Bodily Systems and the Spatial-Functional Structure of the Human Body

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Abstract. The human body is a system made of systems. The body is divided into bodily systems proper, such as the endocrine and circulatory systems, which are subdivided into many sub-systems at a variety of levels, whereby all systems and subsystems engage in massive causal interaction with each other and with their surrounding environments. Here we offer an explicit definition of bodily system and provide a framework for understanding their causal interactions. Medical sciences provide at best informal accounts of basic notions such as *system*, *process*, and *function*, and while such informality is acceptable in documentation created for human beings, it falls short of what is needed for computer representations. In our analysis we will accordingly provide the framework for a formal definition of *bodily system* and of associated notions.

1. Introduction

Ontology plays an increasingly significant role in work on terminology and knowledge management systems in the domain of biomedical informatics, and we hold that it will play an essential role in the biomedical research of the future. The term 'ontology' must, however, be understood in the right way. [1] According to the dominant paradigm, which might be referred to as 'applications ontology,' the ontologist should focus primarily on the construction of ontologies as working software applications. This paradigm goes hand in hand with the thesis that the expressive power of an ontology should be limited, effectively, to that of one or other version of Description Logic. [2] This means that an ontology, when applied to complex domains such as those of biomedicine, is forced to deal with simplified models.

There is, however, a second 'reference ontology' school of thought, which focuses primarily on the development of ontological *theories* of the entities in given domains. Such theories are marked by a high degree of representational adequacy and are designed to be used as controls on the results achieved by working applications rather than as substitutes for these working applications themselves. [3]

Three levels of reference ontology can be distinguished in the biomedical domain:

1. formal ontology: a top-level domain-independent theory involving terms such as: *object*, *process*, *identity*, *part*, *location*;
2. domain ontology: a top-level theory applying the structure of a formal ontology to the biomedical domain, involving terms such as: *body*, *life*, *disease*, *organ*, *tissue*, *cell*, *chromosome*;

3. terminology-based ontology: a very large lower-level system, based on medical terminologies such as UMLS or on biological controlled vocabularies such as the Gene Ontology, and involving terms such as: *inflammatory change in the gastric mucosa* or *common-partner SMAD protein phosphorylation*.

The Institute for Formal Ontology and Medical Information Science in Leipzig is constructing a reference ontology for the domain of biomedicine. [4] This ontology is not a computer application but a framework of axioms and definitions relating to general terms such as: organism, tissue, disease, therapy. In this paper we focus on the notion of *bodily system*, which we believe will serve as a central factor in a robust ontology of the human organism.

Rosse and Mejino [5] have recognized the need in bioinformatics for domain ontologies of the human body, and they and their co-workers are creating such a domain ontology of human anatomy, the Foundational Model of Anatomy (hereafter: FMA). [6] The FMA is designed to represent the purely *structural* organization of the human body from the macromolecular to the macroscopic levels. Its goal is to provide a robust and consistent scheme for classifying anatomical entities on the basis of explicit definitions, and to associate with these entities attributes that can support spatial reasoning about the body. This scheme is designed to be maximally neutral (in contrast, for example, to a system like SNOMED, [7] which was designed for the specific purpose of medical record encoding). Thus the FMA is extendable, in principle, also to organisms of other species and to organisms at various stages of development. Further, it can provide a spatial-structural template for representing pathology, physiological function and genotype-phenotype correlations. In this way it can serve as a reference ontology in biomedical informatics.

The FMA is thus in our terminology not an application ontology, but rather a reference ontology. That is, it seeks to provide a theoretical framework which can, when fully developed, serve as the theoretical basis for a variety of applications and special purpose ontologies of different sorts.

1.1 Incorporating Function

The framework advanced below is very much like that of the FMA. Thus it, too is designed to be scalable to all levels of biological organization. But it differs from the FMA in that it integrates the functional with the structural context. Thus where Rosse and Mejino’s ontology represents the anatomy of the human body in a purely structural way, the ontology of bodily systems presented below will encompass anatomical structures in a context which takes account also of functions and their realizations. We aim, in other words, to link anatomy with physiology.

Where the FMA treats *organ systems* from the bottom up (organ systems are effectively systems defined in terms of their parts or members), our notion of *bodily system* is derived from a view of function which starts from the organism at the top and works down to lower-level parts. It is our long-term goal to demonstrate that this top-down perspective can serve as a unifying factor in a robust ontology designed for purposes of biomedical informatics.

This long-term goal reflects an aspect of our methodology which distinguishes it from that of the FMA. The latter rests on an underlying assumption to the effect that we should build our ontologies by first capturing the knowledge developed in the highly specialized and narrow fields of biomedicine from those who generate the primary data, and then formalizing this information within one or another preferred framework. The task is then one of linking together these different sub-domain ontologies into higher-level ontologies in a way that could serve as a reference for well-defined fields of biology and medicine.

From the perspective defended here, in contrast, the primary focus is on the issue of how to facilitate the necessary *linking* between such separate technical views. If sub-domain specialists are using terms like ‘function’ or ‘system’ (or ‘cell’ or ‘gene’) in consistent fashions then such linking will ensue unproblematically. If, on the other hand (as the evidence suggests), they are using such terms in highly inconsistent ways, [8] then a linking together of the corresponding views can be effected only on the basis of an analysis along the lines presented below, an analysis which takes the whole organism as starting point. Some analysis of this sort is indeed required in either case, since to establish whether usage is consistent we need to establish what given sub-domain specialists standardly mean when they use the mentioned terms, and that too is part of the endeavor here described.

2. Bodily Systems in the Medical Domain

Notions like *system* and *function* are used throughout contemporary medical science, and medical references and textbooks overflow with reasoning about systems of different kinds within the body. Much implicit medical knowledge factors into such representations. Our goal here is to apply philosophical rigor to a definition of ‘bodily system’ and associated notions in a way that makes this knowledge explicit.

Contemporary medical science represents the living human body (a term we shall use synonymously in what follows with ‘human organism’) as a system made of systems. The body’s systems serve as major provinces in our maps of human anatomy; they thus play a central role also in a variety of domains, from medical pedagogy and dynamic modeling to computer visualization.

An understanding of *system* is moreover a necessary part of any understanding of cognate terms such as *organ* and *function*, and it is a prerequisite for understanding systemic diseases, both those which are localized in single systems and those, such as diabetes, which affect a plurality of systems simultaneously.

We are interested here primarily in the upper-level nodes in the hierarchy of bodily systems; i.e., in those major bodily systems towards whose functioning other, smaller systems contribute. The term bodily system will refer in what follows only to those highest nodes: the circulatory system, the digestive system, the endocrine system, and so on, which are situated in the body’s hierarchical organization immediately below the body itself. We analyze the notion of bodily system under which they fall, and examine whether contemporary medical science is justified in partitioning these systems as it has.

First we must note that there is no consensus within contemporary medical science itself about how to partition bodily systems, as the sampling of sources in Table 1 shows. Part of the ambiguity rests on the fact that writers of medical texts must find ways of expressing in summary form the findings of those who work towards advancing knowledge by experimentation and data gathering. Assumptions often result that spawn ambiguities. The respiratory system is treated similarly in most accounts, for example, but the treatments of the reproductive system are marked by important differences.

We hypothesize that differences in what medical scientists think fits under the heading bodily system can largely be attributed to the lack of an explicit definition of this term. There seems, however, to be a core intuition about what a bodily system is which applies unproblematically to focal examples such as the respiratory and circulatory systems. But this intuition is frayed around the edges, as is revealed by the disagreement for example about whether the reproductive system ought to be treated on a par with other systems.

