“Physics Envy” and Engineering Design

Paul Winkelman
University of British Columbia
pwinkel@mech.ubc.ca

Abstract

“Physics envy” is the condition where non-physicists attempt to model their discipline after physics in the hope of gaining credibility. This ailment is not uncommon among engineers and its negative impact is most strongly felt in engineering design. Biology offers some insights into this phenomenon for it, too, suffers from “physics envy” but has the luxury of a strong philosophical base to draw on. Much of what separates engineering and biology from physics can be attributed to a preoccupation with function. Within the paradigm of physics, however, function is a foreign concept. We can ponder the function of a human organ or a mechanical part, but the entities of physics, such as atoms, have no functions, only effects. Function implies the possibility of failure, such as a heart failure or a mechanical breakdown, but atoms never fail; they simply are. Function speaks of systems which cannot be contained within spatiotemporal boundaries, boundaries which physics cannot transgress. “Physics envy” therefore serves to undermine research and practice in engineering design.

1. Introduction

Dennett [1] claims that some biologists (or philosophers of biology) suffer from “physics envy”. For instance, Kauffman, according to Lewin, is on a quest for “the physics of biology” ([1], p. 227). This quest is often manifested as a search for new laws. The problem, maintains Dennett, is that this quest “distorts so much of the philosophical thinking about biology” ([1], p. 227).

At first glance, the claim that physics distorts biology may seem counterintuitive. Physics and biology are, after all, both *sciences*. Both are bounded by physical laws, those regularities that we seem to see in the world around us. However, some regularities cannot (or should not) be reduced to physical laws. We observe nutritional regularities in nature, but this does not necessarily speak of *laws* of

nutrition [1].

We may also assume that physics and biology are mutually supportive in that they satisfy our curiosity in ways that only science can, answering those nagging “why” questions (why is the sky blue? why do birds fly south for the winter?). But this, too, is misleading, for the “why” of physics is, more often than not, very different from the “why” of biology.

Suppose I am talking to a friend and I am having difficulty hearing her. I might ask, “Why are you whispering?” She might answer, “My throat is sore”, or “I don’t want anyone to hear”. The first response assumes I wish to know the cause or reason for the whispering (“how come?”); the second assumes I am interested in the purpose of the whispering (“what for?”).

Physics deals almost exclusively with the first kind of “why” question. Hence, if I ask a knowledgeable physicist, “Why is the earth tilted on its axes?”, I would expect an answer which describes those events which *caused* the earth to be tilted. It is highly unlikely that the physicist would interpret my question as seeking the purpose of the earth’s tilt, leading to answers such as, “To bring seasonal variation”.

Biology, on the other hand, is very fond of purposive “why” questions. If I ask a question such as, “Why do humans have a pancreas?”, biologists are likely to assume that I am interested in the *purpose* of the pancreas, what a pancreas *does*. They may also assume, like physicists, that I am asking a causal type of “why” questions. A response in this case might be a description of those events which led to humans having a pancreas.

Some fundamental differences therefore exist between biology and physics, for biology favours the very questions that physics disallows. Any attempt, therefore, on the part of biologists to align their discipline with physics risks rendering the purposive type of “why” question null and void. Biology, as we know it, would cease to be.

“Physics envy” therefore does biology no favours. It does engineering no favours, either, for Dennett claims that “physics envy” is “anti-engineering” ([1],

p. 227). For those engineers inclined to readily associate engineering with physics, this, too, would seem counterintuitive. How can physics go *against* engineering?

Dennett devotes an entire chapter where he develops his argument succinctly contained in his bold statement, “Biology is engineering” ([1], p. 187). He appears to defend this statement by positing an organic entity as an engineering artefact. For example, he maintains that biologists use reverse engineering. Within engineering itself, reverse engineering refers to examining an existing product to determine how it works. To carry out this procedure, one *must* assume that the various components of the product are there for a reason (as distinct from a *cause*). Biologists take the same basic stance. It is very difficult to imagine a non-engineering way of determining how a heart works.

If we find Dennett’s claim plausible, and biology really *is* engineering, then as physics is against biology, so it is against engineering. Furthermore, if biology suffers from “physics envy”, then it is quite possible that engineering, too, suffers from “physics envy”. And if “physics envy” distorts the view of biology, then it may also distort the view of engineering.

