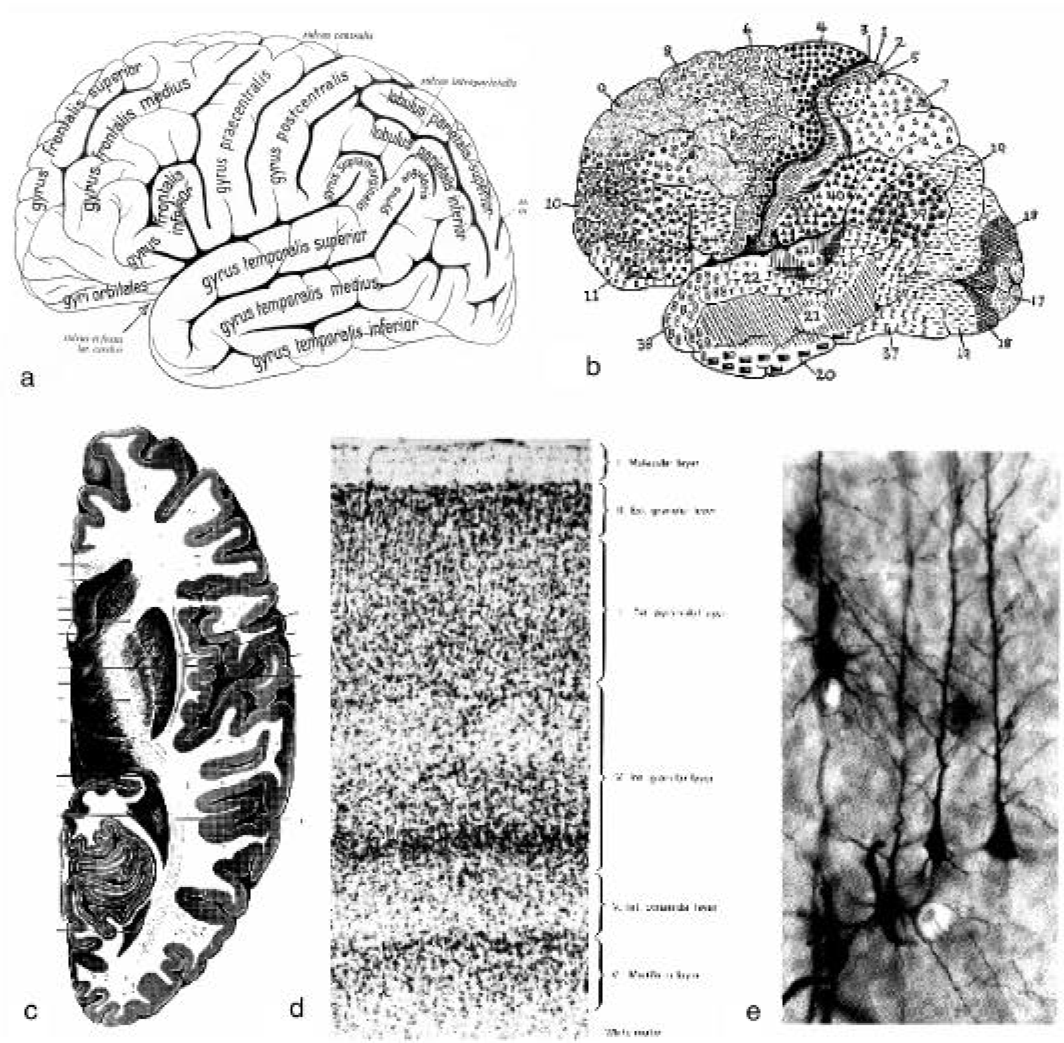


Figure 1: Different motivated partitions of the cerebral cortex: a) Gyri and sulci (morphological), b) Brodmann areas (cytoarchitecture, functional), c) White and grey matter (histological) d) Layers of the grey matter (cellular), e) Cell distribution (pyramid cells) in one layer (images a and c from Sobotta, J.: Atlas des Menschen, editors: Ferner, H., Staubesand, J., Urban und Schwarzenberg, München, 1982).

The example of the cerebral cortex might suggest that anatomical partitions are always complete in a sense that from a spatial view, the sum of the resulting parts constitute the complete whole. As figure 2 shows, this is not true for many anatomical partitions. It is a common and frequently occuring situation that an anatomical object is incompletely divided into further details. Some amount of the object remains and cannot be identified by it's own name – there is no terminological equivalent for it.