Terminologia Anatomica [9]	**GALEN** [10]	**MeSH** [11]	**Wolf-Heidegger's Atlas of Human Anatomy** [12]
Systemic Anatomy Skeletal System Muscular System Alimentary System Respiratory System Thoracic Cavity Urinary System Genital System Abdominopelvic Cavity Endocrine Glands Cardiovascular System Lymphoid System Nervous System Sense Organs The Integument	**Body Systems** **Functional Systems** Respiratory Functional System Lymphoreticular System Reticuloendothelial System Immune System Reproductive System Psychological System **Anatomical Systems** Nervous System Autonomic Nervous System Sympathetic Nervous System Limbic System Peripheral Nervous System Musculoskeletal System Lymphatic System Sensory System Visual System Olfactory System Gustatory System Touch System Lacrimal System Skin System Orodental System Chemoreceptor System CerebroVascular System Pulmonary Vascular System Portal Vascular System Vascular System Endocrine System Cardiovascular System GenitoUrinary System Digestive System Respiratory System	**'System' Terms (subheads under 'Anatomy')** Musculoskeletal System Digestive System Respiratory System Urogenital System Endocrine System Cardiovascular System Nervous System Stomatognathic System Hemic and Immune Systems Integumentary System	Motor system Bones Joints Synovial Joint, Muscle, Tendon Skin Skin and Fingernails Circulatory System Cardiovascular System Adult Circulatory System Fetal Circulatory System Blood Vessels of Trunk Lymphatic and Organ Systems Lymphatic System and Endocrine Organs Digestive and Respiratory Systems Urogenital System Central and Peripheral Nervous Systems Central and Peripheral Nervous Systems Spinal Cord and Spinal Nerves Automatic Nervous System Vegetative Nervous System

Table 1: ***Overview of bodily systems distilled from four standard sources***

2.1 Systems in the FMA

The FMA currently contains two lists under the heading 'system,' which are presented in Table 2.

FMA [6]	**OpenFMA [**6]

Integumentary System
Musculoskeletal System
Nervous System
  Neuraxis
  Peripheral Nervous System
  Autonomic Nervous System
  Somatic Nervous System
  Enteric Nervous System
  Sympathetic Nervous System
  Parasympathetic Nervous System
Hematopoietic System
Cardiovascular System
Alimentary System
Urinary System
Male Genital System
Female Genital System
Respiratory System
Hemolymphoid System
Endocrine System
	Integumentary System
	Respiratory System
	Cardiovascular System
	Nervous System
	Alimentary System
	Urinary System
	Musculoskeletal System
	Deep Fascial System
	Reproductive System
	  Genital System
	    Female Genital System
	    Male Genital System

Table 2: ***Body systems from FMA and Open FMA (fma.biostr.washington.edu)***

One way in which our work goes beyond the FMA is in providing a definition of the term *system*. The FMA (version as of 4 February 2004) defines *organ system* as follows:

> *Organ system*: Anatomical structure, which consists of members of predominantly one organ subclass; these members are interconnected by zones of continuity. Examples: skeletal system, cardiovascular system, alimentary system.

This definition provides neither a necessary nor a sufficient condition. It is not necessary because there are bodily systems in which anatomical continuity is lacking; for example the endocrine and immune systems, which the FMA classifies under the heading *Non-physical anatomical entities*. It is not sufficient, because there are continuous aggregates of organs, such as arbitrarily delineated areas of skin, which do not form systems. In response to the first problem Rosse proposes (personal communication) that it may be possible to regard the blood, lymph and interstitial fluid as the connecting factors that provide the structural basis for the functioning of these systems. This, however, would force a weakening of the definition provided. In response to the second problem, one would need to amend the definition by including some condition of maximality along the lines suggested below.

2.2 Partitions of the Body

Medical literature rests on informal explications of the different sorts of systems included in such lists as those provided in Table 1, and rarely if ever does it offer anything more than a passing explanation of the notions that these explications presuppose. While physicians understand perfectly well how the living human body is organized and what the functions of bodily systems are – they deal with such systems and their workings every day of their lives – they do not formulate this knowledge in an explicit way. While such informality is acceptable in documentation created for human beings, who can use their tacit knowledge of the entities involved to achieve sufficient understanding, biomedical information systems require precise and explicit definitions of the relevant terms.

Partitioning the body into systems is a cognitive process. But it is a cognitive process which involves representing aspects of reality. The body is not homogenous in terms of its material or structure; it thus lends itself to some partitions more easily than to others. We hold that the body lends itself to partitioning into bodily systems and sub-systems (along the lines described below), but we recognize also that it lends itself also to other sorts of partitions, for example into what anatomists call '*regions*,' such as the foot, the left upper lobe of the lung and other body parts which are, in our terms, not such as to form systems. There are diseases that affect such body parts, and the success, for example, of radiation therapy depends critically on accurately delineating the target volume, which is the region of known or suspected disease in a patient. Non-system body parts are the principal focus of the surgically oriented specialties: surgeons operate on, or image, not the digestive system but the upper abdomen, the foot, or head. Importantly some non-system body parts, like the hand or foot, are genetically determined by the coordinated expressions of corresponding groups of genes, determined primarily by inducing mutations in other organisms.

There are regional, as well as systemic, textbooks of anatomy, and the FMA has recognized the need to address the challenge of correlating these two perspectives. The same challenge must be faced also by a top-level ontology along the lines presented below.

2.3 A Brief Summary

In summary, our argument proceeds as follows. A bodily system is a part of the body that is necessary for the organism's survival. Without its digestive system, the organism would not survive, and the digestive system is not a part of any larger system that is also necessary for the organism's survival. Further, the body, as we will see below, is structured in a modular fashion. On the analysis we shall defend in what follows, the kidney is a sub-system of the urinary system, and it is composed of sub-systems and sub-sub-systems in its turn. The kidney is thus not what we call a *bodily* system.

It is top-level systems like the circulatory, digestive, urinary, and endocrine systems to which we refer in what follows with the term *bodily system.* One feature that is shared in common by all bodily systems unique among all the parts involved in the body's spatial-functional hierarchy is that their ceasing to function is sufficient for the body to die.

In what follows we will introduce and clarify further terms that will prove necessary to our analysis of *body system*, including: *element*, *part*, *function*, and *critical function*. In addition we will make use of certain ontological tools in order to clarify these terms; these will include: a theory of perdurants and endurants, a theory of granular partitions, and an account of what we shall call the spatial-functional hierarchy of the human body.

3. Defining 'System'

The task of reference ontology is not to replace medical science. Rather, its job is to provide a framework within which medical knowledge can be formalized in a way that supports causally predictive theories, and at the same time counteracts the effects of terminological and other inconsistency and imprecision in a way that makes possible the integration of data deriving from heterogeneous life science sources. Such a framework must start out from the ways knowledge is formulated in the medical literature, and one indication of whether we are on the right track with our definition of 'system' will be the degree to which it yields a roster of systems that is very like the standard rosters.

Of course this cannot be a criterion for the soundness of our definition. But we think it is reasonable to assume, in the absence of countervailing evidence, that medical scientists have good reasons for subdividing the body in certain ways, even if these reasons are not explicitly stated. As we have seen, however, we need to go beyond textbook formulations if we are to achieve the sort of formal clarity we need for the purposes of reference ontology.

How, then, are we to define the notion of a bodily system? The discipline of systems theory – which is *prima facie* the obvious place to look – is in fact of little help to us here, since its definition of a system as a *complex of interacting parts* [13] is far too general for our purposes and is made more specific only by the use of mathematical tools which leave unanswered precisely those questions pertaining to the specific domain of biological systems which we are called upon to answer.

We can make some progress, on the other hand, if we examine how the word 'system' is most commonly used in both technical and non-technical contexts by speakers of English. The *Oxford English Dictionary* defines 'system' under the principal heading of 'an organized or connected group of objects,' or more precisely: 'A set or assemblage of things connected, associated, or interdependent, so as to form a complex unity; a whole composed of parts in orderly arrangement according to some scheme or plan.' Under the heading 'Biology' it gives: 'A set of organs or parts in an animal body of the same or similar structure, or subserving the same function, as the nervous, muscular, osseous, etc. systems, the digestive, respiratory, reproductive, etc. systems.'