2. Objective

My basic premise is that engineers often suffer from “physics envy” and this distorts their view of engineering. My objective is not so much to demonstrate the existence of “physics envy”, but rather how this envy sets up unnecessary obstacles to engineering research and practice, particularly with respect to design.

I will be drawing heavily on the philosophy of biology to develop my arguments. The reason for this approach is that the philosophy of biology is much richer than the philosophy of engineering (Dennett maintains that many assume “there couldn’t possibly be enough conceptual material of interest in engineering for a philosopher to specialize in”, ([1], p. 188)) and many of the issues relevant to biology are also relevant to engineering. And perhaps this may demonstrate that there *can* be a philosophy of engineering.

3. Beginnings

The beginnings of physics can perhaps be traced to Galilei Galileo (1564-1642), the “father of modern physics” ([2], p. 155). Galileo is probably best known for his promotion of the Copernican model of the universe. Galileo claimed that observational data

suggested that the sun rather than the earth was the centre of the solar system. As this was contrary to the established view, a confrontation ensued between Galileo and religious authorities. The issue would seem to have been whether the removal of the earth from the *geometric* centre implied that humans should also be removed from what might be called a “*cosmic*” centre. From a physics point of view, however, Galileo was merely fitting data to a (Euclidean) geometric model. Galileo’s “fatherhood” and the “modernity” of physics are based on the idea that theories of the cosmos should be based not on preconceived ideas, but rather on observational data supported by mathematical modelling.

Biology’s beginnings were not quite so long ago and did not seem to make the grand entrance that has made Galileo a household name. According to Foucault [3], biology began to take shape with the work of Georges Cuvier (1769-1832), a French natural historian, often credited with the founding of comparative anatomy and paleontology [4]. Cuvier conceived of the notion of “correlation of parts”. He noticed that, for a given organism, certain characteristics can predictably be seen to occur together. For instance, if an organism has sharp teeth, we can expect this same organism to have sharp claws and a particular kind of digestive tract. In its extreme case, we can think of reconstructing an entire organism based on a single bone.

What is significant about Cuvier’s work was that he was connecting parts of an organism that were physically separate, for the fangs, stomach and claws of a lion are not in physical contact with each other. Cuvier joined these disparate parts together using the concept of a *system*. Thus began biology.

To a certain extent, physics, too, deals with systems. Indeed, Galileo’s work was concerned with the solar *system*. It is so called presumably because of its geometrical qualities, with a geometric centre (the sun), planetary pathways around this centre and fairly well defined boundaries (the orbits of Pluto and/or Neptune). This system was held together with that later-defined Newtonian glue termed “gravity”.

Cuvier’s system resembled Galileo’s system in that it required the construction of a pathway. For example, he connected the claws, teeth and digestive tract by tracing the path of food through the animal’s body. This path, however, is not circular. We can infuse some circularity if we extend the pathway to the more comprehensive carbon cycle. The circularity here is, of course, metaphorical, not geometrical. As a *process*, Cuvier could not hold his pathway together with gravity or mathematics. He needed a new, non-Newtonian glue. This he found in *function*.

Biology thus embodies a form–function conceptual

paradigm. The form-function concept is not sufficient to define biology for function *had* been applied to living organisms or organs before Cuvier. What was different, according to Foucault [3], was that, previously, form and function had been applied independently, yet coincidentally, to a given organ. The former was used for purposes of *identification*, and the latter to describe its *utility*. With Cuvier, the concept of function was placed within a system rather than confined to an individual organ.

4. That Which is Hidden

Prior to Cuvier, classification systems of living things had been based on readily apparent attributes, described with four basic variables: form, number, arrangement and magnitude. Thanks to Cuvier's "correlation of parts", a new classification system became available, but with reference to characteristics that were not so apparent. Cuvier had exposed that which had been hidden [3]. We can think of the hiding as occurring on two different levels.

The first level is based on the formal qualities of organisms and organs. Using the old classification scheme, a horse and a dog, for example, would be placed in separate classes, for a horse does not look like a dog. Both have four feet, but the feet are quite different. We can, however, find greater similarities by probing *inside* the animals. The heart of a dog is quite similar to the heart of a horse. Exterior differences melt away as we move inside. Hence, these two species are, "connected by the inaccessible, and separated by the apparent" for "multiplicity is apparent and unity is hidden" ([3], p. 267).

