

Before we can determine what is fundamental and what is not, we first need to determine what *kinds* of things the question refers to. Are we discussing whether substance is more fundamental or less fundamental than process is? Are we assuming that substance is fundamental and then discussing what particular substance is the most fundamental of all? Or are we talking about scientific theories and trying to ascertain what makes one theory more (or less) fundamental than another theory? Let's start out by trying to address this question in order to set the stage for the rest of the argument.

I will argue that what we regard as fundamental must ultimately be an explanatory structure. To propose that electrons and quarks are fundamental or that space and time are fundamental or that information is fundamental all these statements are not statements about things, they are statements about ideas. Of course, I'm not arguing that these "things" do not have any objective reality; instead, I am arguing that our discourse about them is exactly that: our discourse. We shouldn't confuse our discourse with the objective reality we strive to understand. This reasoning underlies my emphasis on explanatory structures in an exploration of what the meaning of fundamental is.

I am using the term "explanatory structure" to collectively include the theoretical constructs, paradigms, conceptual models, mathematical equations, and interpretations of experimental information employed to understand phenomena. In some ways, the term is almost synonymous with "theory," but I think that it also includes somewhat broader connotations that justify the use of a different terminology in the present context.

A better idea of what I mean by an explanatory structure might be suggested by a specific case. Consider, for example, the conceptual history of electrons. Several centuries ago, electrostatic forces were already known empirically and subjected to experiment. An important conceptual model at that time was that some sort of subtle single fluid exists, with electrical forces being caused by having an excess or deficiency of that fluid (the etymology of our "positive" and "negative" nomenclature). Eventually, the rival "two-fluid" theory gained prominence. Much later, J. J. Thomson and R. A. Millikan famously demonstrated that the negative "fluid" is a component of atoms (previously thought to be indivisible), and that this component has considerably less mass than an atom. It was initially unclear whether the substance in question was a fluid continuum or a corpuscular particle, but experimental work settled that question by both demonstrating its corpuscular nature and by measuring the charge and mass of the corpuscle. In a sense, the electron, as a particle-like conceptual entity, comes into existence at that juncture. The Rutherford/Bohr model and the eventual development of quantum theory further refined our conceptual understanding of the nature of electrons, accompanied by a mathematical formalism and an array of further experimental

results. This historical process culminates in quantum field theory, which was broader and more complete, and which also explained the existence of the electron's intrinsic angular momentum (previously an *ad hoc* inclusion). At each stage of this process, there is a different explanatory structure that is used to understand the phenomenon.

Importantly, each of the explanations is a refinement and improvement of those that came earlier. But are the later explanations "more fundamental" in some sense? Are any of them (including the last, quantum field theory) fundamental in *any* sense? Given the line of reasoning here, the important question becomes: how do we ascertain whether an explanatory structure is fundamental or not? Now, we might simply say that each of those explanations was fundamental in its time, since there was nothing better at that time.

But this contention is unsatisfying, because it offers us no real criteria by which to judge fundamentality, and it ignores important differences between these explanations. For example, modern theory fits into a larger explanatory structure (including atomic & molecular physics, solid state physics, and so on), which the earlier paradigms did not. Another difference is the axiomatic structure of more recent explanations, again not shared by older ideas. Finally, nonrelativistic quantum theory can be thought of as an approximation to relativistic quantum theory under appropriate conditions, in contrast to the distinct (and in some cases incommensurable) character of some earlier ideas. Each of these attributes of the present explanatory structure of the electron might be used as a criterion to argue that our present understanding is more fundamental than earlier theories. In fact, I think these are valid criteria for such an argument. We can use such criteria to develop a hierarchy of relative degrees of fundamentality. But this still begs the question of whether even our modern explanatory structure is *truly* fundamental, fundamental in the sense of being more fundamental than anything else could be. How would it be possible to determine that? Indeed, what would the claim even mean?

I think the common answer that many people might give is that the truly fundamental explanatory structure is the one that explains everything and cannot itself be explained in terms of anything else. Such a proverbial Theory Of Everything gives us *the* fundamental explanation, and every other idea or phenomenon in the universe is derivable from it. (Indeed, sometimes the proponents of this position don't even restrict themselves to a single universe.) This framework of thinking is known as reductionism. In a reductionist reckoning, there is a kind of ladder of fundamentality: sociology is reducible to psychology, psychology is reducible to biology, biology is reducible to chemistry, chemistry is reducible to physics, and physics is reducible to the Theory Of Everything. I do not believe this position is correct, and I am arguing here against reductionism as a gauge of fundamentality.

