Why Physics Exists

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Bern University, February 2011

In the following, I present a few thoughts that may shed some light on the question why physics exists. People seem not to talk about this very much. All I'll have to say is therefore wide open for criticism and far from being well established. While the text also addresses some questions at the interface of physics and philosophy, it does not comply with the conceptual rigor of the latter discipline. For example, in the text below the notion of "existence" is not defined or clarified further in a philosophical context. The reader is assumed to be familiar with some notions of modern physics, such as, for example, the concept of an effective field theory.

Structures and Physicists

Physics is the man-made observation and experimental investigation as well as the theoretical mathematical description of Nature. As such, the existence of physics requires the existence of physicists, i.e. the existence of curious minds and capable brains. Of course, it is equally important that there is something "out there" to be discovered, i.e. that Nature does contain structures that can be adequately described in mathematical terms. Both such structures as well as curious minds and capable brains obviously do exist in our Universe. Of course, we can easily imagine much simpler hypothetical "Universes" that follow some strict mathematical laws of Nature. For example, we can imagine a "Universe" consisting of just two Newtonian point particles, to be called Sun and Earth, orbiting their center of mass in elliptical orbits for the rest of time. While such a simple system can easily be understood from outside, it is obvious that it cannot understand itself from within. Remarkably, by evolving the human subspecies of the experimental and theoretical physicist, in some sense our Universe is "thinking" about itself. This requires an enormous degree of complexity.

Space, Time, and Separable Entities

In order to understand something from within, one must still be able to distant oneself from the object of study, at least to some extent. It is the existence of space and time that allows us to do just that. While we currently do not understand the origin of space and time, the related puzzles lead to the deepest questions we can currently ask in physics. After all, space and time are fundamental ordering principles, deeply rooted in physical reality, that allow us to separate ourselves from other more or less independent entities. In this sense, space and time are necessary prerequisites for doing physics from within the system. It should be pointed out that we can easily imagine a mathematical "Universe" without invoking the concept of time. For example, equilibrium statistical mechanics follows strict mathematical rules, but knows nothing about time. Indeed, a "Universe" following just the rules of equilibrium statistical mechanics would have a hard "time" understanding even part of itself from within.

Space-Time Locality

Along with the concepts of space and time comes the concept of space-time locality. Indeed without locality, space and time would loose their meaning as the most basic ordering principles, and would therefore cease to be useful concepts. In our hypothetical "Universe" consisting of just Sun and Earth interacting via instantaneous Newtonian gravity, there is locality in time but not in space. As a consequence, space is not even a very useful concept in a hypothetical world like this. The coordinates of the two particles as well as their distance are completely sufficient. Thinking about the particles as existing in an otherwise empty space seems natural to us, who live in a much more dynamical space. However, in the very restricted two-particle "Universe" the whole concept of space is to a large extent an unnecessary luxury. The situation changes drastically when we endow the two point particles with Einstein gravity (i.e. general relativity). Then there is a metric attached to each point in space-time, which becomes a dynamical entity governed by local laws of Nature.

Hierarchies of Scales

The existence of curious minds and capable brains is likely to require the existence of vastly different length scales. If every separable entity would be of a similar size, for example, if everything including the potential physicist would exist at atomic scales, it is unlikely that physics would ever have taken off. This is because, in that case, one must identify the correct "Theory of Everything" (TOE) before physics can get started. In a hypothetical "Universe" consisting only of atomic scale entities governed by the rules of quantum mechanics, even if something like a "brain" would exist, it would almost certainly not be capable enough to discover quantum mechanics (which we may think of as the TOE in that world), in one gigantic strike of genius.

Anthropic Arguments

Although we don't know why they exist in our Universe, we have identified the existence of mathematical structures including space, time, and locality, as well as hierarchies of vastly different length scales as necessary prerequisites for the existence of physics. Today it is all too popular to invoke the anthropic principle. Still, the above mentioned prerequisites for the existence of physics may very well be necessary conditions for the existence of curious minds and capable brains as well. Hence, we can argue that potential physicists (i.e. curious minds and capable brains) can only exist in a world in which the basis for doing physics also automatically exists. Invoking the anthropic principle, i.e. using the fact of our own existence, we can then explain why the basis for physics exists as well.