The second level of hiding requires more abstract constructs. If we are convinced that the foot of a dog should be in the same class as the foot of a horse, it is very difficult to do so based solely on their physical appearance. However, once we assign a function to each of this disparate forms, union becomes straightforward, for they have similar patterns of use. The use patterns imply that we view these appendages as part of a larger system. Thus, function confined to an individual organ does not strongly suggest a classification scheme; it is only when function is seen from a systems perspective that the classification becomes workable. We can rephrase Foucault's statement as: "connected by function and separated by form".

Returning to the two "why" questions, it becomes clearer why biology is able to handle the purpose-type "why" questions. When we ask, Why do humans have a pancreas?, what we want to know is the *function* of the pancreas.

Physics, on the other hand, cannot accommodate

purposive "why" questions, for function does not exist within its paradigm. Physics is afunctional. Questions such as, What is the function of the earth's tilt? are incomprehensible. For the physicist, the seasonal variation is not a function but an *effect* of the earth's tilt (the cause).

Engineering, like biology, relies heavily on the concept of function. This is particularly true in design. Physics cannot tell us which parts to bring together to form a system that functions as a unit. The analytical power that physics provides can only come into play after the parts have been brought together, where form, number, arrangement and magnitude become evident. Hence, physics relies on the very classification system that biology necessarily rejected.

5. Hierarchies

As we move from the inside of an organism to the outside, we move from what unites various species to what separates them. At the same time, we move from what is essential to the organism to what is more expendable or accessory. A horse, for example, can live with three legs, or perhaps even no legs, but it cannot live if its heart is removed. Therefore, what unites various species and what is essential to them are one and the same.

The extent to which a given organ is essential to an organism speaks of its importance. A heart is more important than a leg. With this reasoning, a particular level of importance can be assigned to each functional system as it is identified. As different levels of importance are assigned, a hierarchy is created. Hierarchies are, of course, not unique to biology, but not all hierarchies are created equal. Lane's [5] four kinds of hierarchies can serve to highlight some of the unique features of biological hierarchies.

An *order* hierarchy consists of entities which are ordered according to some selected variable. For example, we can create a hierarchy of cities based on population.

The second type is the *inclusion* hierarchy. Here Lane makes extensive reference to Simon's "Chinese boxes", where one box is located within another. An entity is thus a container which contains other containers. In order to arrive at a given container, one must pass through all the containers which contain it.

The *control* hierarchy is commonly used to describe social organizations. These hierarchies are often constructed with a single entity at the highest rank. A good example of a control hierarchy is the military where the soldiers constitute the entities (note that if the entities are command units, such as platoons and companies, the arrangement forms an inclusion hierarchy). An important concept of the control

hierarchy is that of *flow*: orders flow down and requests and information flow up (similar to criminal organizations where governance flows down and money flows up [6]). Those of the lower ranks are expected to *obey* those of the higher ranks.

The *level* hierarchy consists of entities arranged in levels according to their particular spatiotemporal scales. Entities within a given level are fairly autonomous from entities of other levels. This type of hierarchy is characterized by causation: upward causation refers to higher-level entities being composed of lower level entities; downward causation refers to changes to the properties and interaction modalities of the lower-level entities as they are incorporated into the higher level entities. Examples of this kind of hierarchy include physics/chemistry (elementary particles, atoms, molecules), biology (cells, organs, individuals, species), economics (individuals, departments, firms) and linguistics (letters, words, phrases, sentences). Some may also be classified as inclusion hierarchies.

Lane unfortunately makes no notable distinction between biology and physics for he describes *both* as using level hierarchies. Cells are presented as the biological equivalent of the elementary particles of physics (*i.e.*, as building blocks). This parallelism fails to capture Cuvier's biology where living things are arranged by functional systems, not space and time, for cells alone can never unite fangs, claws and stomachs. Something has been left out.

The misstep becomes clearer with reference to engineering design where hierarchies are typically used to create form-function maps. Function is normally at the topmost (most abstract) level, and forms of varying specification are positioned towards the bottom. As each function can be fulfilled with a range of forms, the inclusion hierarchy seems appropriate. However, this misrepresents the form-function connection since the opposite is also true: a single form may fulfill more than one function (*i.e.*, a "box" must be simultaneously contained within two or more un-nested boxes).