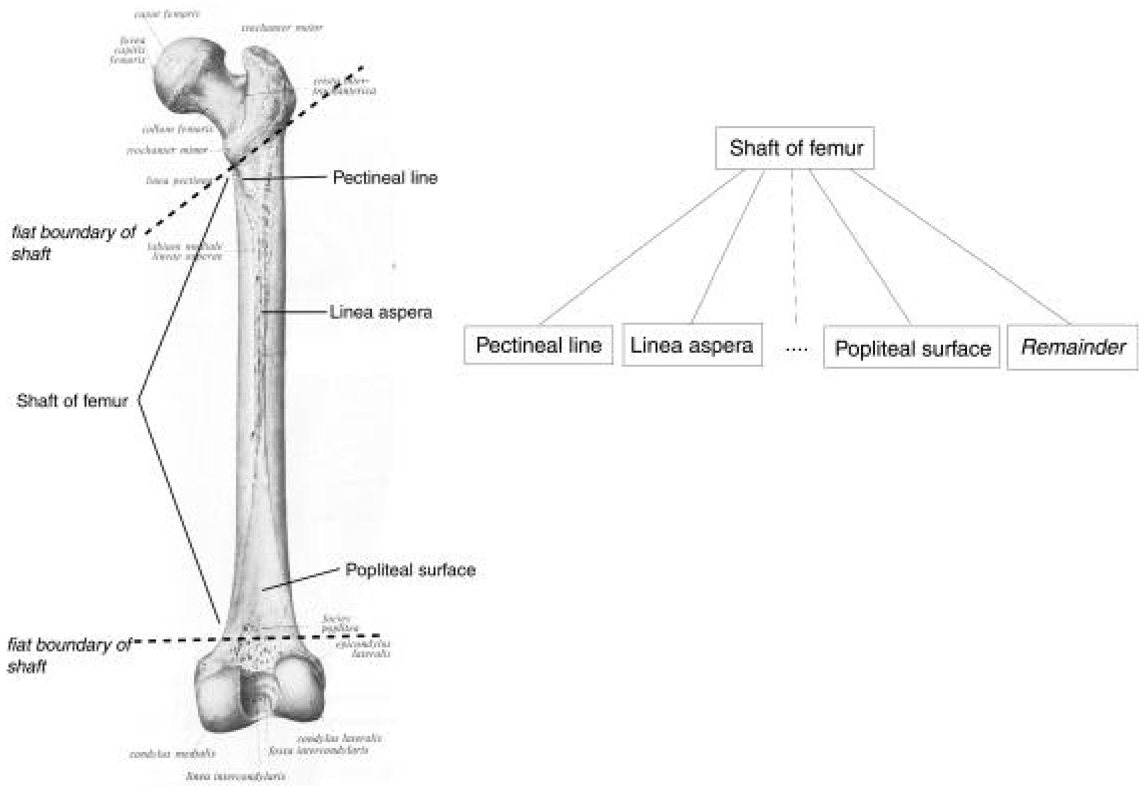


Figure 2: Example of spatial remainder in certain partitions. The shaft of the femur is divided into different details (left). The remaining mass of the shaft is not denoted in anatomical terminology (right, according to *Terminologia Anatomica* [19], image of femur from Sobotta, J.: Atlas des Menschen, editors: Ferner, H., Staubesand, J., Urban und Schwarzenberg, München, 1982).

Another typical aspect of anatomical partitions is their diverse granularity. Within a similar motivation, granularity is changing as we move from one abstraction or one scale to another. An indivisible object of one partition can be further divided in another partition. Cascading partitions of different abstractions will lead to generic hierarchies, e.g. a classification of tissues. Cascading partitions of different scale will result in mereological hierarchies, e.g. describing the preceding division of the cortex from macroscopic hemispheres to microscopic cells. Thereby some partitions lie between the scales. For instance the macroscopic division of the cerebral cortex into grey and white matter results from a microscopic effect (distribution of nuclei, forming grey matter, and of axons, forming white matter). Simultaneously this partition represents a strong degree of abstraction since it reduces granularity from 10 billions of neurons to the two objects of grey and white matter.

Topology

Using anatomical knowledge usually means to focus on one specific partition but having the surrounding cascade in mind, prepared to move through it if necessary. The relations between objects of different partitions carries important spatial knowledge. If a partition is complete, we have the simple classical case of GEM [1]: The sum of the objects of this partition constitutes a whole, well-defined anatomical object. Otherwise the relation is more complex and uncertain. The object may be a proper part of the whole, or it may merely overlap the whole (so that it shares parts in common therewith). This is true also for its relations to objects of other partitions of the same whole or even other wholes. It is obvious that these situations, together with other relations of spatial neighborhood, have to be explicitly modeled by topological relations. The indivisibility of mereology and topology was described before and resulted in mereological topologies [3-9].

