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The 10 Biggest Unsolved Problems in Physics

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Abstract

In 1900, the British physicist Lord Kelvin declared: “There is nothing new to discover in physics. All that remains is to more accurately measure its quantities.” In the same year quantum physics was born and three decades later it, and Einstein’s theory of relativity, had completely revolutionized and transformed physics. Today, hardly anyone would dare say that our knowledge of the universe, and everything in it, is almost complete. On the contrary, every new discovery appears to open a Pandora’s Box of larger and deeper issues. I have selected some of today’s biggest unsolved riddles in physics. Just like Moses, I stop arbitrarily at 10. Here follow these “Ten Com...plications” with a brief explanation/justification. They may be seen as a roadmap for future important work.

Keywords

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“If you thought that science was certain - well that is just an error on your part.”

Richard Feynman

1. Quantum Gravity

The biggest unsolved problem in fundamental physics is how gravity and the quantum will be made to coexist within the same theory. Quantum Gravity [1] is required to make the whole of physics logically consistent. The problem is that quantum physics and general relativity already overlap each other’s domains, but do not fit together.

The biggest challenge with quantum gravity, from a scientific point of view, is that we cannot do the experiments required. For example, a particle accelerator based on present technology would have to be larger than our whole galaxy in order to directly test the effects. This means that quantum gravity today is not yet science in the strict sense. No experimental input exists that can inspire and control theoretical ideas, and historically we know that theoretical “progress” then usually occurs in completely wrong directions.

Einstein’s dream was to describe the whole of nature in a single theory. That dream is still not realized.

2. Particle Masses

The so-called standard model of particle physics, the most fundamental theory which is *tested* [2] and which we know is true (within the energies tested so far) contains 18 free parameters, and even more if neutrinos are not strictly massless. These parameters cannot be calculated or predicted theoretically. One can look at them as 18 adjustment knobs we can twiddle to best adapt the theory to all known data. The problem is that this is just too many. The famous mathematician John von Neumann once said: “With four parameters I can fit an elephant, and with five, I can make him wiggle his trunk.” The absolute majority of the eighteen are related to the different values for the masses of the elementary particles. From a theoretical point of view, then, the particle masses are a total mystery - they might as well have been random numbers drawn from a hat. The repetition

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of particles, with increasing masses, has also remained a mystery ever since the electron's "fatter cousin" the muon (over 200 times heavier) was discovered in the 1930s. Matter particles in the standard model can be arranged in generations or families. The first generation - which contains the electron, the electron-neutrino, the up-quark and the down-quark are followed by two additional copies which appear identical in everything except their masses. Ourselves and everything we know of, both on earth and in the cosmos, consist only of particles from the first generation. What are the heavier ones for?

3. The "Measurement" Problem

In the strange world of electrons, photons and other fundamental particles quantum mechanics is law. Particles do not behave like little bullets, but as waves spread over a large region. Each particle is described by a wave function that tells what its location, speed and other characteristics are more likely to be, but not what these properties *are*. The particle instead has countless opportunities for each, until one experimentally measures one of them - location, for example - then the particle wave function "collapses" and, apparently at random, a single well-defined position is observed. But how and why does a measurement on a particle make its wave function collapse, which in turn produces the concrete reality we perceive? This issue, the Measurement Problem in quantum physics [3], may seem esoteric, but our understanding of what reality is, or if it even exists, depends on the answer. Even worse: according to quantum physics it should be impossible to ever get a certain value for anything. It is characteristic of quantum physics that many different states coexist. The problem is that quantum mechanics is supposed to be universal, that is, should apply regardless of the size of the things we describe. Why then do we not see ghostly superpositions of objects even at our level? This problem is still unsolved. When can something be said to have happened at all? Without additional assumptions beyond quantum physics, nothing can ever happen! This is because the wave function mathematically is described by so-called linear equations, where states that have ever coexisted will do so forever. Despite this, we know that specific outcomes are entirely possible, and moreover happen all the time. Another strange thing is that the uncertainty in quantum physics arises only in the measurement. Before that, quantum mechanics is just as deterministic as classical physics, or even more so, because it is exactly linear and thus "simple". Only when we understand how our objective macroscopic world arises from the ghostly microscopic world, where everything that is not strictly forbidden is compulsory, can we say that we truly know how nature really works.

4. Turbulence

Turbulence has been called the last unsolved problem of classical physics. The famous physicist Werner Heisenberg (of uncertainty relation fame) is said on his deathbed to have uttered: "God! Why relativity? Why turbulence?" One cannot in general solve the set of equations describing the behavior of fluids; water, air and other liquids and gases. In fact, it is not known whether a general solution to the Navier-Stokes equations (for incompressible fluids) even exists, and, if there is a solution, whether it fully describes the fluid or contains unknowable points - singularities. The kind of chaos inherent in turbulence - in both time and space - is still a mystery [4]. One has come to suspect that, for example, the weather is not only difficult to predict, but fundamentally impossible. Does turbulence exceed the human physical understanding and mathematical ability, or would it become intelligible if only we tackled it with the right methods? There is also a purely worldly reward for those who manage to solve this: a cash prize of $1,000,000 from Clay Institute.