The design situation resembles what Lane [5] calls a "tangled" hierarchy. As the entanglement increases, the legitimacy of the hierarchy is called into question, perhaps to the point where the hierarchy itself becomes impotent. Although function may invite a hierarchical structure, it is not a straightforward affair. Cuvier encountered similar problems of entanglement, for the systems of the human body frequently overlap.

Hierarchies are often used as a means of explaining science itself. Lane, for instance, considers the work of Anderson who arranges sciences thus: elementary particle physics, solid state or many-body physics, chemistry, molecular biology, cell biology and on to

physiology, psychology and social sciences at the top. As each field is studied quite independently, we might view the arrangement as a level hierarchy. "Upward" causation refers to elementary particles of physics which are expected to be the building blocks of all reality. Downward causation might be akin to Holland's [5] "emergent" properties where simple rules produce novel, complex patterns. Alternatively, we might claim that this arrangement of sciences is a control hierarchy, for the non-physics science are expected to *obey the laws* of physics. As governance flows down, physics moves to the topmost position. But what is flowing up?

Engineering is not mentioned within the hierarchy of sciences. This fact draws our attention once again to how hierarchies leave things out. Engineering can acquire some solace by claiming it uses science, but is itself not a science. "Physics envy" would imply, however, that engineering *wants* to be a (physics-like) science.

6. The Coalescence of "Why"

Although biology and engineering share the concept of function, this very concept gives rise to a point of contention. Engineers associate function with intentionality; biologists generally do not. This has compelled biologists (or philosophers of biology) to examine the intricacies of function in greater detail than engineers would deem necessary. The debate has led to two basic views of function in biology: the aetiological approach and functional analysis [7].

Wright [8] is normally associated with the aetiological approach. Contrary to Foucault [3], he sees neither utility nor the existence of a system as sufficient for the identification of a function. For example, the second hand on his watch, with the function of "reading seconds more easily", he finds quite useless; the beating sound of a heart, though not a function, can be useful, such as in the diagnosis of heart ailments. For Wright, what makes a particular behaviour of an object a function is that the function *explains* the presence of the object. The heart is part of the body *because* it pumps blood. The heart makes a beating sound by *accident*, and therefore cannot be considered to be a function.

Wright's aetiological approach portrays function as addressing a causal type of "why" question. Eschewing intentionality, Wright maintains that the function of a particular form can only be determined by reconstructing the form's history. The history consists of a series of cause-and-effect links which tells what *caused* a particular feature of an organism to come into existence or, more precisely, to be selected (termed "natural selection"). Hence, where there is no

history, there can be no function. Function is a thing of the past.

Cummins [9] denies that a behaviour of a form is designated “function” because it explains the presence of the form. Rather, a behaviour of a form is designated a function because it describes a *capacity* of the form. Furthermore, this capacity is realized within a containing system. Hence, pumping is a function of the heart because the heart has a capacity to pump blood and it does so within a containing (circulatory) system. The concept of “system” links Cummins’ analysis with that of Foucault.

To a certain degree, Cummins’ functional analysis addresses the purposive type of “why” question. A capacity within a containing system is so identified as it makes a contribution to, or serves a purpose within, that system.

An important feature of Cummins’ approach is that function refers to a capacity at the time of observation. Hence, functional analysis makes no attempt to reconstruct the past and cannot, therefore, answer the causal type of “why” question. The heart has a function regardless of where it came from (*i.e.*, its evolutionary origins). This is not unreasonable, for as Cummins himself states, it is quite possible to carry out a functional analysis independently of evolutionary considerations. However, lacking causal explanation, the model fails to distinguish between “real” functions and accidental functions. Hence, the beating sound of the heart could easily be construed as a function.

It is perhaps this weakness of Cummins’ approach that functional analysis is viewed as “never gaining the immense popularity of aetiological analyses” ([7], p. 115). “Physics envy” would have predicted this as Wright’s insistence on causal connections necessarily aligns him with physics. Does this mean that the concept of function as purpose has become obsolete in biology?

Despite appearances, Wright’s analysis can be shown to address questions of purpose through his reference to “selection”. The heart, for example, was consistently selected over an extended period of time because it pumps blood. Hence, the questions, “What is the purpose of the heart?” and, “What caused humans to have a heart?” coalesce for those events that caused humans to have a heart also tell us the purpose of the heart.