3.1 Systems as Dynamic

One might be critical of such definitions on the grounds that a system is not a mere set or aggregate, but rather something *dynamic* (think of the hydraulic system in your car). We can do justice to such criticisms, however, by distinguishing systems themselves from the *processes* in which they are involved. [14] As we shall see, systems are able to carry out certain specific kinds of processes, only because they have a certain kind of physical structure. [15] Systems on this view are dynamic in nature in just the way that organisms are. Indeed organisms *are* systems on the analysis we shall defend.

Each of the bodily systems listed in Tables 1 and 2 consists of a certain organized group of objects – such as organs, associated tissues, and populations of cells – with which specific kinds of processes are associated. There are of course many organized collections of parts of the body with which processes can be associated, including some of the bodily 'regions' mentioned above. In order to make our analysis of system work, therefore, and to yield the sorts of answers we need for our questions about bodily systems, we will need to provide a specification of the particular kinds of processes to which systems give rise. Roughly, they are those processes which are the realizations of *functions* on behalf of the systems in question. Hence in what follows we shall need to provide also an analysis of *function.*

We will distinguish between a part of the body, and an element of a body system, as follows. When we refer to a part of the body, we mean a proper part in the mereological sense. Examples are: the hand, the solar plexus, the thyroid, the right half of the liver, the whole liver, a white blood cell. A part is identified only by its mereological relation to the body. An element, in contrast, is a mereological part of the body, in fact an aggregate of mereological parts, that has in addition a specific function in its own right. The notion of *element* can be understood, roughly, as a generalization of notions such as *organ, cell*, and indeed of *bodily system* itself. Examples of elements are: the heart, a skin cell, a bicep muscle, the digestive system. Note that most elements are systems in and of themselves: they have functions, and are often composed of a complex of interacting elements on lower levels of granularity each of which has a function in its turn. Thus the elements of the body compose a complex modular hierarchy that is arranged by function as well as by spatial location and size. As we will see, the bodily systems we have defined above are themselves elements of the system that is the body as a whole. Our approach is based on the supposition that every element is composed of elements that enable it to realize its function, and that this is the case all the way down to an as yet unspecified bottom level.

3.2 The Body's Modular Hierarchy

There is a collection of bits of biological matter in the human body that medical science designates as the circulatory system. What is it about this collection of vessels, organs, and blood in virtue of which it is referred to as a *system*? Could we designate as a system some arbitrarily demarcated area of skin? Or the mereological sum of our heart plus our salivary glands plus our right ear? Clearly, the reason that the circulatory system is considered as forming a system is because the heart, vessels, and blood are related to each other in a special way. There are first of all structural connections, which can be described in terms of mereological and mereotopological relations: the left ventricle is part of the heart, a capillary is continuous with a venule. But to distinguish systems from arbitrary connected aggregates of body parts we need also to recognize that there are physiological connections, which can only be described in terms of causal relations: the electro-chemical impulses cause the myocardium to contract and relax, and these processes cause the heart to pump. In other words, a system is characterized simultaneously by a certain complex *structure*, and by a set of *processes* in which that structure participates.

It is this complex structure that allows each system to participate as it does in these and those processes. Without a tendon connecting a muscle to a bone and a group of motoneurons connecting the muscle to the central nervous system, the process of movement could not take place. But of course arbitrary collections of body parts can be seen as engaging in (correspondingly arbitrarily delineated) processes too. Hence there is still more that needs to be said. To anticipate, we shall show that the multiplicity of complex processes that takes place in the body corresponds to a modular structure on the side of the body itself. The body, in other words, is a whole that can be divided into units or modules, each of which is capable of being divided in its turn into sub-units, and so on, both along the dimension of body parts and along the dimension of processes.

3.3 Relatively Isolated Systems

Every complex organism has modular units at several levels. Your brain contains neurons, the neurons contain organelles, the organelles contain molecules, which are composed of atoms, which are composed in turn of subatomic particles. Modular units at lower levels stand in vertical mereological relationships to those modular units which stand above them in the hierarchy. The alveoli are parts of the respiratory system at a lower level than the lobes of the lungs.

Modular units also stand, as it were horizontally, in causal relations with modular units in other systems. The alveoli are parts of the lungs and have a function in the context of the respiratory system. The alveoli have a horizontal causal relationship of the mentioned sort with the capillaries, which have a function in the context of the circulatory system. It is the alveoli and the capillary wall where the exchange of oxygen and carbon dioxide takes place between the blood and the air.

Modular units within given systems may thus contribute causally to the functioning of other systems. The liver, for example, is an element in the alimentary system, but it has functions in the context of several other bodily systems at various levels. In the context of the circulatory system, it produces proteins for the coagulation of blood. In the context of the digestive system, it produces bile for breaking down chyme. Bile also has a function in the context of the excretory system: the body mixes chyme with bile and excretes this mixture as feces. The liver also produces proteins that have a receptor function in the context of the immune system.

The existence of this interleaved structure is nonetheless compatible with the fact that physiological processes form a modular hierarchy of their own. For the interleaving has limits, and it is these limits which allow us to talk in terms of 'systems' at all as if they were separate parts of the body.

The crucial notion here is that of *causal relative isolation*. As the philosopher Roman Ingarden expressed the matter, each multi-cellular organism is

> a relatively isolated system of a very high order, and as such contains in itself very numerous, likewise relatively isolated, systems of lower and lower levels, which are hierarchically ordered and variously situated within the organism, and are at the same time both partially interconnected and also partially segregated, as a consequence of which they can exercise the specific functions which are characteristic to them relatively undisturbed. [16]

Our task here is to provide the beginnings of an account of this modular hierarchy of relatively isolated systems and of the layers from out of which it is built, from macromolecules via cells and organs through to the whole organism, but in a context that is determined by paying attention also to the modular hierarchy of processes – and functions – associated therewith.

3.4 SNAP and SPAN in Bodily Systems

Ontology offers certain basic tools for formalizing the aspects of anatomy and physiology we have just discussed. The first tool we will need provides us with a way of distinguishing between the body's complex structure and the processes in which that structure participates. The structure itself occupies three spatial dimensions; processes require in addition the fourth dimension of time. Ontology also provides a way of talking about the relationship between structures and processes. What is called for is an ontology that distinguishes between three-dimensional objects that endure through time (*endurants* or *continuants*, for short), and the four-dimensional processes (*perdurants* or *occurrents*) in which these objects participate. Grenon and Smith provide such an ontology in [17], and they apply it to medicine in their paper with Goldberg in this volume [4].

The body and its parts are three-dimensional entities: they can be apprehended as it were in one glance, as in a snapshot; hence Grenon and Smith call the ontology appropriate for such entities a SNAP ontology. A SNAP ontology of the circulatory system includes not only whole organisms but also other endurants such as the heart and the blood. (We will see that functions, too, fall under the heading of SNAP entities.)

The processes that take place in the body are four-dimensional: they cannot be captured in a snapshot, but require instead something like a videotape, which allows them to be captured in their temporal extendedness as they unfold over a certain timespan – hence 'SPAN' ontology. A SPAN ontology of the circulatory system includes perdurants such as the beating of the heart and the flowing of the blood.

In a SNAP ontology, endurants are visible but perdurants are not; in a SPAN ontology, perdurants are visible but endurants are not. SNAP and SPAN thus represent two complementary perspectives on the same reality. In order to talk about bodily systems, we need both of these perspectives. We need a SNAP ontology of the endurant structures in the body that make up the modular hierarchy, and we need a SPAN ontology of the perdurant processes that these structures enable. It is the appeal to both endurants and perdurants that will allow us to explain why the heart, blood, and blood vessels comprise a circulatory system, and why our heart taken together with our salivary glands and our right ear do not.