[1] GEM: General Extentional Mereology [16, 17]

Nature of anatomical Objects

Types of objects

We already mentioned the elementary distinction between bona fide and fiat objects. Since the motivation and the scale of our partitions differ and therefore result in different kinds of objects becoming visible, these two categories can be further typified. For 3d-applications it is initially spatial objects which are of interest – non-spatial entities like processes or situations are not considered at this stage.
Orthogonal to the bona fide / fiat division, we can distinguish substantial objects, composed of biological matter and physically filling a portion of space, from non-substantial objects like holes, boundaries, locations, and landmarks. Both categories may contain both fiat and bona fide objects. Since Aristotle's work *On the parts of Animals*, anatomy knows many different types of such objects, for instance simple substantial ones, like blood or cerebro-spinal-fluid, or very complex organs, like the heart or the brain and finally the whole organism. The type of an object effects other properties. A certain type can be associated with typical partitions. For example a tissue compound can always be divided into its layers, whereas a complex composition like the brain is associated with many differently motivated partitions. The object type also implies a certain spatial distribution and shape, e.g. linear organized objects like vessels or nerves tend to extend across long distances, overlapping and sharing parts with various wholes. Even the circumstances of existence interfere with the type of an object – homogeneous or aggregated objects like blood, the liver, or the skeleton retain their identity if portions are removed, but complex compositions or linear organized objects like the heart or a vessel do not.

Shapes of objects

From a spatial point of view, the 3d-shape of an anatomical object is an outstanding property. For a 3d-application a digital representation of the objects (e.g. polygons, voxel models etc.) can hold this information [10-15]. For purposes of application to the anatomy of some individual patient, such representations may include information about typical variations in a probabilistic or prototypical manner. Depending on the scale of (and work invested in) such representations, all necessary shape information is implicitly present. Therefore the shape of a concrete object can be visualized in terms of a 3d-image or metric values, but an explicit interpretation like „the kidney has an ellipsoid shape with an indentation at one side" needs a human observer.
Although an explicit description of shape would be very desirable, it is very difficult to satisfy this wish. Anatomical terminology supplies some terms to enable shape-based classification like „long bone", „short bone", or „flat bone", but this scheme is incomplete, fuzzy, incoherent, and the included shape information is again mainly implicit – no anatomist can describe shape exclusively by means of anatomical terminology.

Although human beings obviously can explain and communicate shape descriptions, explicit computerized shape descriptions still remains an unsolved problem and 3d-applications have to be satisfied with a digital, geometrical representation.

Terminology

Anatomy does not use some unified terminology. Different systems have been developed for different clinical, administrative, and other purposes. Although the UMLS (Unified Medical Language System) [18] provides an integrating system for all relevant terminologies, the original motivation of the single terminology is always evident and often not suitable for a focussed anatomical modeling scheme. This situation results in effects such as different terms for the same or only slightly incongruent spatial object, hierarchies driven by funtional, clinical and other non-spatial criterions, and nearly always spatial incompleteness.
The only terminology strictly motivated by an anatomical point of view is the „Terminologia Anatomica" [19]. But even this „stock-in-trade" of the anatomist is spatially incomplete (remember fig. 2) and uses implicit and incoherent hierarchies.
UMLS tries to overcome some of these (spatial) drawbacks by supplying a semantic network to make explicit the relations between different terminologies and terms. It is obvious, that this network has much more to care about than spatial anatomy and therefore has to manage problems that don't play a role for 3d-applications. *Rosse et al.* introduced extensions to the UMLS to achieve spatial completeness [20] and described an Ontology containing a classification of anatomical objects and used the semantic network to describe is-a- and part-of hierarchies within the UMLS framework [21]. The GALEN system supplies a consistent semantic model of medical terminology but is based on a clinical point of view [22]. However, these attempts fail in representing

multiple partitions, they do not distinguish bona fide from fiat objects or boundaries, and they do not model mereotopology and object types in an explicit abstract way.
Nevertheless, many 3d-applications will need a mapping of the spatial objects they handle to different terminologies. In the case, the desired terminology includes anatomical terms, it can be understood as an additional (often incomplete) partition in the above described sense. Otherwise, e.g. in the case of clinical terminologies for symptoms or deseases, more complex relations have to be introduced – but this is a problem far apart from our spatial point of view. However, UMLS and GALEN will be very helpful for these purposes.

Conclusion: What is anatomy made of?

The above analysis shows that a spatial anatomical ontology has to fulfill at least four requirements:

1. It has to consider multiple, cascading, overlapping **partitions** of different motivation and scale.
2. It has to describe **topological relations** between objects.
3. It has to classify different spatial **types of objects**.
4. It has to describe the **shape of objects**, at least with a digital geometrical model.

