The Digital Anatomist Structural Abstraction: a Scheme for the Spatial Description of Anatomical Entities

Pamela J. Neal[1], Linda G. Shapiro, PhD[2], and Cornelius Rosse MD, DSc[3]

Structural Informatics Group
Departments of [1]Electrical Engineering,
[2]Computer Science and Engineering, and [3]Biological Structure,
University of Washington, Seattle, WA 98195

ABSTRACT

In this paper, we propose a generalized scheme for the symbolic description of the spatial attributes of anatomical entities. The power of the scheme lies in the ability to model the spatial objects at the highest level of granularity: information can be obtained at the desired level of detail needed for a given application.

This scheme uses the topological classes of point, line, surface, and volume to represent zero-D, one-D, two-D and three-D objects. A spatial object participates as a node in three complementary networks; the topology network, the part-of network, and the spatial associations network. The topology network describes a spatial object in terms of its boundaries, the part-of network describes a spatial object in terms of its parts, and the spatial associations network describes the spatial object in terms of its relationships to other spatial objects. All three of the networks can be used in combination or alone to answer queries to the spatial information system. The Digital Anatomist Structural Abstraction together with the other components of the Digital Anatomist Foundational Model[1] will provide the information for describing and reasoning about anatomical entities.

INTRODUCTION

An implicit understanding of spatial relationships among macroscopic anatomical entities is a fundamental requirement for drawing conclusions from symptoms and signs, as well as from diagnostic procedures that involve medical imaging and invasion of the human body. Although anatomical concepts are extensively represented in current clinical terminology projects, explicit and comprehensive description of spatial relationships that exist among physical anatomical entities is not yet available. Computer-processable spatial descriptions of anatomical entities would facilitate the development of knowledge-based approaches to tasks such as object recognition and segmentation in medical images and also for inferring the location in medical images of those anatomical structures that remain unrevealed by the procedure that generated the image.

The Digital Anatomist foundational model[1] calls for a structural abstraction in order to symbolically model partitive and spatial adjacency relationships of physical anatomical entities. In this report we propose a general scheme for describing spatial objects and will assess the validity of the abstraction for the foundational model of anatomy by mapping to the structural abstraction scheme concepts from diverse classes of the Digital Anatomist ontology.[2] It is our hypothesis that by developing a scheme for the spatially most complex subclass of *Anatomical structure*, the abstraction will accommodate the other subclasses of *Anatomical structure* and *Anatomical spatial entity* (two of the three root concepts of the ontology; the third being *Body substance*). Although empirical validation of this hypothesis calls for extensive data entry, for the purpose of this report it will suffice to map an anatomical structure, such as the lung, to the structural abstraction. We can then assess the extent to which the abstraction captures the spatial elements that occur in narrative text descriptions of the lung.[3]

METHOD OF APPROACH

After evaluating several spatial description and information systems,[4–7] we selected the Image Understanding Environment (IUE)[8] as a guide for developing the Digital Anatomist Structural Abstraction (ASA) of the Digital Anatomist Foundational Model.[1] Rather than using the geometrically-oriented IUE classes, we adopted IUE concepts for spatial object, part-of network and topology network, and redefined these concepts in order to fit a non-geometric representation, which is a requirement for a foundational model of anatomy. As in our previous and ongoing work in anatomical knowledge representation,[2] our aim has been to maximize expressivity; the spatial descriptions provided by ASA are at the highest level of granularity. Our justification for this strategy is to assure that the Digital Anatomist foundational model can support applications that require anatomical information ranging from the most elementary to the most sophisticated levels. This report first presents the classification we propose for spatial objects and is supported by anatomical examples. It then describes the part-of and topology networks using the left lung as an example. It also describes the spatial associations network, which we developed in order to represent spatial association relationships. The results are largely the outcome of introspective and iterative processes we have pursued through a graduate course in computer science and biological structure: Knowledge Representation in Anatomy (CSE 590BR), and are being implemented in the Digital Anatomist Symbolic Knowledge Base.[2]

CLASSIFICATION OF SPATIAL OBJECTS

We classify spatial objects according to their spatial dimension. This simple classification allows assertions to be made about the relationships of spatial objects that correspond to anatomical entities of different dimensions. The four classes we propose are: point, line, surface, and volume,* which represent spatial objects of zero, one, two, and three dimensions, respectively. In order to match the granularity and specificity of the anatomical ontology we established,[2] we have subdivided each spatial class into two or three generations of subclasses in an inheritance hierarchy (spatial ontology) as shown in Figure 1. We have defined each node of this ontology in terms of generalia and differentia, but here we comment only on concepts requiring clarification in terms of correlation with the anatomical ontology.