The heart, blood, and blood vessels are parts of the human body. They are also parts of the circulatory system. A SNAP ontology such as the FMA shows us how these parts relate to each other spatially. But in order to see how these relations play out in the form of processes in which the corresponding objects participate, we need a SPAN ontology. In reality, SNAP and SPAN entities are superimposed upon one another: SNAP and SPAN are complementary *views* of one and the same dynamic reality. [4] SNAP entities are related to SPAN entities by two relations: of *participation* and *dependence.* Three-dimensional SNAP entities participate in four-dimensional processes, and four-dimensional processes are dependent on the three-dimensional continuant entities which are their bearers.

Hence our distinction between two kinds of parts: parts of the body *simpliciter*, which can be apprehended in SNAP alone à la FMA; and elements, which are the results of demarcating the body into systems in a way that takes account not only of the SNAP but also of the SPAN ontology. Elements are located in SNAP, because they are three-dimensional entities. But that they form *systems* is something that can be understood only in a context in which we take account also of the specific manner of their participation in four-dimensional processes.

3.5 Elements

Elements are those specific kinds of parts of the organism from which *systems* are constructed. At the highest level of the modular hierarchy, the bodily systems proper are elements of the system that is the whole human body. If it turns out that there are nine bodily systems, then the human body will be a system composed of nine elements, which may to some degree overlap.

If an element becomes causally disconnected from its system, as when a heart is refrigerated in the course of a heart-transplant operation, then it ceases to be an element for a certain period of time. As Aristotle expressed it: ‘A dead body has exactly the same configuration as a living one; but for all that it is not a man … no part of a dead body, such I mean as its eye or its hand, is really an eye or a hand.’ [18]

Cases in which elements of systems have been replaced by prosthetic devices (hearts, hips, etc.), or in which the system is artificially supported (such as by intravenous feeding), are a gray area for the mereology of the human body. [30] Leaving such cases aside, all elements of the body are also parts of the body. The heart is an element of the circulatory system, and it is a part of the circulatory system’s complex physical structure, which is in turn a part of the body. Certain parts of the foot, such as its bones, capillaries, or nerve endings, are unproblematically elements of larger overarching systems. The bones are elements in the skeletal system, the nerve endings in the nervous system, and the capillaries in the circulatory system. Not all parts of the body, however, are also elements (consider your right leg from the knee down, or arbitrary parts formed by summing together elements from different systems that are not directly connected).

Whether the foot is an element within the modular structure of the human organism is something which we here wish to leave open. Certainly the foot has causal relations with larger wholes, namely with the two lower limbs, pelvis and vertebral column, all designed to transmit the body’s weight to the foot and to absorb and propagate the propulsive impetus from the foot to the rest of the body. As Rosse suggests (personal communication) these elements may together constitute what we might call the *Locomotor system*. Likewise, the entire upper limb, including the pectoral girdle with all its joints, might be seen as forming a

Prehensile system. If you compromise any of these elements in either of these systems, you will have compromised locomotion or prehension. Against this, however, speaks the fact that locomotor and prehensile systems are not included in the standard lists of bodily systems which we find in the medical literature. Certainly they are not highest-level systems in the sense that will be specified below.

The elements of the digestive system include the esophagus and the stomach, the serous membrane, the layers of smooth muscular tissue, and so forth. Some corresponding functions are: to provide the way for a bolus to pass from the mouth cavity into the stomach, to advance the process of digestion by mixing the bolus with hydrochloric acid and pepsin (gastric juice), to allow for the external coverage of the stomach and its constriction.

Each cell is a system that standardly consists of elements such as nucleus, mitochondria, endoplasmic reticulum, ribosomes, which are in turn systems in their own right with their own specific functions. The blood consists of cellular elements (red blood cells, leucocytes, lymphocytes, monocytes, platelets) and plasma, which contains albumins, globulins and hormones.

As we have seen, elements are often shared by different systems, and are then involved in distinct processes in parallel – one or more in the context of each system to which they belong. For instance, the pharynx enables both the passage of the bolus into the digestive tract and the passage of air into the lungs; as such it is an element of the digestive and the respiratory systems simultaneously.

3.6 Granular Partitions and System Elements

A further ontological tool we will need is the theory of *granular partitions.* [19] This provides a way of formalizing our description of the structure of the body's modular hierarchy. A theory of granular partitions represents reality in terms of partitions, each of which highlights entities of a different grain. An organism is a single object: it exists independently of our partitions. But an organism can be viewed also as a totality of atoms, or as a totality of molecules, a totality of cells, a totality of regions, and so forth. All of these different views express distinct granular partitions of one and the same portion of reality.

The theory of granular partitions preserves realism even as it accounts for the possibility of different perspectives on reality. For each granular partition highlights certain really existing aspects of a given unified whole. Think of a tourist map as a granular partition: it represents a given city, but it highlights only certain selected tourist locations. A map of bus routes is another granular partition of the same city. Each grain in the partition is an item on the map. Grains themselves are divisible into smaller grains, which become visible through a more refined partition. Within each granularity, too, we can have different views, for example different views of the coarse anatomy of the human organism reflecting the perspectives of the surgeon and of the radiologist, respectively. This possibility, too, is allowed for in the theory of granular partitions.

All of the items appearing on the tourist map have one attribute in common: they are of interest to tourists. All of the items on the bus map have something else in common: they are relevant to the purpose of navigating through the city by bus. Similarly, any given granular partition of the body's anatomy will highlight those items in the body that have certain features in common, and leave out items that do not have these features. [20] The feature in virtue of which a given class of body parts is included in the FMA partition is (when the story is told to its conclusion) the presence of *structural genes* whose coordinated expression gives rise to the corresponding instances. We will see that the feature in virtue of which a given class of body parts is included in the anatomical partition advanced here is: the presence of *constituent functions* which are realized by the corresponding instances. In the end, of course, these two partitions must be correlated; this act of correlation however presupposes that both of the corresponding views have been worked out in formal detail.

3.7 Functions in Bodily Systems

A system is characterized simultaneously by a complex modular *structure*, which is a SNAP entity, and by a multi-leveled family of associated *processes,* which are SPAN entities. The processes occur as they do because the body is structured in such a way as to sustain a complex modular hierarchy of *functions*.

We cannot provide a definition of (biological) function here. Rather we can only set forth certain general propositions which describe what is characteristic of those entities biologists call 'functions,' propositions which will be subjected to further commentary below:

1. Functions, like other entities studied by biological science, exist both as individuals (or instances of tokens) and as universals (or classes or types). [21] The function of your heart, to pump blood, is an individual, dependent for its existence on you. The function of hearts in general – to pump blood – is a class, of which that individual function is an instance.

2. Functions are endurants. The function of your heart begins to exist with the beginning to exist of your heart, and continues to exist, self-identically, until (roughly) your heart ceases to exist.

3. Functions have bearers, which are also endurants: the bearer of the function of your heart is: your heart.

4. Functions can exist even when they are not being realized.

5. The processes taking place in or involving entities which are bearers of functions can be divided into two types: those which are realizations of their functions (also called *functionings*) and processes of other types.

6. If an organism Y has a constituent part X, and if X is the bearer of a function Z, then those processes which are the realizations of the function Z are (in normal circumstances) such as to sustain the organism in existence.

A multi-leveled hierarchy of granular partitions is needed if we are to highlight the human body's systems and their elements on successive levels. Each element is distinguished by a specific structure that allows for it to engender specific physiological processes. In the everyday language of the life sciences, this element is said to have a *function*. A function, like an element, is a SNAP entity or endurant.