To enable a communication with human users, a mapping to standard terminologies has to be established.

A Theory of Granular Partitions

As mentioned before, the partition-based structure of anatomy is practically used in our everyday activities; it corresponds to common sense. That is why modeling approaches based on set theory and other abstract schemes often result in problematic, complex, partial and incomprehensible models. This is true due not only to the fact that, in anatomy as well as in common sense, structures usually are not regarded as sets, but also to the fact, that typical set operations, especially the operation of building unions, make sense only in certain situations, depending on the viewed object types and scale. For example: what is the meaning of the union of my knee joint and my left eyeball? Where in my body can I find infinity or empty sets?
Recently, *Smith* introduced a method for interpreting the common-sense world in terms of „Granular Partitions“ as an alternative approach to set-theory based ontologies [23]. This method can be understood as a well-founded extension of the Aristotelean idea of describing the world by categories. Although it is not a formalized theory yet, this concept includes previously formulated anatomical demands [24, 25] and promises to perfectly reflect the situation found in anatomy in important aspects. A short description should outline the main ideas.

The world is viewed through an arbitrary number of partitions. A partition divides the world or a portion of it into cells. One partition can hold at least one but always a finite number of cells. Partitions are either transparent or opaque – in a transparent partition the cells correspond to a defined portion of reality (e.g. anatomical partitions), opaque partions don’t (e.g. the partion of Pythagorian spheres). All or some cells of a partition can be empty (e.g. the partition of demonstrably found aliens on earth). Therefore partitions can be complete or incomplete. Partitions can be hierarchally cascaded or they can overlapp or be disjoint to each other. Partitions on the same level can be glued together, extended, and so on.
Cells contain objects that are prototypes of individual objects in reality. They describe common, usually found properties and therefore individuals can nearly always be identified that are exceptions to this prototype description. Exceptions can be handled by moving to another more fine-grained partition which provides a more detailed distinction of prototypes at the finer resolution. This is called „Ontological Zooming“ by Smith. Although not described by Smith, anatomical exceptions require also some „Ontological Shifting“, which means, if an exception occurs e.g. in a shape-based partition, it may be solved by moving into a functional or evolutionary motivated partition without changing scale.
The features of this method for interpreting the common-sense world meet the above listed requirements of anatomical partitions and suggest an application to anatomy. The next section will outline an ontology using this method for the basic structure of the anatomical domain.

Outline of an Ontology for Spatial Anatomy

We now can lay down the principles of a spatial oriented Ontology of Anatomy. Figure 3 presents a sketch of the global structure, which is defined as follows.

Structure

Spatial anatomy is structured by an arbitrary number of partitions as defined above. All these partitions have in common that they are spatially transparent – their cells correspond to defined portions of the space demarcated by the human body. Some partitions are essential:

1. The one-cell partition containing the human body as a whole, defining the extent of the domain.
2. Partitions dividing the body into objects of different spatial types, like bona fide, fiat, substantial, geometrical, compounds, compositions, boundaries, or holes.
3. Anatomical terminologies are partitions with cells containing their terms.
4. All partitions dividing the body into the common anatomical objects on different scale and with different motivation, e.g. systematical, topographical, or functional anatomical hierarchies in macroscopy and microscopy. In many cases these partitions are reflected more or less accurately in anatomical terminologies.
5. A partition, dividing the body into objects of different shape. As described before, this partition currently can be established only in an indirect and implicit way by providing a digital geometric representation linked to an incomplete shape describing terminology.