Effective Field Theory

Once we have mathematical structures, space-time locality, hierarchies of different length scales, as well as curious minds and capable brains, we are suddenly in business for doing physics. In particular, thanks to space-time locality and the existence of hierarchies, we are free to do physics at some length scale, without the need to discover the "Theory of Everything" before we can even get started. Identifying the relevant degrees of freedom at some scale, and constructing the most general local dynamics while respecting the relevant symmetries is the technique of systematic effective field theory. Being able to understand aspects of the world step by step in scale, is a major reason why physics is so successful. An effective field theory always contains some a priori unknown physical parameters, whose values can be fixed, for example, by comparison with experiments. Eventually, one may reach a deeper level of understanding by matching these parameters to a more fundamental effective theory valid at shorter length scales. In this way, by matching effective field theories, we may patch together a "quilt" of mathematical descriptions of Nature that may eventually cover the entire landscape of physical phenomena.

Renormalization Group, Universality, and the Benefit of 4-d

The success of the effective field theory method relies on Kenneth Wilson's renormalization group and the related concept of universality. Universality implies that the physics at long distances or low energies is insensitive to the details of what happens at much higher energy scales. In the process of renormalization, the dynamics is attracted to a renormalization group fixed point that is characteristic of a universality class. Theories which may differ substantially at high energies may still flow to the same fixed point at low energies. This implies that we need not know all about physics (i.e. the TOE) before we can start to explore the low-energy regime. As a flip-side of the same coin, it is practically impossible to infer the correct TOE from low-energy data. In view of universality, doing successful fundamental physics is reduced to identifying the correct renormalization group fixed point, which makes life a lot easier. This is also thanks to the dimension of space-time. In particular, in the 4-dimensional space-time we live in, there are relatively few non-trivial fixed points of the renormalization group, namely those related to non-Abelian gauge theories. Indeed, it is non-Abelian gauge fields that dominate the physics of the Standard Model of Particle Physics — our most fundamental theory today. In a 2-d space-time, for example, the situation would be very different. In 2-d, there is an enormous number of non-trivial fixed points, such that identifying the correct one would be much more difficult than in 4-d. As Martin Lüscher from CERN once said: in 2 space-time dimensions, physics would be as complicated as politics. Thanks to our 4-d space-time, as complicated as physics may seem, it does, in fact, exist because it is not too difficult (for the more capable brains).

The Theory of Everything

By moving towards ever decreasing length scales (and thus ever increasing energy scales), we may (or may not) eventually discover the true "Theory of Everything". Already the Standard Model of Particle Physics is based on fundamental objects such as quarks or W-bosons, which are precise embodiments of abstract mathematical concepts. Even if physicists may eventually discover the ultimate TOE, which would obviously be a tremendous achievement, this would in no way obviate the need for effective field theories covering the low-energy domain. Just as the Standard Model is extremely powerful at particle physics energy scales, but pretty useless for understanding the complex dynamics of condensed matter, the TOE would be really useful only at the shortest distance scales. In this sense, the "Theory of Everything" may very well be a "Theory of Nothing" relevant at presently accessible energy scales. Furthermore, just as Bertrand Russell's Principia Mathematica, a "Theory of Everything" may suffer from Gödelian incompletenesses. We may have to be content with consistency, instead of urging for completeness.

Model Building

When doing physics, it is often useful to build models. Our model "Universe" consisting of just Sun and Earth is a good example. In this way, by mentally or even experimentally isolating a small part of the world from external influences, we have a chance to completely understand it. In some sense, Newton's classical mechanics is the theory of everything that is important to understand the dynamics of slowly moving macroscopic objects under the influence of gravity. Similarly, the Hubbard model describes the "world" inside doped antiferromagnets. Experts argue whether or not the Hubbard model is the theory of everything that is necessary to understand the origin of high-temperature superconductivity. Quantum Chromodynamics (QCD) is far more than just a model in this sense. In fact, it is an integral part of our most fundamental description of Nature — the Standard Model of Particle Physics. While (due to its "triviality" in the renormalization group sense) the Standard Model is necessarily "just" an effective theory, thanks to its asymptotic freedom, QCD could hold at arbitrarily high energy scales. In this sense, it may be considered as the "Theory of Everything" about the strong interaction. Isolated "worlds" like the Hubbard model or QCD are still sufficiently complicated that we cannot understand them completely analytically. In that case, effective field theory again plays an important role. The low-energy regimes of both the Hubbard model at low doping and QCD at low baryon density can be described by systematic low-energy effective field theories. Although they cannot be derived rigorously from the underlying microscopic theories, the physical consequences of emergent phenomena like antiferromagnetism or chiral symmetry breaking can then be addressed quantitatively in the low-energy effective theory. The matching between the underlying short-distance and the emergent long-distance theory works, because it connects two local theories which are mathematically formulated using the basic concepts of space and time.