Unlike an element, however, a function is an endurant that is *ontologically dependent* on another endurant. Your heart's (token) function (to pump blood) could not exist if your heart did not exist. Similarly, color is a dependent SNAP entity: your eyes have a token color (brown) which could not exist if your eyes did not exist. The color brown as a type would of course exist, but *this particular* brown of *your particular* eyes would not. Each token function is dependent for its existence on a SNAP entity; but it is *realized* in token processes, which are SPAN entities. The heart's function is realized in processes of blood being pumped. We will refer to processes that are realizations of functions as 'functional processes.'

Many elements have functions which are never realized in processes. It is not only true of but essential to the nature of fish eggs that, other things being equal, they develop into fish. In fact, however, the vast majority of eggs in many fish species never develop into fish, most being eaten or destroyed. And yet each fish egg has the function: to develop into a fish. It is a function of a woman's uterus to house an embryo whether or not she does in fact become pregnant.

It may look as though recognizing both functions and functionings in an ontology represents a case of ontological double-counting. This is not so, however. For while it is true that every function is correlated with some class of processes at some given level, many processes are not realizations of functions (think, for example, of those processes in the human body which are caused by some interference from the body's environment).

Some philosophers have criticized the function talk used unreflectively by life scientists (for example in the designation of disciplines like *functional genomics*), and have tried to eliminate the notion of function and replace it exclusively with notions of causality or natural selection. [22-24] We hold, however, that biological functions are real, that they are irreducible features of the biological world, and that the phenomena that life scientists designate with the term 'function' have enough in common to justify unifying them under the single heading. This realist attitude towards functions is indeed captured precisely in the use of the expression 'functional genomics' for what many currently regard as the fundamental discipline of the life sciences.

With Johansson *et al*. [25] we support the view that the functions of bodily systems and their elements are *constituent* functions: that is, they are functions of *parts* within the context of some larger whole (and ultimately of the whole organism). Constituent functions are similar to what Cummins calls 'roles in containing systems.' [26] Elements are components of a bodily system distinguishable by their structure and by the specific processes which that structure enables. An element is only an element *of* some larger system. Thus the function that the element has can also only exist within the context of this larger system. Further, it is only in the context of a larger system that the function can be realized in a process of functioning. This is what Aristotle has in mind when he says that an eye is an eye only in the context of the human body. [18]

For our definition of bodily system we will employ the taxonomic formula developed in [25] for describing functions in the human body. The resultant theory is described as 'bi-ontological,' because it involves simultaneous appeal to both SNAP and SPAN ontologies. When we say that the function of a given element E is: to F, then we are in fact conveying information to the effect that:

SNAP

(a) There is a whole W (a certain system),
(b) E is an element (a spatial part and functional sub-unit) of W,
(c) one function of E within W is, by means of E's parts and functional sub-elements C_1 to C_n,
(d) to F;

SPAN

(e) The functioning P which is the realization of F has temporal parts,
(f) the phases P_1 to P_n (for example a beginning, a middle, and an end), which may be either fiat parts (a matter of our conventional demarcation) [27] or bona fide parts (demarcated by real physical discontinuities).

This bipartite formula can be applied iteratively as well as recursively. It can be applied iteratively to all the parts of a functional unit that belong to the same spatial-functional level, and it can be repeated recursively, as the element on level (b) is in the next cycle turned into the overarching whole on level (a). Examples are:

(a) In the human body (W),
(b) the circulatory system (E) is an element of W,

(c) one function of E within W is, by means of its circulatory fluids (C_1), vessel system (C_2), and heart (C_3),
(d) to F = to transport substances between bodily systems X, Y, Z …;
(e) this function (F) has in its functioning as temporal parts
(f) either fiat parts of the continuous fluid flow or bona fide parts in relation to the substances transported;

(a) In the circulatory system (B),
(b) one function of the heart (C) is,
(c) by means of its atria (D_1), ventricles (D_2), and valves (D_3),
(d) to F = to pump blood (X) through the blood vessel system (Y);
(e) this function (F) has in its functioning (P) as temporal parts
(f) the diastolic phase (P_1) and the systolic phase (P_2).

3.8 The Body as Spatial-Functional Hierarchy

We have now arrived at a picture of the body as a complex modular hierarchy that is at once spatial and functional. The heart, for example, is at once a *part of* the circulatory system and an *element* in that system. As a part, it is a mereological component of a physical structure visible exclusively in a SNAP ontology such as the FMA. As an element, it has a function that is realized in processes, and therefore it requires for its demarcation also reference to a SPAN ontology.

On the spatial-functional hierarchy here defended, the circulatory system is at the top level, the heart is located at the next level down, and its elements – ventricles, atria, valves, and so on – at the next level thereafter. Each of the latter bears a function in relation to the higher-level functioning of the heart. The circulatory system itself is an element of the human body taken as a whole.

Now, of course, we run into a problem: what is the function of the human body, in relation to which the circulatory system and other bodily systems can be said to have constituent functions? [25] distinguish several possible types of functions the human body may be said to have: (a) a constituent function of some larger whole, say a species; (b) an objectively existing function, which is intrinsic to the human body; or (c) a functional *purpose* merely ascribed or imputed to the human body in the conventions of language-using subjects (along the lines proposed by Searle [22]).

Alternative (c) is inconsistent with our presupposition that the functions of bodily systems exist in objective reality. It would also ‘seem to license cultural relativity or even pure subjectivity to enter into science’ [25]. The life sciences themselves, on the other hand, often talk about functions intuitively as if they exist in objective reality. Neither (a) nor (b) contradicts the proposition that constituent functions exist objectively, and it is possible to hold either (a) or (b) consistently with an account of constituent functions as existing at a plurality of levels below the human body itself.

Even so, both (a) and (b) are problematic for their own reasons: (a) is problematic because it calls for an account of what the larger whole is within which the human body functions, and seems thereafter to threaten a vicious regress: where does the spatial-functional hierarchy stop as we move upwards to ever larger wholes? (b) is problematic because definitions of ‘intrinsic function’ thus far proposed (e.g., [28]) are highly problematic.

Here, therefore, following Johansson *et al.*, we shall bracket the question of what kind of function (if any) the human body has, and concern ourselves only with the functioning of its elements.

We also take over from [25] the idea of a *spatial-functional* hierarchy, which, in contrast to the FMA, supports an assay of the body's anatomical structures *in tandem with* an assay of the corresponding functions. The spatial side of this hierarchy taxonomizes the body's anatomy according to a modular structure (i.e. in terms of what is element of what). The functional side of the hierarchy taxonomizes the body according to which functional processes cause, or enable, which other functional processes to occur. Fusing a spatial taxonomy with a functional taxonomy yields a spatial-functional hierarchy.

The two sides match up, first of all because functions are dependent SNAP entities which depend for their existence on the independent SNAP entities which are their bearers, and secondly because their bearers have been selected (demarcated) precisely by taking account of the fact that they are bearers of corresponding functions. The body's complex anatomical structure allows for processes to occur, which means that the body is structured in such a way that the functions realized by the body can be ordered in a hierarchy parallel to its spatial-functional hierarchy of elements. Thus a cellular mitochondrion in a myocyte provides the chemical energy without which the myocyte cannot contract, and therefore contributes to the pumping of the heart. This is how physiology textbooks generally explain the relationship of the body's structure with the processes that that structure enables. We shall now attempt to express this relationship in formal terms.

4. 'Element' Defined

With an ontology that can account for endurants and processes, with a theory of granular partitions, and with a hierarchy of constituent functions, we are now in a position where we can define the term 'element':

X is an *element* of Y if and only if:

(i) X and Y are parts of an organism;
(ii) X is lower on the spatial-functional hierarchy than the organism as a whole, and lower than the system of which it is an element;
(iii) X has one or more specific functions;
(iv) X is causally relatively isolated from the parts of the organism that surround it;
(v) X is maximal, in the sense that it is not a proper part of any item on the same level of the spatial-functional hierarchy satisfying conditions (i) to (iv).