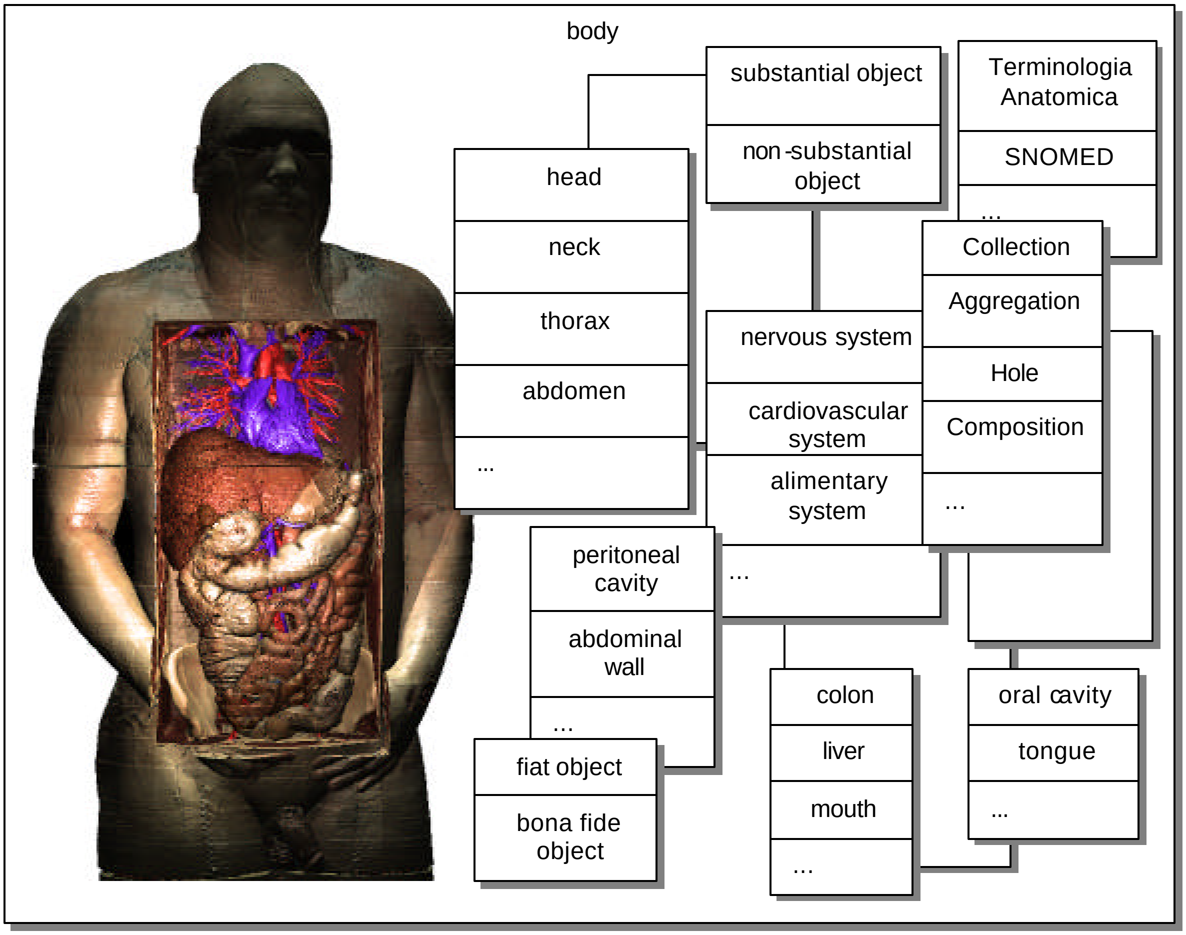


Figure 3: Illustration of the global structure of the outlined ontology, including a digital geometric model (left [26]) and an arbitrary number of partitions (indicated by the frames), representing differently motivated divisions of the body. The cells of the partitions correspond to a real anatomical spatial entity and therefore to an object of the digital model if represented there. Some partitions form granular cascades by representing changing levels of abstraction (e.g. oral cavity *is a* hole) or by representing different scales (e.g. colon *is part of* abdomen). The relations between partitions, between cells and partitions, and between cells have to be explicitly declared (see text).

There are other partitions, e.g. considering physical properties of different tissues, that have to be included, if they are relevant for a certain application, e.g. surgical simulations.
Partitions may be cascaded due to their granularity is changing as we move from one abstraction or one scale to another, resulting in generic or mereological hierarchies.

Ontological „Zooming“ and „Shifting“ is always possible, which means, one cell of a given partition can always be viewed through another partition of different scale/granularity or motivation. For these two operations, (mainly mereotopological) spatial relations between cells of different partitions have to be declared or derived from a geometrical representation.

Content

The partition-based structure is not only an elegant description, it can also be implemented in a straightforward way (see figure 4). Partitions do not explain in detail, how to design essential features like the concrete content of the partition of spatial object types and the definition of mereotopological relations between cells of different partitions, enabling the zooming and shifting operations.

