Bodily Systems and the Modular Structure of the Human Body

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Abstract. Medical science conceives the human body as a system comprised of many subsystems at a variety of levels. At the highest level are bodily systems proper, such as the endocrine system, which are central to our understanding of human anatomy, and play a key role in diagnosis and in dynamic modeling as well as in medical pedagogy and computer visualization. But there is no explicit definition of what a bodily system is; such informality is acceptable in documentation created for human beings, but falls short of what is needed for computer representations. Our analysis is intended as a first step towards filling this gap.

1. Bodily Systems and Medical Ontology

The Institute for Formal Ontology and Medical Information Science in Leipzig is constructing a reference ontology for the medical domain. It is designed not as a computer application in its own right but as a framework of axioms and definitions relating to such general concepts as: *organism*, *tissue*, *disease*, *therapy*. Here we focus on the concept *bodily system*, which we believe will serve as a central factor in a robust ontology of the human organism.

The division of the body into its major bodily systems is by no means unproblematic. The *National Library of Medicine*[1] lists eight body systems, including the urogenital system; *Wolf-Heidegger's Atlas of Human Anatomy*[2] lists only seven systems, etc. Standard sources often divide systems into three groups of *supportive systems* (the integumentary and musculoskeletal systems), *exchange systems* (the digestive, respiratory, circulatory, and urogenital systems), and *regulatory systems* (the nervous, endocrine, and immune systems). However there are elements of exchange systems (for example parts of the liver and pancreas) which play a role also in regulatory systems, and the three regulatory systems themselves effect their functions of regulation via a certain sort of substance-exchange.

Medical textbooks rest on informal explications of the general concepts of 'system' and 'function' which concern us here. While such informality is acceptable in documentation created for human beings, who can draw on their tacit knowledge of the entities involved, medical information systems require precise and explicit definitions of the relevant terms. The analysis presented here is intended as a first step towards providing a framework for such definitions.

2. Body Systems, Elements, and their Functions

The first step in making sense of standard rosters of bodily systems is to recognize that we can divide the living human body (referred to in what follows as the 'body') into components of specific kinds, which we shall call *elements*. 'Element' can be understood as a generalization of concepts such as *organ* and *cell*.

Elements are distinguished from other parts of the body by their *causal relative isolation* from their surroundings and by the *functional role* they have in the workings of the body as a whole. Elements are elements only *for* larger systems to which they belong. Some elements of the digestive system are the stomach, the serous membrane, the layers of smooth muscular tissue, and so forth. Corresponding functions include: providing the stage for the digesting process by mixing the bolus with hydrochloric acid and pepsin, external coverage of the stomach and its constriction.

Elements can be distinguished on a number of different levels of granularity.[3] *Granularity* is a means of representing the hierarchy among elements of bodily systems; such a hierarchy is arranged according to the functions of the respective elements. Functions located at lower levels interact in complex ways to enable functions at higher levels. At all but the highest level, each function of a system is a sub-function for an umbrella system at a higher level. The kidney's function is to excrete urine, which it does via a composite process consisting 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.

The dividing of functions into sub-functions mirrors the dividing of systems into elements: what is a system at a lower level may be an element at a higher one. The heart itself is a system consisting of the myocardium, endocardium, pericardium, etc. The latter have their own specific functions and comprehend their own elements (e.g., different types of cells). Each cell is a system that consists of elements such as nucleus, mitochondria, endoplasmic reticulum, which are in turn systems in their own right with their own specific functions.

Element and function have a parallel relationship in that an element's place in the body's granular hierarchy is determined by its function. However, every organ in the body performs a multiplicity of functions – which is why it is crucial to distinguish between a body part and a system element. A body part belongs to the body by virtue of its physical attachment; an element belongs to a system by virtue of the function it performs for the system. The kidney is a part of the body whether the body is dead or alive, functioning or not, but it will only be an element of the urinary system while the system is capable of functioning, i.e., as long as the body is alive.

It is by virtue of the complex organization of the body's granular hierarchy according to the functioning of systems and subsystems that enables the body to regulate its own state and structure. Its ability to perform this regulation depends on the very specific type of organization which is present already in single-celled organisms, where we find processes of metabolism, waste excretion, DNA replication, and structural support performed by corresponding elements arranged in modular fashion into systems. Without the performance of such functions the body will die. It is this fact which yields the principle for the division of the body into its major systems.

The body's systems and elements were developed by evolutionary processes. Our bodily systems exist as they do because the bodies of our immediate predecessors had similar systems, which performed functions that proved conducive to their survival. Those functions of a given element that enable the whole organism to survive, and thus reproduce successive generations of the same type of element, are called the *proper functions* of this element.[4]

We can now state our definition of 'element': X is an *element* of Y if and only if: (i) X is a *proper part* of Y and Y exists on a higher level of granularity than X; (ii) X is *causally relatively isolated* from the surrounding parts of Y; (iii) X has a *proper function* which contributes to the proper function of Y; (iv) X is *maximal*, in the sense that X is not a proper part of any item on the same level of granularity satisfying conditions (i) to (iii).