An element is an element (i) only in the context of an organism, and (ii) only in the context of a given system (which may be identical with the organism as a whole), within and in relation to which it has a constituent function. The body as a whole is not an element of any larger organic system. Thus only items that are proper parts of the body can be elements.

(iii) Functions in bodily systems are functions relative to some larger whole. The causal processes in which an element is involved are made possible by the structure of that element. [29] It is in virtue of this structure that the element has a function, namely to realize certain causal processes within the context of its overarching system. It should be noted that there is no reason to exclude an element's having more than one function, or of its having functions within the context of more than one system. The liver has, relative to the digestive system, the function: to produce bile. Relative to the circulatory system it has the function: to produce plasma enzymes that contribute to the clotting function of the blood. The liver is accordingly an element both of the circulatory and of the digestive systems.

In the context of the digestive system, the blood's function is to transport nutrients and allow for nutrient and waste exchange at the cellular level, and to nourish the components of the digestive system; in the context of the respiratory system, its function is to transport gases and allow for gas exchange at the cellular level. Blood, therefore, like most elements, can be located simultaneously at different horizontal levels of the spatial-functional hierarchy, for it has different functions within the context of different systems, and blood is an element of each. More precisely, we might want to say that at any given time different potentially overlapping parts of the blood in the body are parceled out as elements of different systems. Which these parts are will then vary from one moment to the next.

According to our definition of element, only those entities which have constituent functions in the body are elements of the body. Thus a virus may take on a functional role in your body, directing the cell to construct certain proteins that the virus needs for reproduction. The virus is however not an element of your body – indeed it is not even a part of your body – because the directions given by the virus interfere with your body's functioning. [30]

(iv) The body is articulated. The complex structure of bodily systems enables certain processes to take place in virtue of that fact that it involves elements which enjoy a relative causal isolation from other elements in the same and other systems. The relevant causal processes can occur only if other causal processes do not interfere. In other words, causal connections of the right sorts within and between elements require some degree of causal isolation from the processes of other elements.

Each element is partially isolated from outside causal influences (for example by the presence of a porous membrane which allows only certain kinds of substances to encroach into its interior). This relative causal isolation is what allows systems or elements – including the whole organism – to be self-contained yet responsive to stimuli from the outside. Some elements depend for their functioning on spatial and causal association with elements of other systems. Even so, the body's modular organization, because it is constructed out of relatively isolated systems, allows the integrity of individual elements to be preserved at the same time as they engage in causal relationships with other elements.

(v) Elements are maximal: this means that on any given level of the hierarchy an element is not a proper part of any element on the same level. A cell is an element; a half-cell is not. The bottom half of a lung does not have a separate function from the whole lung. It is the lung as a whole that is causally relatively isolated from the rest of the organs and fluids in the thorax. The lung's relative causal isolation is what enables it to exchange oxygen and carbon dioxide without disrupting or being disrupted by other processes in the body. It achieves this, however, only in conjunction with other elements whose functioning constitutes complementary phases of the relevant total causal process. Thus the lung cannot move air in and out of itself. To perform this function it needs to be associated with the plural sacs and the mechanisms of the thorax.

For an element to realize its function a type and a degree of causal isolation is required that is specific to each case. If this causal relative isolation is disturbed, the element will no longer be able to realize its function, and other elements in the body will be prevented from realizing theirs. A clogged artery signifies too much isolation between heart and peripheral tissues. A ruptured lung signifies too little isolation between the inside of the lung and the thorax.

Just as systems can be divided into elements, so functions can be divided into sub-functions (corresponding to the elements which perform them). Functions located at lower levels of the spatial-functional hierarchy interact in complex ways to enable functions at higher levels. For example, the function of a particular neuron (to provide a path for electric impulses), is realized in a composite process that consists of smaller interrelated processes, such as the exchange of potassium and sodium ions through the cellular membrane. One of the kidney's functions is to excrete urine. This function is realized by a composite process that consists of smaller interrelated processes that occur on lower levels of granularity: the excretion of urea and creatinine, absorption of necessary ions and excretion of redundant ions and water. So the realization of a function in a process often entails the realization of sub-functions in sub-processes.

5. Elements, Functions, and Criticality

The relation between elements and functions is complicated by the fact that there is not a perfect one-to-one correspondence between the two. This is because many elements in the human body have a multiplicity of functions, and also because the body's redundancy means that some functions can be performed by substitute elements.

The hierarchy of elements in the body, including its top-level bodily systems, are unified together within a single whole (the body) which is able to regulate its own state and structure. It is within the context of this whole that elements have the constituent functions that they have.

We must now discuss the interconnections among the bodily systems in more detail. We have thus far pointed out that bodily systems and their elements are marked by a complex structure that enables causal connection and causal isolation of elements. We have also pointed out that elements have constituent functions relative to the larger system to which the elements belong, and that the largest system that is a whole in relation to these functions is the human body itself.

5.1 Evaluating Functionings

Medical science can demarcate one bodily system from another in terms of the way each contributes to the task of keeping the human body alive. It now becomes possible to evaluate the functioning of each particular type of system based on the success or failure of its contribution to this matter of survival.

The spatial-functional hierarchy gives us a means by which we can effect an evaluation of functionings. In a spatial-functional hierarchy built in reflection of constituent functions on successive levels, an element succeeds in performing its function when that performance contributes to the functioning of each overarching whole on each successive level, until we reach the processes relevant to the survival of the whole human body. The body's survival then becomes the benchmark for the evaluation of the functionings of its respective elements.

For example, all else being equal, a circulatory system with clogged arteries is less efficient, and therefore less successful, than a circulatory system with clear arteries. This is because the former contributes less well than does the latter to the survival of the body as a whole.

There are in the real world degrees of functioning, each of which can be understood in relation to one or more prototypical functionings. [15] points out that an element's functioning can be measured by a prototype in a similar way to that in which an object's weight can be measured by a scale. In order for a functioning to be successful, it need not match, but it must come close to (within the range of) this prototype. Thus a screwdriver can still realize its function even though its head is somewhat loose.

There are many dimensions along which a functioning can be plotted in relation to its prototype. One dimension we are concerned with here is that of the success or failure of a given functioning to enable functionings at higher levels. Presumably there is an ideal, or prototypical, pumping of the heart that contributes optimally to the survival of the body as a whole. If the pumping of the heart is disabled by a myocardial infarction, then its functioning can move sufficiently far away from the prototypical functioning that it no longer succeeds in supplying the brain with oxygen. As we move away from the prototype, we can order actual pumpings, and actual transportings of blood by the arteries, according to the degree to which they contribute to the systems to which their elements belong.

There are of course many gray areas along the continuum of functional processes where the distinction between functioning and malfunctioning blurs. A weakened myocardium may realize the same function as a healthy one, and yet the heart is still diagnosed as malfunctioning. But once a functioning crosses a particular threshold at a particular distance from the prototype, then the underlying element is no longer performing well enough to play its part in the functioning of the whole system, to a degree that, unless some other element can take over as substitute, its malfunctioning leads to death.

The threshold for success of a given type of functioning – for example, the taking in of oxygen by the lungs – is relative both to the individual organism and to its specific environment at any given time. A bioinformatician sitting at a computer all day has a different threshold for successful oxygen intake than a manual laborer on a high-altitude farm in the Andes.

The survival of the body as a whole can be used as an objective standard for evaluating functionings in the body. Prototype functionings are those possible functionings that are most conducive to enabling the functioning of the system one level up. As we will see, having this standard of evaluation brings us one step closer to uncovering the reasoning behind medical science's demarcation of the body into bodily systems.