CORRELATION OF SPATIAL AND ANATOMICAL ONTOLOGIES

All subclasses of *Anatomical structure* (physical objects that constitute the body) and *Body space* (itself a subclass of *Anatomical spatial entity*) map to *Volume*. Of the other subclasses of *Anatomical spatial entity*, *Body region* and all its hyponyms (descendants) map to *Surface*; whereas descendants of *Anatomical landmark* and *Anatomical feature* map to *Surface*, *Line*, or *Point*. For example, the lung and the pleural cavity map to *Volume*; the epigastrium and the diaphragmatic surface of the left lung map to *Surface*, as does the fossa ovalis of the right atrium. The sternal angle and linea aspera map to *Line*, and the midinguinal point maps to *Point*. While most of the subclasses shown in Fig. 1 are self-explanatory, some clarification is called for. We distinguish between real and virtual points, lines and surfaces. For instance, the surfaces that enclose a lobe of the lung are real surfaces, whereas the surfaces that subdivide a lobe into bronchopulmonary segments (subvolumes) are virtual surfaces. The lineae aspera and semilunaris are real curves, because they are palpable or visible, whereas the midclavicular line or midinguinal point are virtual spatial objects, necessary for describing real anatomical surfaces, lines and volumes. A virtual line is an imaginary line formed by the intersection of a real and a virtual surface. A virtual point is an imaginary point formed by the intersection of two virtual lines, or the intersection of a virtual and a real line.

Although ovoid, cylinder, sheet (e.g. external oblique aponeurosis, tympanic membrane) and polyhedron need not be defined here, some clarification is warranted about their subclasses. Conventional ovoids, such as eyeball and head of femur, and conventional cylinders, such as abdominal aorta and shaft of femur, approximate the geometric shape implied by their name. We classify highly irregular anatomical structures, such as pararenal fat and celiac ganglion, and spaces, such as lesser sac of peritoneum and pleural cavity, as irregular ovoids. Nerves and most blood vessel are classified as attenuated cylinders; their cross-sectional radius is orders of magnitude smaller than their length.

STRUCTURAL NETWORKS

We consider spatial objects in the context of three different, but coaxial, networks: the *topology network*, the *part-of network*, and the *spatial associations network*. Every spatial object may have any or all three networks. The context of the query determines which network (or combination of networks) can provide the answer to the query. We use a semicone (a polyhedron) and compare it with

*The terms point, line, surface and volume are not used in the strictest geometric sense. We allow some latitude in that we refer to topological as well as geometric information using these terms.