Numerical Simulation

To accurately investigate model "worlds" such as the Hubbard model or (lattice) QCD, numerical simulations play an important role. For example, the low-energy parameters of the corresponding effective theories can be derived numerically from the underlying microscopic models. Still, in several interesting cases accurate numerical simulations are prevented by severe sign or complex action problems. For example, the exploration of high-temperature superconductivity in the Hubbard model is hindered by a severe fermion sign problem, and the exploration of the "condensed matter physics of QCD" (as Krishna Rajagopal and Frank Wilczek from MIT have called it) is hindered by a severe complex action problem of lattice QCD at non-zero baryon chemical potential. Quantum simulation, i.e. the use of special purpose quantum analog computers, is currently arising as a promising tool that may eventually help us to overcome such problems.

Different Layers of Reality and Limits of Physics

As we have discussed, in physics we patch together effective theories valid at different length scales. Indeed there are different layers of physical reality, each with its own appropriate mathematical description. While the dynamics at the shortest presently accessible distances are described by the Standard Model of particle physics, atomic nuclei are described by their own effective field theory valid at larger distance scales. Stepping further up in length scale, we reach atoms, molecules, and then condensed matter, which are all described by their own effective theories. While the resulting "quilt" of effective theories may eventually cover all physical phenomena, it is very unlikely to cover even a small fraction of other layers of reality. After all, the success of physics relies on the identification of subsystems with a sufficiently structured dynamics in space and time that can be described mathematically. While mathematics is a universal language that even Nature uses to express herself in, it is not a useful tool for talking about other layers of reality, such as art and poetry, or mind, consciousness, and free will. Those are very unlikely to ever become subjects of physics, just because mathematics is not an appropriate language for communicating about these emergent concepts which cannot be appropriately described, for example, in terms of space-time coordinates. While the subjects of physics are thus somewhat limited, the Universe is such a rich and diverse place that there is no reason to think that physics will be exhausted any time soon.

Understanding our own Brain

As suggested above, by means of physicists the Universe is "thinking" about itself, thus enabling an understanding of part of the system from within. This all happens thanks to the wonderful device we carry around in our head. Will physicists, biologists, or neuroscientists ever be able to understand the brain itself, essentially by using it to think hard enough about itself? While Gödelian self-referential situations are likely to prevent complete understanding, there may be no reason to be overly pessimistic. In particular, numerical simulations of certain brain functions should be possible. Except for that, however, the brain is probably the last system a typical physicist is well prepared to deal with. First of all, due to its large interconnectedness, the structure of the brain is to a large degree spatially non-local. Due to long-term memories stored in the brain, locality in time is disfigured as well. Furthermore, due to a lack of obvious hierarchies in length scales, it seems difficult to identify relevant degrees of freedom that can be separated from the rest of the system. In other words, the physicist's most powerful tool of effective field theory is not expected to work in an environment as complex as the brain itself.

Neuroscience as a "Theory of Everything" related to Neuronal Activity?

In recent years, some influential neuroscientists including Gerhard Roth and Wolf Singer have come to the conclusion that free will is an illusion, because conscious decisions are preceded by sub-conscious neuronal events in the brain. This has even led them to argue that law should be rewritten, in order to take into account that people cannot be held responsible for their actions. As a physicist working with effective field theories applied to different layers of physical reality, I find these arguments rather absurd. The neuronal scale "effective theory" of the neuroscientist has not been properly matched to the framework of mind and free will used in the humanities. Cross-communication between these different layers of reality is hence not possible in a truly meaningful way. A neuroscientist, who claims that free will is an illusion, uses his neuronal scale "effective theory" as a "Theory of Everything" related to neuronal activity. While emergent concepts like free will or consciousness should indeed not be inconsistent with fundamental theories underlying neuronal activity, they can neither be derived nor disproved by these theories. Therefore, the "Theory of Everything" concerning neuronal activity is very likely at the same time a "Theory of Nothing" relevant to legislation. Interestingly, based on arguments of a similar nature, some philosophers including Peter Bieri, David Chalmers, Joseph Levine, and Thomas Nagel have reached the same conclusion.