5.2 Critical Functions

We have just pointed out that functionings can be ordered according to their success or failure in contributing to the functioning of the overarching system to which they belong. A functioning is successful if it matches or comes close to the relevant prototype, and it fails the instant it crosses a threshold beyond which it no longer contributes sufficiently to the functioning of the higher-level system.

It is also possible to order functions themselves. This can be done in different ways, but the way that concerns us here is an ordering of functions on the basis of the degree to which they are indispensable to the functioning of the relevant overarching whole. The heart's function (to pump blood) is for example more important for the survival of the body than is the function of one skin cell to guard the body against the invasion of foreign substances. Or, as we will say, the heart's function is more *critical* to the survival of the body than is the function of one skin cell. After we subject the notion of criticality to further analysis, we will see that it is this dimension for the evaluation of functions that yields the principle for the division of the body into its major systems.

But first a note about the difference between a *successful functioning*, which is a SPAN entity, and a *critical function*, which is a SNAP entity. We have suggested a means of evaluating functionings qualitatively, based on their proximity to a prototype functioning. The latter exemplifies the ideal functioning of an element in relation to the ideal functioning of the system to which it belongs. Evaluating functionings means comparing one case of functioning, say your heart's beating, here and now, with the prototypical functioning of an ideal heart. Successful functionings are functionings sufficiently close to whatever is the relevant prototype.

Ordering functions according to how critical they are to the body's survival, on the other hand, means comparing one type of function with another type of function, say the function of the heart with that of a skin cell. The terms of comparison are: how critical is a given type of function to the survival of the body as a living organism?

It should be noted that we here use the notion of criticality in a somewhat expanded sense. In everyday speech, criticality refers to some highest degree of importance: a drought can approach criticality by becoming more and more severe. In physics a point of criticality is the point at which a nuclear reaction becomes self-sustaining. In medical science, criticality refers to the point at which the body can no longer survive: a disease is critical if it threatens the patient's life. Along similar lines, we understand a function to be critical if the body as a whole cannot survive without it. [29]

F is a *critical function* for organism Y if and only if:

(i) some element X of Y has F as its function;
(ii) the survival of organism Y is causally dependent on the continued performing of F by X to the degree that if X loses the potential to realize F then Y will die.

The function exercised by the digestive system is as critical to the survival of the body, in this sense, as is that of the immune system.

An element's function can also be critical for the continued functioning of a system at levels below that of the whole organism. Our definition of critical function can be restated with the overarching system as context as follows [29]:

F is a *critical function* for system Y if and only if:

(i) some element X of Y has F as its function;
(ii) the continued functioning of system Y is causally dependent on the continued performing of F by X.

Thus if a chloride channel in a mucous-producing gland has a certain kind of genetically inherited defect, then this can cause the gland to malfunction and produce an excessively thick fluid. If the gland is in the respiratory epithelium, where its function is to produce a thin slime to moisten the surface of the epithelium, then this can cause problems in respiration. If the gland is in the pancreas, it can cause the pancreatic fluid to be too viscous to leave the pancreas. In this case, the pancreas malfunctions and causes problems related to nutrition-intake. Thus it is possible for one low-level element to be critical for more than one system.

5.3 Degrees of Criticality

Criticality can also admit of degrees. The function of the vocal cords is not critical to the survival of the body, and neither is the function of the thigh muscle. But the function of the thigh muscle is probably *more critical*, or in other words has a *higher degree of criticality*, than the function of the vocal cords. This is because, at least in the case of most organisms and most environments, it is harder for an organism to survive if it cannot run or walk than if it cannot utter sound.

A system element has a low degree of criticality if the system can still achieve its function even if the element is set out of action. For example, the circulatory system still functions if some particular arterial branch is occluded by a thrombus in such a way that it no longer functions to supply certain regions with blood. For in practice, in some parts of the body (though not in others), the needed blood flow will be provided via collateral arteries. That means that this particular arterial vessel has a low degree of criticality to the circulatory system as a whole.

All of the branches of the aorta taken together, on the other hand, have a high degree of criticality in relation to the circulatory system. If they are set out of action this does not mean that the system will stop functioning, but it does mean that it will be impaired to a much higher degree than in the case of the absence of a smaller branch, or in the absence of only one branch of the aorta. And in some cases branches of an aorta being set out of action can issue in the death of the organism.

The criticality of a given function to the survival of a given individual is sometimes relative to the individual and to its environment. In this respect, an evaluation of functions according to their criticality is similar to an evaluation of functionings according to their success or failure. Note however that criticality of functions can only be relativized in certain limited cases. The function of the heart is always more critical than is the function of the thigh muscle.

There are other respects in which an evaluation of functions according to criticality overlaps with an evaluation of functionings according to success or failure. There is not enough room here for a comprehensive account of this overlap. Suffice it to mention a few brief points. One is that an element with a critical function probably has a thinner margin within which its functioning can deteriorate from its prototype without ill effects for the organism as a whole, as compared to an element without a critical function. The liver, for example, must realize its function to remove waste much more successfully than the tonsils must realize their function to guard the oropharynx.

Another point at which evaluation of the success of a functioning overlaps with evaluation of the criticality of a function is in certain abnormal circumstances. For example, the lungs and kidneys are both elements of systems responsible for the maintenance of the body’s homeostasis. One function of the kidneys is to maintain ion and water balance, which they realize in part by excreting redundant ions in order to avoid acidosis (i.e. blood pH level becoming over-acidic). If the kidneys are unsuccessful in this performance, then the lungs take over: they can maintain the blood pH level, making it more alkaline by means of a more intensive gas exchange. But the lungs can substitute for the kidneys in this way only temporarily. The lungs, then, have one function that becomes critical only in the unusual circumstance of kidney failure.

5.4 Critical Functions and the Spatial-Functional Hierarchy

Recall that the spatial-functional hierarchy is organized on the basis of two features of the body: its complex anatomical structure, and the functions that are realized through the processes that this structure allows for. Elements on lower levels are parts of elements on higher levels, and, correspondingly, their functioning contributes to the functioning of the elements on these higher levels.

The circulatory system exists one level down from the body as a whole. As such, its functioning (transporting nutrients, waste material, oxygen, and cells among bodily systems) contributes to the survival of the whole body. The heart is an element of the circulatory system one level down: it is both a part of the circulatory system, and it has a function that contributes to its function.

We can now see that a correlation emerges between criticality and spatial-functional level. Elements with functions at higher spatial-functional levels are also more critical. In other words (and as a rule of thumb only) the fewer systems you have to count upward from a function before you reach the function of the body as a whole, the more critical the function is to the whole organism. For example, the brain exists on a high spatial-functional level: there is only one brain in the whole body, and it has a critical function. Each single neuron, on the other hand, exists on a low spatial-functional level and does not have a critical function because it stands in a relation of redundancy to other neurons.

This correlation between criticality and spatial-functional level casts light on the way in which redundancy factors into the spatial-functional hierarchy. Briefly, we can say that the lower the spatio-functional level, the fewer examples we find of criticality and the greater the redundancy of functionings. Thus the mutation of one single cell does not cause cancer in normal conditions (which means: where the immune system is functioning successfully). For this we need the presence of the same mutant gene in a multiplicity of cells within a single tissue.

It should further be noted that it is functions, not elements, that are critical. It might sound strange to say that it is your aorta's function that is critical to the functioning of your heart rather than the aorta itself. But consider what happens when your aorta is replaced by a prosthesis: the prosthesis then provides a substitute for the aorta in the context of your body.

Finally, elements may be paired with other elements. One of your two kidneys has a non-critical function in the body's normal state, but it becomes critical if the contralateral kidney is damaged or removed and nothing else performs its function. Your kidneys taken together, however, do have a critical function.