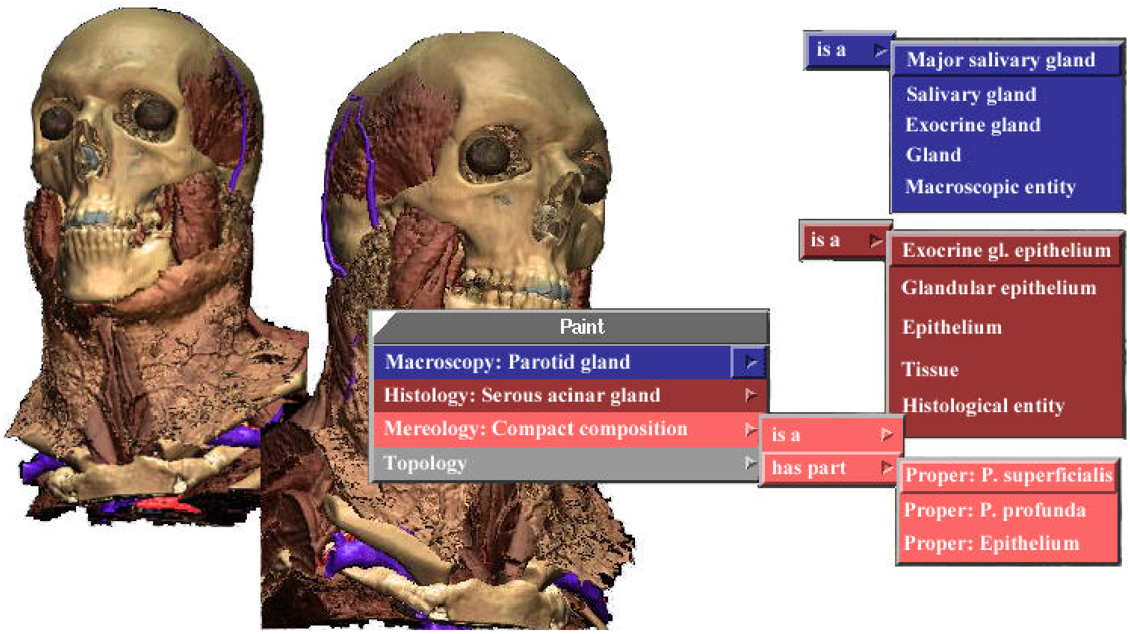
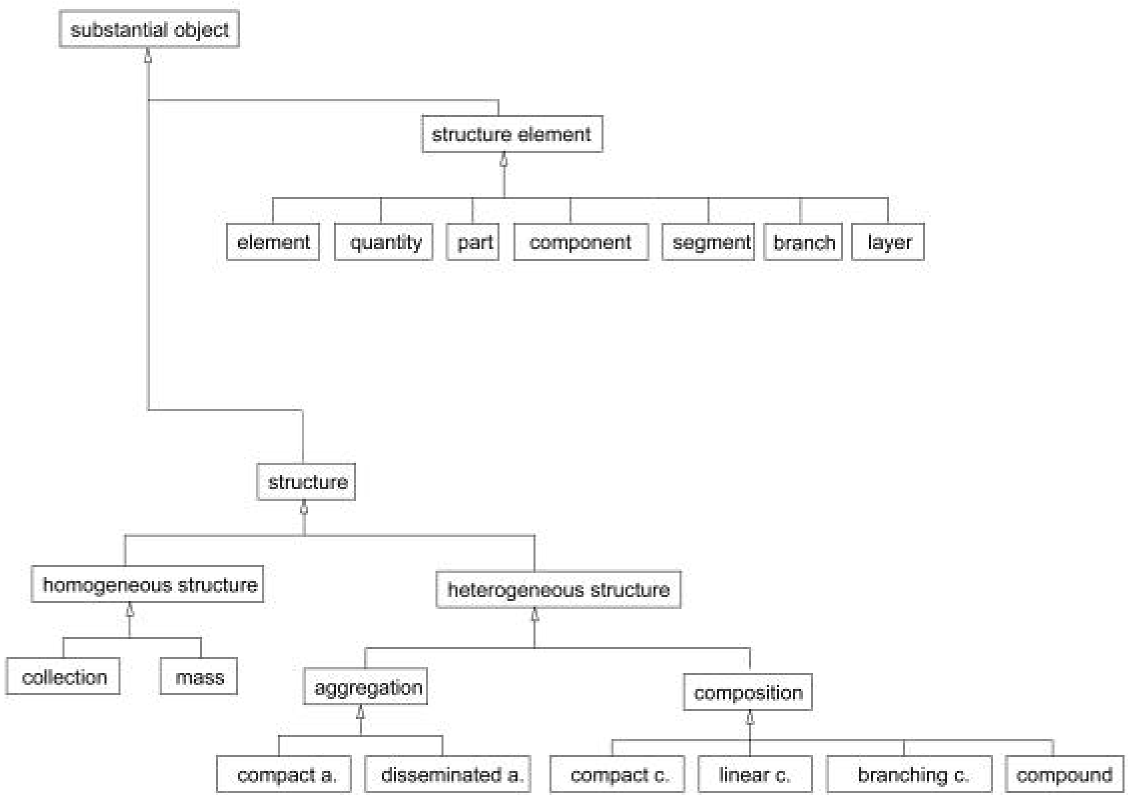


Figure 4: Implementation of the partition-based structure in the VOXEL-MAN environment [10,11,12]. The system contains digital 3d-models of different parts of the body, which can be interactively visualized from any point of view and with a user defined state of dissection. The popup-menus demonstrate the reaction on a mouse click on the parotid gland. The content of partions of different scale (macroscopy, histology) and motivation (mereology, topology) are shown.