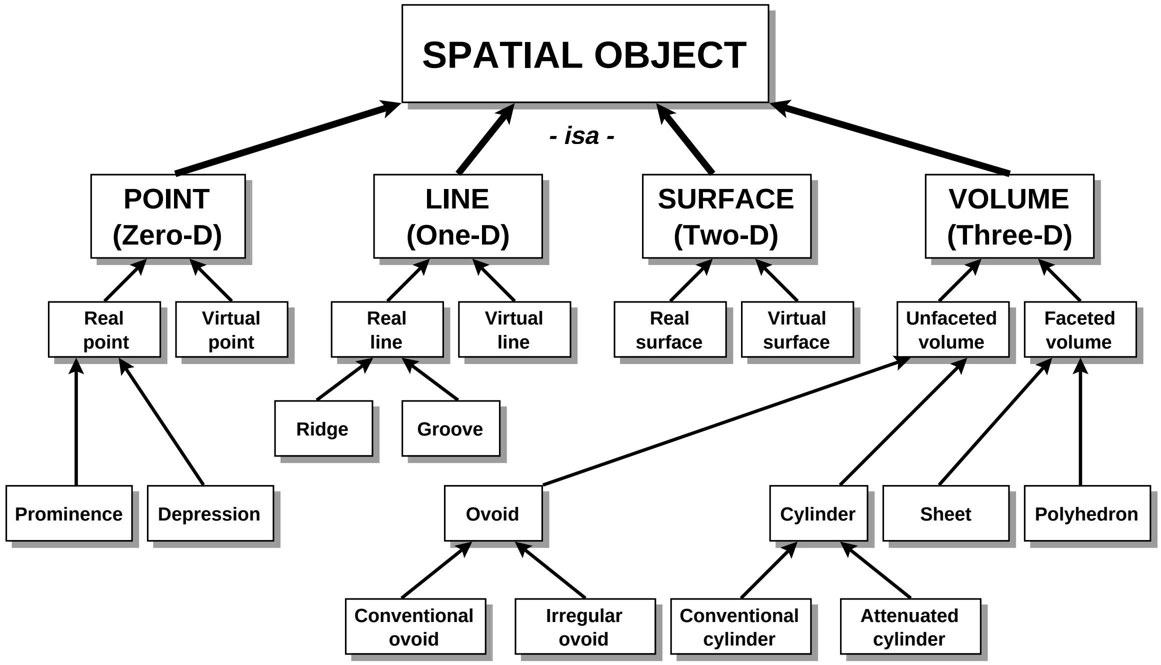

Figure 1: The Spatial Ontology.

a viscus (the left lung), as shown in Figure 2, to illustrate the networks.

Topology Network

The topology network describes a spatial object in terms of its boundaries. The nodes of the network are also spatial objects, but always of a lower dimension than the object the network describes. The links in the network are -*bounded by*- and -*boundary of*-. A spatial object may take part (as a node) in the topology network of other spatial objects, which allows the node to be properly classifed in any given context. We can classify nodes as *bounded* or *bounding*. For instance, in Fig. 2A, the polyhedral volume of the semicone, PV, is bounded by its surfaces S_1, S_2, S_3; the node PV is the bounded object and the nodes S_1, S_2, S_3 are the bounding objects. By analogy the volume of the left lung, LLV, is bounded by the costal, mediastinal and diaphragmatic surfaces (Fig. 2B).

Part-of Network

The part-of network describes spatial objects as component parts. Its nodes are spatial objects of the same dimension as the network describes, and the links are -*part of*-, and its inverse, -*has part*-. The attributes *superobject* and *subobject* describe the links and indicate which nodes have which links. In Fig. 2, polyhedral volume PV is subdivided into PV_1 and PV_2; PV has subobjects PV_1 and PV_2. It has no superobject. Similarly, left lung LLV has two subobjects, Upper lobe and Lower lobe. In Fig. 2B it has no superobject, though in the context of the body the superobject is the Thoracic Cavity.

Spatial Associations Network

The spatial associations network describes different kinds of spatial relationships of spatial objects to other spatial objects. The nodes of the spatial associations network are spatial objects and the links are the different types of relationships. The attributes of the spatial association links are *location*, *orientation*, and *adjacency*.

While in geometric datasets, such as the Visible Human, relational attributes may be stated in terms of quantitative coordinates, the Digital Anatomist Foundational Model, which deals with canonical anatomy, calls for a qualitative coordinate system. We adopt the anatomical position as the fixed, standard reference for the orientation of the body and all of its component parts, and make use of three orthogonal axes that have been canonized by long established usage in anatomy:

-*anterior*-, and its inverse, -*posterior*-
-*superior*-, and its inverse, -*inferior*-
-*right*-, and its inverse, -*left*-