There are clearly many types of criticality. Is the heart more critical than the stomach because the body will die sooner in virtue of a malfunctioning of the heart? An expansion of this account can break down criticality into its different types. For now, however, since we have explored how the criticality of a function goes hand in hand with its placement on the spatial-functional hierarchy, we have what we need to explain the reasoning behind a division of the body into its major systems.

6. How the Body is Demarcated into Bodily Systems

6.1 Bodily Systems as Fiat Objects

Note, first of all, that the demarcation lines among bodily systems are to some degree a matter of fiat; they are boundaries inserted by human beings for the purposes of constructing good (predictively powerful) causal theories. [31] There are physical discontinuities, such as membranes, between many of the elements in bodily systems, but as we have noted these discontinuities only provide partial causal isolation. And many elements have functions for more than one system. A further argument for the fiat status of bodily systems is that no identifiable group of genes has been discovered in any creature for the creation of any of the systems included in the lists above. To accept that the demarcation of the body into bodily systems is to some degree a matter of fiat is not, however, to imply that bodily systems do not in fact exist. Mount Rainier, too, is an entity demarcated at least in part as a matter of fiat. [32] Moreover, the hand and arm are demarcated from the rest of the body in virtue of fiat demarcations and not in virtue of any real physical discontinuities, and this is so even though there are identifiable groups of genes for their creation. Finally it should be stressed that every bodily system will be marked out by demarcations, for example of its organs, which are almost entirely of the bona fide sort.

6.2 Critical Systems

We suggest that it is some implicit notion of criticality that has provided the basis for the reasoning underlying current classifications of bodily systems. Medical scientists, in delineating such systems, had to take into account the whole body, since it is in the context of the latter that constituent elements realize their functions. And all of the top-level elements of the body standardly accepted as bodily systems are critical to the body's continued survival.

We can see that the bodily systems are interconnected in such a way that if one system ceases to function then so also, by virtue of the ensuing death of the whole organism, do all the other systems. The death of one is the death of all. However, there is a certain sequentiality to this interdependence, so that the pathologist is in the overwhelming majority of cases able to establish *which* system was responsible for causing the organism's life processes to cease.

Consider how this applies to the regulatory systems. The autonomous nervous system, which is a regulatory system of the vegetative functions of the body, has as one critical element the brain stem. A mild stroke in the area of the hypothalamus, where the vegetative centres of regulation are localized, is life-threatening. Another regulatory system is the endocrine system, of which the pancreas is a critical element. If the pancreas does not realize its function to secrete insulin, the organism will not be able to use glucose, and it will die. The immune system has as critical elements T-lymphocytes, whose function is to kill alien cells. If this function is not performed, the organism can die of something as simple as sepsis caused by the saprophytic microflora that normally inhabit the lungs and the intestines (as for example in the case of AIDS).

Our approach suggests also how we might formulate an explanation of the reason why the standard rosters of bodily systems, while including certain commonalities, still differ among themselves in certain specific ways. As we saw, there is a certain sequentiality to the interdependence of bodily systems. If one system ceases to function, then others will follow in its train and in a certain order. If two putatively distinct systems always cease to function simultaneously – as in the case of the pulmonary and the systemic components of the circulatory system – then they may for this reason be counted as *parts of the same system* rather than as systems in their own right. Do the bones and muscles constitute two separate systems or only one? To answer this question is to answer the question whether one can fail without the other thereby failing also.

We now wish to assert the hypothesis that *all critical functions performed by elements of the body's hierarchical organization at lower spatial-functional levels are contributions to the performance of critical functions by larger systems on higher levels.* Eventually we reach some maximal level, where we are dealing with critical functions belonging to elements that contribute to the functioning of no larger system of the body than the body as a whole. The elements on this maximal level are precisely the body's major systems.

We can then define:

X is a bodily system for organism Y if and only if:

(i) X is an element of Y;
(ii) X has a critical function for Y;
(iii) X is not a part of any other system that has a critical function for Y.

Bodily systems are in other words the *largest elements* of the human body that have critical functions. Note that (ii) does not exclude elements of X having critical functions in other systems. This is important in accounting for how the failure of one system can cause the failure of other systems. For example, liver failure causes the osmotic pressure in the blood to fail, which causes wide disturbances in the body's homeostasis. In addition, the liver cannot produce components of the coagulation system, and generalized hemorrhage will occur.

Just as some elements belong to a spatial-functional level that is immediately below that of the system of which they form a part – the heart is an example of such an element, since it is not a proper part of any other element of the circulatory system – so bodily systems belong to the spatial-functional level that is immediately below that of the whole organism. The functions performed by the body's systems are given in Table 3.

System	Function
Integumentary	To separate the internal environment from the external medium
Musculoskeletal	To move (including: to maintain the shape of the body and its movement in confrontation with gravity; to separate sub-environments inside the body)
Digestive	To digest (to exchange substances: solid substances in-out, liquids in)
Respiratory	To breathe (to exchange substances: gas in-out)
Circulatory	To supply all the systems of the organism with blood
Nervous	To regulate the movement of the body (somatic part) and the vegetative functions of the internal organs (autonomous part)
Endocrine	To regulate metabolism, growth and development and the sexual differentiation of the organism
Immune	To preserve the substantial integrity of the organism
Urinary	To urinate (to exchange substances: liquid out)

Table 3: *Bodily systems and their functions*

Of course it is possible that, if an element several levels below the body as a whole ceases to function, then the life of the body itself could be brought to an end. Does this undercut our conception of the spatial-functional hierarchy? No; rather it forces us to take into account causal processes that relate one spatial-functional level to another. The heart is a critical element of the circulatory system; the circulatory system is a critical element of the whole body. If the heart stops, the body dies. But it is not the heart's stopping that directly *causes* the body to die; rather, the heart's stopping causes the circulatory system to stop functioning, which in turn is what causes the body to die. So an element on a lower spatial-functional level, separated from the body as a whole by several other levels, does not directly cause the body to stop working. It does so only by means of intermediate causal links. A spatial-functional hierarchy accounts for these links.

You do not die because you lose a foot or your eyes. Standard sources do not classify the visual and other perceptual systems as bodily systems alongside those given in our list above – in keeping with our thesis that visual perception is not a critical function of the human organism. Our analysis enables us to understand why there is no shared opinion on how to classify the reproductive system in the standard sources. Some accounts tack the reproductive system onto the urinary system and refer to one composite 'urogenital system.' Some accounts refer to a 'genital system.' And some accounts do not mention reproduction at all. We see this as additional evidence for the correctness of our analysis, for it means that it casts light not only on what is broadly shared by standard rosters of the body's systems but also on the ways in which these rosters differ among themselves.

Clearly the reproductive system does not have a critical function in maintaining the body's life processes (though it might be said that it does have a function critical for the survival of the species, if our account of *system* turned out to be applicable to systems outside the locus of the body itself). The reproductive system differs further from the other systems in that it comes in two, mutually complementary forms. For its functioning we need individuals of two sexes, each of which contains only part (a half) of the system as a whole.

Our approach suggests, too, how we might formulate an explanation of the reason why some textbooks of anatomy include both bones and joints in the skeletal system, while others, including both the *Nomina* [33] and the *Terminologia Anatomica* [9], represent bones and joints as two separate systems.

7. Conclusion

We have sought to set out the tools for providing an analysis of 'bodily system' in a way that will do justice to the way this term is used in existing standard sources, while at the same time providing the necessary degree of formal precision to form the basis for a future domain ontology of spatial-functional anatomy. Our account yields a roster of bodily systems that corresponds to a large extent to those given in the standard reference sources. If we are correct, we have hit upon some important characteristics that the systems listed in the standard rosters have in common. This does not prove that we are correct in thinking that those systems are correctly described by using the same term, or that 'bodily system' is that term. But the strong correlation between standard rosters and our account pushes us in the direction of believing that we are on the right track.

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