For the former problem partial solutions are available. As described above, two general orthogonal categorisations divide objects on one hand into bona fide and fiat objects, depending on their boundaries and on the other hand into manifest, physical objects and geometrical, non-physical objects.
Based on *Euclid*, we can classify primitive geometrical objects into points, lines, and planes. A more sophisticated treatment is needed for different types of holes and boundaries. For the case of holes, *Casati and Varzi* developed a well-founded extensive ontology, which is waiting to be applied to anatomy [27]. Boundaries play an important role in anatomy. They not only demarcate objects, they are also important landmarks for e.g. functional, pathological, and surgical processes. The theory of bona fide / fiat boundaries allows to understand and describe problems associated with different kinds of boundaries, e.g. the problem of defining suitable boundaries of the body in case of a closed or opened mouth [1, 2].
For the group of physically manifest objects we propose the classification shown in figure 5. This hierarchy stands out as a result of its strictly structural point of view. Other described classifications often include functional or shape-oriented criterions, which complicate their application.
For zooming and shifting with and between different partitions, the mereotopological relations between their cells have to be formalized. Since this problem not only occurs in modeling anatomy, several concepts and calculi have been described (for an overview see [28, 3, 5, 8]). Especially in Geographical Information Systems (GIS), a high standard of such solutions is reached. It still has to be studied if and how these concept can be applied to 3d-anatomy.

Remaining problems

Beside the mentioned tasks of future work of including a mereotopological calculus and integrating the proposed concepts for object typology, there are important other points that are not touched upon by the outlined ontology. First of all, an elementary property of a living human being is dynamic change of different kind, e.g. growing, moving, and breathing. Since dynamics can only be described as changes relative to a starting situation, it is a good idea and also in accordance to the anatomical point of view, to develop an adequate static model first and then try to make it dynamic in a second step.
This is also true for anatomical variations and pathologies. Anatomy describes them as divergences from a prototype – which is supplied by this ontology.



.
Figure 5: The proposed mereological classification to reflect the types of constitution fo und for anatomical objects (for details see [25]).

Conclusions

This paper does not supply a formalism that is ready to implement, but rather it introduces an outline for a spatial ontology which is elegant, comprehensive, and well suited for the anatomical domain. It includes a concept to formalize the multiple, orthogonal, and overlapping partitions, that are typical for anatomy. It is multi-scaled and enables zooming as well as changing the point of view to refer an certain object in a e.g. topographical, systematical, or functional motivated partition. In contrast to other approaches it reflects the common-sense style of anatomy. The ontology is independent of special terminologies, but includes them as one anatomical expression among others.
The sum of these characteristics differs from other approaches and promises to provide a suitable and sufficient framework for development of concrete, applied anatomical representations.
One prominent feature is that it easily can be extended by any spatially oriented view without changing the basic concept.
Beside these advantages, the abstract, explicit description of shape remains an unsolved problem with this ontology too, but can be worked around by using a geometrical model as implicit representation.
Future work has to concentrate on formalizing the up to now only conceptually described parts of the ontology. Eventually, the ontology has to be prove it's usefulness by concrete implementation and application, which is work in progress.

Acknowledgement

Sincere thanks go to Barry Smith for valuable discussions on this work and many important comments and hints. Discussions with Karl Heinz Höhne and Andreas Pommert were very helpful to bring this paper into its final form. Many of the presented ideas and concepts are based on the work for my Habilitation-Thesis "Symbolisch-Räumliche Computermodelle der Anatomie" ("Symbolic-Spatial Computermodels for Anatomy") which was partly supported by the Deutsche Forschungs Gemeinschaft (DFG) grant #Hö 899/4.