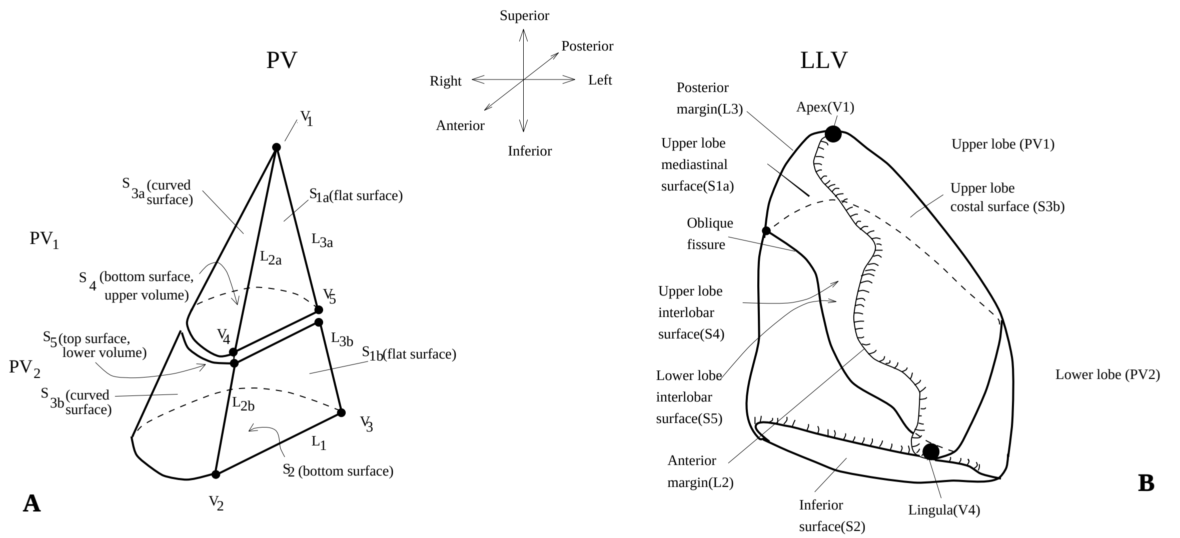

Figure 2: A Semicone(A) and a Viscus(B). The semicone, PV, is bounded by surfaces S_1 (the triangular flat surface), S_2 (the bottom surface), and S_3 (the curved surface). Each surface is bounded by a set of lines. Surface S_1 is bounded by L_1, L_2, and L_3. The lines meet at vertices (points); lines L_2 and L_3 meet at the top of the semicone, at vertex V_1. Surfaces S_1, S_3, and lines L_2, L_3, are labeled as their *a* and *b* parts. The left lung is shown with several of its surfaces, lines and points labeled. The corresponding semicone objects are indicated in parentheses.

Since a virtual median plane divides the body into similar right and left halves, relationships along the right-left axis are often stated as -*medial*-, and its inverse, -*lateral*-, describing a position that is nearer to, or farther from, the median plane, regardless of the side of the body.

Like the other networks, the spatial associations network is conceptually object-centered – everything is relative to the spatial object being modeled. Location and orientation take into account the higher-order entities in which the spatial object takes part. In order to describe the location of a spatial object, we translate the origin of the coordinate system to the center of the reference volume of the spatial object. *Location* of the given spatial object is then described by beginning at the origin and identifying the relative position of the spatial object. In Fig. 2, if PV_1 is the spatial object being modeled, then the origin is conceptually at the center of PV, and PV_1 is *superior*.

The *orientation* relationship is shape-dependent and is specified in terms of spatial objects of a lower dimension in the topology network of the reference object. In Fig. 2A, the orientation of PV is [(V_1, superior), (S_2, inferior)]. By analogy, the orientation of the left lung is [(Apex,superior),(Inferior surface(base),inferior)].

The *adjacency* relationship describes the relative location of spatial objects to the one being modeled. These objects can be other parts of a common spatial object, or parts of different spatial objects. They must be of the same dimension. This relationship consists of a list of pairs. The first member of the pair is the name of the adjacent spatial object (the node), and the second is the direction of the adjacent spatial object (the link). For example, in Fig. 2, PV has no adjacent spatial objects. PV_1 has (PV_2, inferior). Surface S_1 has adjacency [(S_2,inferior),(S_3,lateral)].

ASA Model: Upper Lobe of Left Lung

The example below shows the ASA model of a real anatomical object, the Upper lobe of the left lung (Fig. 2B).