Reductionism is deeply embedded in the thinking process of many scientists, especially physicists. In fact, I noted with interest that a reductionist mentality was actually built into some of the phrasing explicating the essay question, which might be paraphrased as: “What is fundamental, as opposed to *merely* emergent?” Emergent phenomena, in this way of thinking, are construed as that which is not fundamental. And while it is true that the constituents of the emergent entity might be perfectly simple substances that obey well-known fundamental rules, the whole point of emergence is that the rules governing the emergent entity are precisely what are *not* predicted from those so-called fundamental rules. Remember, we are interested in the fundamentality of the explanatory structure, not that of the substances. The premise of emergence in complex systems theory is that novelty emerges that’s not inherent in the explanatory structures of the simple constituents. Instead, we need new explanatory structures to explain this very emergence of novelty, and I’m claiming that these complex system explanatory structures are fundamental.

Many elements of what someday might be developed as a fundamental theory of emergence have already been discovered. Nonlinear feedback networks are certainly part of the mathematical structure of the sought-for explanation. Physically, we know that open systems (i.e. connected to sources and sinks of matter and energy) that are far from equilibrium are prone to self-organizing into newly emergent structures. Concepts like homeostasis and purposive behavior would also be ingredients of some fundamental explanatory structure that applied to emergent phenomena. In contrast, knowledge concerning the state of the universe during the first several microseconds after the Big Bang, for example, or the nature of dark matter, would shed little insight on the question. We would need two different fundamental explanatory structures, with only some minor overlap between them, in order to understand all of these phenomena.

It may be objected, at this juncture, that I’m missing the point. Objection 1: Even if we may not understand how novelty emerges, it must still be inherent in the properties of matter that a fundamental (reductionist) theory is intended to explain. All we’re really lacking are some trivial details. Objection 2: In addition, the formation of any particular organized structure should not be a fundamental question anyway.

My answer to the second objection is to give two examples of particular cases that are assuredly fundamental: The origin of life from inorganic substances is a phenomenon that requires exactly the kind of complexity science I described; and the emergence of thought from the electrochemical signaling in the brain will also minimally require this kind of science (perhaps also including some other ingredients we don’t yet know). These are not epiphenomena of no importance.

They are fundamental questions, and they will require fundamental explanatory structures to understand them.

My answer to the first question has already been given, but I'll restate it here: I know that it is within the power of matter and energy to self-organize, and that these powers must have been imparted by whatever process created the matter and energy. My point is that the explanatory structure that explains said creation does not also explain the self-organization. Emergent phenomena occur at a different level and require a different fundamental explanation. Otherwise, we would already understand them. In my debates with reductionists, I have inevitably found that they always embed a hidden presupposition of the correctness of reductionism into their initial premises, eventually using it to underlie their argument that reductionism is correct. Because reductionism as a scientific methodology is so extraordinarily powerful and valuable (and virtually a necessity in many cases), it's quite difficult to get beyond it as an ontological commitment. Nevertheless, I am throwing down the gauntlet and claiming that understanding emergence is every bit as fundamental as, for example, understanding grand unification.

I am thus claiming that to be fundamental does not imply uniqueness. We can have more than one single fundamental explanatory structure, even at the deepest and most fundamental levels. There is no Theory Of Everything. Instead, there are a number of fundamental explanatory structures, each operating at its own appropriate level. These fundamental theories cannot be derived from each other or from anything else; that is an important attribute of their fundamentality. They must, however, be commensurable with each other where they overlap. Let me illustrate what I mean by commensurability with a simple example: The emergence of order in the ZB reaction ("chemical clock") arises from the systems-level interactions of the components and is not predictable from the net sum of the individual interactions, yet these individual interactions are no different in this reaction than they otherwise would be in any other reaction. Our understanding of these individual reactions is grounded in our understanding of the properties of electrons from quantum and electromagnetic theories, which must of course be consistent with (and may well be ultimately explainable based on) any sort of grand unified theory. Hence, there can be no inconsistency between these two fundamental explanations, because they are each consistent with the chemical properties that form a region of overlap they share. And yet, neither fundamental explanation is reducible to the other. They are independent (but still commensurable).

What else (beyond irreducibility) makes these explanations fundamental?

Generality is the other important attribute of a fundamental explanation. If a large number of disparate phenomena can all be explained using the same underlying ideas and formalism, then we must consider that explanatory structure to be

fundamental. Lastly, I think that a truly fundamental explanatory structure must have the capacity to grow beyond itself. When a new and unexpected phenomenon arises, a fundamental theory will already be able to explain it, despite our previous ignorance of its existence. Perhaps we can call this attribute “fertility.” We can then summarize the essential attributes of the most fundamental explanatory structures as these four properties: generality, irreducibility, commensurability, and fertility.