If it exists, free will should indeed not be inconsistent with fundamental theories underlying the brain. Isn't this the case if neuronal activity precedes our conscious decisions? As pointed out before, the brain itself is a highly non-local structure both in space and in time. Indeed, it is a wonderful device that turns chemical energy, which can be described mathematically by an effective theory using space-time coordinates, into concepts of the mind, which are subjects of the humanities that exist beyond space and time. Since a conscious decision is an emergent phenomenon which is not associated with a unique time-coordinate, it does not really make sense to say that it was preceded by some specific neuronal activity. Since the fundamental theories of physics are based on quantum uncertainty rather than classical determinism, they are consistent with free will as well, but cannot derive it either. At the moment, we simply don't know how to match the two separate layers of reality in which we can talk about either mind or matter, but not about the relations between both of them.

Matching the Mind and Matter Layers of Reality

The mind-body problem, i.e. to understand how mind and matter are related, and, if possible, to explain how mind emerges from matter, has been around for a long time. Since effective field theory does not work for a structure as complex and non-local as the brain, physics is currently nowhere near contributing to the solution of the mind-body problem. As argued before, neuroscience or any other natural science isn't either. Perhaps simulation by very powerful future computers (either involving classical randomness or quantum indeterminacy) may eventually mimic something like a "brain". While this may contribute to bridging the gap between mind and matter, it will not necessarily lead to deep understanding. In physics, renormalization group theory leads to deep understanding and enables us to match the different layers of physical reality separated by different length scales. Similarly, one may speculate that a future "Theory of Mind and Matter" may be able to match the natural sciences' space-time description of matter with the humanities' description of mind beyond space and time. Developing such a theory, and thus eventually solving the mind-body problem, is a tremendous challenge for both natural science and the humanities. Most likely, time is not ripe yet for this endeavor, because the individual disciplines still need to sharpen their tools before they can address the problem in a meaningful manner. However, it seems very well worth keeping the solution of the mind-body problem on the agenda, as a potential common long-term goal of natural science and the humanities. Negating the problem, by declaring neuroscience as the "Theory of Everything" related to neuronal activity, is much easier but completely misleading.

Evolution, Brain Chemistry, and Physics

After this exploration of the limits of physics and other sciences (including neuroscience), let us return to the question why physics exists. While all necessary conditions for physics are indeed fulfilled in our Universe, we should not forget that physics exists also because it is a lot of fun. Indeed it is the pleasure of figuring things out that is driving many new discoveries. The reward system in our brain, which evolved in order to help our ancestors outsmart predators as well as prey, also seems to encourage the creativity that one needs today as a physicist. However, in order not to paint a too naive picture of what drives physicists, we should also not forget that the power of physics to advance technology, unfortunately including the one used to fight other nations, has also motivated numerous research projects. In any case, mankind's well-being for the rest of the century is likely to benefit from physicists whose imagination is spurred by more honorable causes, including, for example, advancing climate research or medical applications of physics. Still, based on my own experience, I think that curiosity-driven basic research in physics benefits tremendously from our brain chemistry.

Summary

To summarize, as far as I understand, physics crucially depends on the existence of mathematical structures, space-time locality, as well as large hierarchies of length scales. These may all be necessary prerequisites for the existence of curious minds and capable brains of potential physicists as well. Invoking the anthropic principle, taking into account that physics in 4-d is not too difficult and can actually be quite useful, and knowing that it is a pleasure to figure things out, it is perhaps not surprising that physics does indeed exist. To a large extent, the success of physics relies on the powerful tool of effective theories. Model building and numerical simulation are very important tools as well, which are about to be enriched by quantum simulators. Of course, as usual when one invokes the anthropic principle, many questions remain unanswered. As curious minds, we still urge to understand why there are mathematical structures, space and time, locality, as well as large hierarchies. There is no reason not to think about these deep questions. Understanding why there are curious minds seems even harder, and may require a future "Theory of Mind and Matter" that matches the mathematical language of natural science to the concepts of the humanities. While the subjects of physics cover only a small fraction of reality, as far as I'm concerned, there is plenty for a life-time of a curious mind. Finally, taking part in the process of the Universe "thinking" about itself, together with colleagues all around the world, is a fascinating and most rewarding experience (not only in the brain chemistry sense).

Acknowledgments

I like to thank Jürg Gasser and Adrian Wüthrich for a careful critical reading of this manuscript.