Only those entities that have proper functions inside your body are elements of your body according to this definition. 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, but it is neither an element nor a part of your body, because the directions given by the virus interfere with your body's proper functioning.[5]

The proper functioning of your parents' hearts ensured that their circulatory systems worked; combined with the proper functioning of their other bodily systems, this enabled them to produce you and your heart. Thus the proper functions on each granular level need to be lined up in a complex branching structure so that they can be executed to support the survival of the whole organism. To understand the nature of this ordering of bodily functions is to understand the role of the body's major systems in the organization of the body as a whole.

3. Criticality and Bodily Systems

The body is full of redundancy, so any of its elements can cease to function for certain periods, yet the body will still survive as a living organism. But some functions are *critical*: if they are not executed, the body dies. We can define *critical function* as follows: F is a *critical function* for a system Y if and only if: (i) An element of Y has F as its proper function; (ii) F is performed by element X of Y and no other element of Y performs F; (iii) the continuing to function of system Y is causally dependent on the continued performing of F by X.

An element's function may become critical in special circumstances, including cases of disease. Each kidney has a non-critical function in the body's normal state, but it becomes critical if the contralateral kidney is damaged or removed. But your kidneys taken together do perform a critical function by the terms of our definition.

Understanding criticality will help us understand how elements relate to the whole systems of which they form a part. *All critical functions performed by elements of the body's hierarchical organization at lower levels are contributions to the performance of critical functions by larger systems on a higher level of granularity*. Eventually we reach some maximal level where we deal with critical functions that belong to elements of the body that contribute to the functioning of no larger body part except 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 has a critical function for Y; (ii) X is not a proper 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*. Just as some functions belong to a level of granularity that is immediately below that of the bodily system to which they contribute, so bodily systems belong to the level of granularity immediately below that of the whole organism. The body's systems, in spite of their relative causal isolation, are still massively causally interconnected. If one system ceases to function then so, by virtue of the ensuing death of the whole organism, do the others. But this interdependence is sequential in the sense that a pathologist can almost always establish *which* system was responsible for causing the organism's life processes to cease. In order to understand this sequentiality we need to keep careful track of the levels of granularity of elements (systems and subsystems) with which we deal. There then emerges a proportional relationship between granularity and criticality: the fewer umbrella systems you have to count upward from a function before you reach the critical function of a whole bodily system, the more critical the function is – and the higher its granular level. Breaking a finger will not kill you, but losing your liver or heart will.

Evolutionary development has tended to follow a principle of economy (or co-option): given elements can evolve to have functions for two or more systems at different times, and are thus sites for the systems' functional and structural overlapping. The male urethra provides a pathway for both urine and sperm. It thus has the function of allowing urine to exit the bladder and sperm to be ejaculated; the former is critical for the urinary system, the latter for the reproductive system.

The body is full of overlap: every element has functions for multiple systems. The functions of system elements can be classified on a scale of degree of criticality. A function has a low degree of criticality if the system still achieves its function when the element that performs it is disabled. The circulatory system still functions if some arterial branch is occluded by a thrombus and no longer supplies certain regions with blood, for collateral arteries will provide the needed blood flow. So this particular arterial vessel has a low degree of criticality to the circulatory system.

This kind of redundancy contributes to the body's modular structure. The lower the granularity, the fewer examples we find of criticality, and the greater the redundancy. Thus where the immune system is executing its proper function, the mutation of one single cell does not cause cancer. For this we need the presence of the same mutant gene in a multiplicity of cells within a single tissue.

4. Conclusion: Demarcating the Body into Bodily Systems

Our approach suggests how to explain why the standard rosters of bodily systems, while they contain many commonalities, still differ among themselves. Some textbooks of anatomy include both bones and joints in the skeletal system, whereas the *Nomina*[6] and the *Terminologia Anatomica*[7] represent bones and muscles as two separate systems.[8] As we saw, there is a sequentiality to the interdependence of bodily systems: if one system ceases to function, the others will follow, in a certain order. If two putatively distinct systems always cease to function simultaneously – such as the pulmonary and systemic components of the circulatory system – then they are not systems in their own right, but *elements of the same system*.

Note that the demarcation lines among bodily systems are to a degree a matter of fiat; they are boundaries inserted by human beings for the purposes of constructing predicatively powerful causal theories. In this respect bodily systems are comparable to the body's extremities. We say that the human body has arms and legs as parts. But there is no bona fide boundary (no physical discontinuity) constituting the border between your arm and the rest of your body. Here, too, there are fiat boundaries by which we (cognitively) divide the body into parts.[9]

Our analysis comes close to yielding the core roster of bodily systems that standard medical textbooks share. It helps us understand why there is no standard opinion on how to classify the reproductive system within such rosters. Some accounts tack it onto the urinary system and refer to one composite 'urogenital system'; some refer to a 'genital system'. We see this as evidence that our analysis can shed light not only on what is broadly shared by standard rosters of the body's systems but also on the how these rosters differ.

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