UPPER LOBE LEFT LUNG (polyhedral volume)
  Part-of Network
    Superobject { *LEFT LUNG* }
    Subobjects
    { *APICAL SEGMENT,*
      POSTERIOR SEGMENT,
      ANTERIOR SEGMENT,
      SUPERIOR LINGULAR SEGMENT,
      INFERIOR LINGULAR SEGMENT }
  Topology Network
    Bounded Spatial Objects { *none* }
    Bounding Spatial Objects
    { *UPPER LOBE COSTAL SURFACE,*
      UPPER LOBE MEDIAL SURFACE,

UPPER LOBE INTERLOBAR SURFACE }
Spatial Associations Network
Location { *supero-anterior* }
Orientation
{ *(APEX, superior),*
(INTERLOBAR SURFACE,
infero-posterior) }
Adjacency
(VISCERAL PLEURA, lateral),
(VISCERAL PLEURA, medial),
(VISCERAL PLEURA, superior),
(VISCERAL PLEURA, inferior),
(VISCERAL PLEURA, anterior),
(VISCERAL PLEURA, posterior) }

If the same spatial object is adjacent to the reference object in at least four of the six cardinal directions, the object *surrounds* the reference object. It is our strategy to model at the highest level of granularity. For instance, although the pleural cavity and the entire pleural sac surround the lung, the most specific adjacent spatial object is the visceral pleura. We use the link "adjacent" in the strictest sense; the heart in ASA is not adjacent to the lung; there are a number of intervening spatial objects each of which is modeled with its own adjacencies.

DISCUSSION

The ASA is a critical part of the Digital Anatomist foundational model,[1] and as such will provide the structural relationships necessary for the model to be used in a variety of applications. Through the Digital Anatomist tutor interface,[9] the ASA can be used to answer simple queries about the spatial arrangements of anatomical spatial entities. Queries such as "What is the spatial relation of the middle lobe of the right lung to its upper lobe?" can be answered by inspection of the ASA networks.

In a clinical setting, the ASA can assist in determining locations of anatomical structures in medical images. By matching the ASA information to objects visible in the images, the ASA relationships can be used to predict the location of structures unrevealed in the images. The ASA could also assist in locating abnormalities in medical images. For example, given two orthogonal x-ray views of a lung with pneumonia, the ASA could deduce the affected bronchopulmonary segment of the lung. In another application, the transitivity property of the spatial adjacencies can predict which spatial objects would be affected by an invasive object, such as a probe, inserted into the body at a given location in a given direction.

The three networks of the ASA are complete in the sense that they can potentially describe all topological, part-whole, and spatial-association relationships among anatomical structures. They are incomplete in that only a few spatial associations – location, orientation, and adjacency – have been defined so far; their definitions are currently being evaluated with respect to descriptive power for a set of representative structures. Our next step will be to improve these definitions and to expand the set of spatial associations.

References

1. Rosse CR, Shapiro LG, Brinkly JF. The Digital Anatomist foundational model: Principles for defining and structuring its concept domain. AMIA Annual Fall Symp. 1998.
2. Rosse C, Mejino JL, Modayur BR, Jakobovits R, Hinshaw KP, Brinkly JF. Motivation and organizational principles for anatomical knowledge representation: The digital anatomist symbolic knowledge base. J Am Med Inform Assoc. 1998;1:17–40.
3. Rosse C, Gaddum-Rosse P. Hollinshead's Textbook of Anatomy, 5th ed. Philadelphia: Lippincott-Raven, 1997.
4. Truvé S, Richards W. From Waltz to Winston via the connection table. In: Richards W (ed): Natural Computation. Cambridge, Mass: The MIT Press, 1988:138-157.
5. Shapiro LG, Moriarty JD, Haralick RM, Mulgaonkar PG. Matching three-dimensional objects using a relational paradigm. Pattern Recognition 1984;4:385–405.
6. Robinson GP, Colchester ACF, Griffin LD. Model-based recognition of anatomical objects from medical images. Image and Vision Computing 1994;8:499–507.
7. Bean CA. Formative evaluation of a frame-based model of locative relationships in human anatomy. Proc. AMIA Annual Fall Symp. 1997;625–629.
8. Mundy JL. The Image Understanding Environment program. IEEE Expert 1995;6:64–73.
9. Brinkley JF, Rosse C. Requirements for an on-line knowledge-based anatomy information system. AMIA Annual Fall Symp. 1998.