This seamlessness, however, hides a few problems. By insisting on causality, the presence-explaining power of function necessarily relies on a reconstruction of the history of a particular form. It remains unclear, however, how one can reconstruct the history if one does not already have a function in mind. Function itself speaks of a system, for function

is indeterminate if the object is isolated from the system. A system is further implied by the term “selection”, as selection is only possible within a context (*i.e.*, the environment). Selection also hints at utility within that context. Finally, “selection” itself is not used in physics: the sun does not select the earth, there is merely a reaction between the two orbs.

Engineering function can be understood in terms of both the aetiological approach and functional analysis. Functional analysis tells us that a bolt sitting by itself serves no identifiable function. As part of an assembly, however, that same bolt may be viewed as serving the function of, say, “fastening”. The aetiological approach tells us that a bolt sitting by itself *can* have a function. Engineers assume a function based on the history of its use (*i.e.*, standard use) rather than its current context.

The engineering paradigm can also easily handle the two types of “why” questions. The causal “why” can refer to how a part is made, and the purposive “why” refers to the intent of the part. Alternatively, we can construe the “why”-as-cause as referring to behaviour and the “why”-as-purpose as referring to function. This is basically the Function-Behaviour-Structure (F-B-S) model [10]. Models of design with stronger affinities to physics tend to merge function and behaviour.

7. Failure

Function implies the possibility of failure. Engineering components fail. Human organs fail. Whereas form identifies an object (*e.g.*, an organ [3] or engineering component), function identifies a failure of that object.

Physics, being afunctional, need not pay attention to failure, for under what conditions might a building block of matter be said to fail? Perhaps the closest physicists come to failure is a failed experiment, but this merely implies faulty equipment or a misinterpretation of the true nature of nature, not a failure of nature itself. Nature, by definition, does not fail; it simply is.

8. Physics Reconstituted

Suppose we were to introduce the concept of function into physics. What would physics look like? We can get a glimpse of one such physics, I believe, through the idea of the anthropic principle (AP).

The term itself was coined by Brandon Carter who states that “...what we can expect to observe must be restricted by the conditions necessary for our presence as observers” ([11], p. 44). In perhaps more engineering terminology, we can state that “any model

of the universe must account for the model-maker”.

Within AP is the concept of fine-tuning where the physical constants as determined by physicists must have those particular values if life is to exist. Changes to these values, even small changes, would appear to make life impossible. It is as if humans were “built-in” from the beginning. Being forward-looking, the “why” of physics can no longer be confined to causal answers. Thus, when we ask, “Why does water expand as it freezes?”, we might answer, “so that ice floats and life in the ocean is possible”.

AP echoes the concept of “correlation of parts”. Cuvier sought to reconstruct an entire organism based on a single bone; AP attempts to reconstruct the universe based on a human being (or the planet Earth). The human being is quite unlike the elementary particles of physics, for humans are *not* building blocks. Nevertheless, the presence of humans on Earth has much to say about the universe. Perhaps the Earth does have some non-Copernican, central position in the universe after all.

AP serves to tie the sciences together. Within the control hierarchy of the sciences, it is generally assumed that all sciences must obey the natural laws of physics (“downward” flow). With AP, physics must now account for the physicists, and a counterflow ensues, from the social sciences “up” to physics.

9. Conclusions

“Physics envy” has long plagued biology and engineering. There seems to be this yearning to be like physics. Physics seems so neat and tidy, so self-contained, so logical, so mathematical and all-encompassing. It is the place to be. Yet, no matter how hard they try, biology and engineering are never able to get there. Something keeps getting in the way.

That “something”, I believe, is function. Function links engineering and biology together as distinct from physics. Unlike engineering, however, biology prefers to separate intentionality from function, which has led to many a lively debate. Engineering stands to benefit from these debates.

Function reveals that which is hidden. Hidden within the conglomeration of parts are *systems*. The unveiling came with the Cuvier’s “correlation of parts”. The various parts of an organism, previously joined by form, number, arrangement and magnitude were re-assembled into new units, joined by function. The unifying powers of time and space had been superseded.

Physics does not have function; its systems are bound by time and space. Its hierarchies are simple without entanglement. It places no importance on importance. Its “why” questions are always “How come?” and never “What for?” It is no wonder that physics is so neat and tidy.

As long as design remains an integral part of engineering, any effort to align engineering with physics is doomed to failure. It is not because engineering is deficient, but because it is blessed with function.

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