Literature

1. Smith, B., and Varzi, A. C., Fiat and Bona Fide Boundaries, Philosophy and Phenomenological Research, 60: 401-420, 2000.
2. Smith, Barry, Fiat Objects, Topo*i*, 20: 2, 2001.
3. Varzi, A.C., Parts, Wholes, and Part-Whole Relations: The Prospects of Mereotopology, Data and Knowledge Engineering, 20: 259-286, 1996.
4. Eschenbach, C., Heydrich, W., Classical Mereology and Restricted Domains, In N. Guarino and R. Poli (eds.), International Workshop on Formal Ontology in Conceptual Analysis and Knowledge Representation, Padova: CNR-Ladsep, pp. 205-217, 1993.
5. Smith, B., Mereotopology: A theory of parts and boundaries, Data and Knowledge Engineering, 20: 287-303, 1996.
6. Casati R., Varzi A. C., The Structure of Spatial Localization, Philosophical Studies, 82, 205—239, 1996.
7. Asher, N. and Vieu, L. 1995. Toward a Geometry of Common Sense: A Semantics and a Complete Axiomatization of Mereotopology. In Proceedings of International Joint Conference on Artificial Intelligence (IJCAI 95). Montreal, Morgan Kaufmann Publishers, Inc.: 846-852.
8. Cohn, A. G., Hazarika, S. M., Qualitative Spatial Representation and Reasoning: An Overview, Fundamenta Informaticae, 45: 1-29, IOS Press, (2001).
9. Egenhofer, M., A formal definition of the binary topological relationship, Lecture Notes in Computer Science, 367: 457-472, Springer, Berlin, 1989.
10. Schubert, R., Pflesser, B., Pommert, A., Priesmeyer, K., Riemer, M., Schiemann, Th., Tiede, U., Steiner, P., Höhne, K. H.: Interactive volume visualization using ``intelligent movies''. In James D. Westwood et al. (eds.): Medicine meets Virtual Reality, Proc. MMVR '99, Health Technology and Informatics 62, IOS Press, Amsterdam, 1999, 321-327.
11. Schubert, R., Schiemann, Th., Tiede, U., Höhne, K. H.: Applications and perspectives in anatomical 3-dimensional modelling of the Visible Human with VOXEL-MAN. Acta Anat. 160, 2: 123-131, 1997.
12. Höhne, K. H., Pflesser, B., Pommert, A., Riemer, M., Schiemann, Th., Schubert, R., Tiede, U.: A new representation of knowledge concerning human anatomy and function. Nature Med. 1, 6: 506-511, 1995.
13. Brinkley, J. F., Rosse, C., The Digital Anatomist distributed framework and its applications to knowledge-based medical imaging, J. Am. Med. Inf. Ass., 4(3):165-183, 1997.
14. Evans, A. C., et al., Anatomical-functional correlation using an adjustable MRI-based region of interest atlas with positron emission tomography, J. Cereb. Blood Flow Metab., 8(4):513-530, 1988.
15. Kikinis, R. et al., A digital brain atlas for surgical planning, model driven segmentation, and teaching, IEEE Trans. Visualization and Computer Graphics, 2(3):232-241, 1996.
16. Lésniewski, S., Grundzüge eines neuen Systems der Grundlagen der Mathematik, Fundamenta Mathematicae, 14: 1-81, 1929.
17. Simons, P., Parts. A Study in Ontology, Clarendon Press, Oxford, 1987.
18. Lindberg, D. A., Humphreys, B. L., McCray, A. T., The Unified Medical Language System. Methods Inf. Med., 32(4):281-291, 1993.
19. Terminologia Anatomica, International Anatomical Terminology, Editor: FCAT (Federative Committee on Anatomical Terminology), Georg Thieme Verlag, Stuttgart, New York, 2000.
20. Rosse, C. et al. Enhancements of Anatomical Information in UMLS Knowledge Sources, In Annu Symp. Comput. Appl. Med. Care, Proc. SCAMC, pp 873-877, New Orleans, LA, 1995.
21. Rosse, C. et al., Motivation and organizational principles for the digital anatomist symbolic knowledge base: an approach toward standards in anatomical knowledge representation, JAMIA, 5, 17-40, 1998.
22. Rector, A. L., et al., The galen core model schemata for anatomy: Towards a re-usable application-independent model of medical concepts. In P. Barahona, M. Veloso and J. Bryant (eds.), Proceedings of the 12th International Congress of the European Federation for Medical Informatics (MIE94), pp 229-233, IOS Press, 1994.
23. Smith, B., and Brogaard, B., A Unified Theory of Truth and Reference, Loqique et Analyse, 43, 2001.
24. Schubert, R., Höhne, K. H., Partonomies for interactive explorable 3D-models of anatomy. In American Medical Informatics Association, Proc. AMIA '98. Orlando, FL, 1998.
25. Schubert, R., Symbolisch-Räumliche Computermodelle der Anatomie, Habilitationsschrift, Fachbereich Medizin, Universität Hamburg, 1999.
26. Höhne, K. H., Pflesser, B., Pommert, A., Riemer, M., Schubert, R., Schiemann, Th., Tiede, U., Schumacher, U.: A realistic model of human structure from the Visible Human data. Meth. Inform. Med. 40, 2, 2001 (in press).
27. Casati, R., and Varzi, A. C., Holes and other Superficialities, Cambridge (MA): MIT Press, 1994.
28. Casati, R., and Varzi, A. C., Parts and Places. The Structures of Spatial Representation, Cambridge (MA): MIT Press, 1999.