There are a number of other attributes that might be considered necessary, but I think they are merely desirable. For example, many people believe parsimony and elegance are the hallmarks of a fundamental theory. I highly value these qualities, and I hope our fundamental ideas are able to incorporate them, but reality is what it is, and that which is fundamental may turn out to be messy. Still, these are definitely attributes to aspire to in our theories. Likewise, some sort of deductive axiomatic structure is highly desirable, but not essential. Being a physicist, such an axiomatic structure is what I’m accustomed to and what I regard as particularly beautiful and powerful. However, if we are looking for fundamental explanatory structures for all phenomena at all levels, deductive axiomatic structures may be neither possible nor desirable under some conditions, so I would not make this a necessary condition.

This brings us to the last thread of my argument, the unity of science. Despite the utility of splitting our discourse into various disciplinary modalities, there is still only one single natural reality to understand. Thus, I believe that a fundamental understanding should apply to the entirety of this reality, and yet we see that trying to understand various domains and levels seems to require different approaches to understanding. For example, the rules and relationships needed in the explanatory structures for an ecosystem certainly will look radically different from those needed for a black hole, even as both of these systems share an overlapping adherence to some concepts (e.g. conservation laws). But if this is so, how then do we obtain the desired fundamental understanding that applies to all of reality? A traditional answer to the question was to invoke reductionism; if each level is reducible to the underlying level it’s based on, then the problem is solved. As I’ve indicated, I don’t believe that this is a tenable solution to the problem, so I’ve loosened some of the restrictions on fundamentality (e.g. deductive axiomatic structure) that might not apply to some phenomena (e.g. ethological studies of animal behavior) where the fundamental explanatory structures must take a different form. I will argue that this approach does allow us to still retain the unity of science in the absence of reductionism. Before taking that final step, though, let’s digress a little bit to consider the role of explanatory structures that are fundamental within some limited domain but do not achieve ultimate fundamentality.

Consider, for example, classical dynamics. Although often derided as being outdated and merely an approximation, classical dynamics is in fact virtually exact within the distance, time, mass, and velocity scales that are appropriate to its application, and

these are basically the only scales that humans ever encountered for thousands of years. It has many of the attributes of a fundamental theory: a huge panoply of disparate phenomena can all be explained by a single simple explanatory structure (Newton's Laws); it's commensurable with many other branches of science; it has a history of what I've termed fertility (recall, e.g., the discovery of Neptune); and of course it has an elegant deductive axiomatic structure. So why is classical dynamics not truly fundamental? You know the answer. It is not irreducible. Although it is fundamental within its own domain of applicability, it is also derivable as a special case from more fundamental theories whose explanatory structures extend to further ranges of distance, time, mass, and velocity. There are, of course, several other such examples in physics, such as thermodynamics and electromagnetism. There are also examples from other sciences; for example, natural selection (including the other aspects of the neo-Darwinian synthesis) is widely considered a central organizing principle in the life sciences, with great generality, commensurability, and fertility (no pun intended). However, it can only explain the sculpting of novelty into observed forms, not the origins of novelty itself, and recent advances in epigenetics point to a yet more general theory to which natural selection will be a limited approximation. I am suggesting here that we should entertain the notion of a kind of hierarchy of fundamentality, with a number of fundamental explanatory structures (or perhaps quasi-fundamental would be a better terminology) that we use in our ordering and understanding of reality.

But we are here primarily interested in those few explanatory structures that do seem to be irreducible and thus qualify as being *truly* fundamental. The cases described in the previous paragraph then serve as a kind of intellectual scaffolding to flesh out and complete our understanding. This process then extends to more narrow sub-disciplines such as solid state physics, which have their own sets of fundamental principles (e.g. Bloch's Theorem) and explain a further panoply of specific cases and real-life applications, all of which (taken collectively) are necessary to have confidence in the truth of the larger fundamental explanatory structures serving as their foundation. This collection of irreducible fundamental explanatory structures, general in their scope and continually successful in explaining novel phenomena, and all commensurable with each other in order to insure unity of knowledge, is the goal of science.

As of now, this goal has not been attained. Will it ever be attained? We can't be certain, but based on the remarkable progress attained so far, I am optimistic that this might be achieved if civilization lasts long enough. If we ever do achieve our goal and attain such a fundamental level of understanding, would that then mean that no fundamentally new insights were possible? I do not think that this is the case. I believe that Being will always be able to surprise us with new mysteries to solve, and the history of science (including recent history) is certainly on my side in

this prediction. I don't regard this as a pessimistic attitude, though, because in our quest for understanding, the journey is more important than the destination.