5. Dark Energy

50 years ago it was "self-evident" that the universe was dominated by mat- ter. Back in the late 1920s it was discovered that the universe is expanding, and as matter acts like a brake, because of its attractive gravitational force, all agreed that the universe's expansion rate should slow. As late as 1998, two major studies were published [5],[6], originally designed to more precisely than ever measure this deceleration. The surprise was therefore total when the observational data instead seemed to indicate that the universe is accelerating, i.e. increases its rate of expansion - as if the cosmos recently moved its foot from the brake pedal to the accelerator. The best fit to the cosmological standard model (developed in the 1920's by Friedmann, Lemaitre, Robertson and Walker) showed that about 70% of the energy of the universe seemed to be of a completely unknown form, which has been named Dark Energy. As so often, it was Einstein who first introduced the concept. He invented his cosmological constant, which represents a form of dark repulsive vacuum energy; already back in 1917 - but in a completely different context. The mystery is that no one still knows what dark energy is (or if it even exists).

6. Dark Matter

Other observations indicate that about 90 percent of the matter itself in the universe is made up of an exotic, unknown variety that neither absorbs nor emits light. Dark Matter, as it is called, cannot be seen directly, and has never been discovered [7]. Instead, the existence of dark matter is still hypothetical [8] and its large abundance derived from its gravitational effects on visible matter, radiation and structure formation in the universe. This strange in- visible matter is thought to not only permeate the outskirts of galaxies, but the entire universe and may, possibly, consist of weakly interacting massive particles (WIMPs) or massive compact halo objects (MACHOs). There are today several experiments around the world in search of them.

7. Complexity

Although the four known fundamental forces of nature (gravity, electromagnetism, strong nuclear and weak nuclear) are all relatively simple, it is almost always impossible to directly from them in detail predict the behavior of even mildly complex systems. Is this a real aspect of nature, or just a result of our theories so far being formulated in non-ideal ways? The logical possibility also exist that the world is not reductionist (or rather, constructionist), that is, that a handful of fundamental laws are not sufficient to build up (reconstruct) all the complexity that we see around us, but rather that these may have to be supplemented by new (unknown) principles on different scales.

We know, however, from both observations and theoretical models, that some complex systems can exhibit surprisingly simple collective behavior, as when, for example, thousands of fireflies spontaneously start blinking in sync without any "conductor" to control them [9]. Disorder apparently spontaneously self-organizes to order, in contrast to the traditional notion that the disorder/entropy must always increase. Many believe that this field of re- search will be essential for understanding and explaining phenomena such as the origin of life (and what life really *is*) and how consciousness seemingly miraculously can arise from mindless atoms in the brain.

8. The Matter-Antimatter Asymmetry

The question of why there is so much more matter than its oppositely charged mirror image, antimatter, is actually the crucial question of why anything exists at all [10]. It is assumed that the universe when it is born treats mat- ter and antimatter symmetrically. Thus, the Big Bang should have produced equal parts matter and antimatter. This should then have resulted in a total annihilation of the two: protons would have annihilated with antiprotons, electrons with antielectrons (positrons), neutrons with antineutrons, and so on, which would have left behind a structure-less sea of photons in a matter- less void. For some reason there remained a tiny excess of matter that was not annihilated. And here we are. This has not yet any explanation. Because what we mean by matter is only a definition, we see that we could just as well have obtained a universe dominated by antimatter. But that in turn means that the answer to this riddle must contain a fundamental time direction, the universe cannot be run backwards because two completely different final states (matter or antimatter) would have arisen from the same initial state. A more complicated way of saying the same thing is that today's most fundamental theory is CPT-invariant [11], i.e. the same when simultaneously changing the particle charges (C), mirror-reflecting their state (P) and re- versing the direction of time (T). And because we know that CP is broken for some reactions [12], this means that also T is broken, i.e., that the theory (or nature itself) is asymmetrical in the time direction. The problem is that the known CP-violation is far too weak and insignificant to explain why we today have only matter.

9. Friction

It may seem strange and surprising that in physics we still do not understand how something so "obvious" as friction arises. But at the microscopic atomic level there is no friction, this can be easily seen by ogling the basic formula of quantum physics - the Schr¨odinger equation. Everything, however, consists of atoms, so how can friction then appear on our level? Since friction bleeds away energy from a process in the form of heat, it is very possible that this problem is intimately connected with some of our other unsolved mysteries e.g. how structures can form and why time only flows forward. On a microscopic frictionless level, one can freely reverse the temporal direction and still get a perfectly possible behavior. If we imagine a movie where two electrons collide, it is impossible to say if it runs in the right direction or not. But if we instead see a hockey puck that glides along the ice and stops (due to friction), we can immediately sense if the movie runs forwards or backwards.

10. The "Arrow of Time"

It is sometimes argued that time moves forward due to the fact that a property of the universe called entropy, defined as the degree of disorder, never decreases for a macroscopic system. There is thus no way to reverse an increase in the total entropy after it has occurred. The fact that the entropy increases is because there are many more disordered ways of arranging something than there are ordered ones, so when things change this tends to increase the disorder. But the underlying and unresolved question then becomes: why was the entropy so low in the past? In other words, why was the universe so ordered in the beginning, when a huge amount of energy was contained in a very small space? We have merely replaced one mystery with an at least equally great. As mentioned above, it seems that even microscopically there is a very small asymmetry between time forwards and backwards, because of the measured CP-violation in the weak nuclear interaction. But this symmetry breaking is far too weak to explain the time arrow and also only operates on extremely short length scales, mainly inside atomic nuclei. Maybe even time, as we so far have described it in our theories, is really just an illusion [13]?

11. Solutions

My own private crystal ball tells me that several of the great mysteries are not independent but can/should/must be solved simultaneously. I believe the solution is spelled n-o-n-l-i-n-e-a-r-i-t-y. In a linear theory the whole is exactly equal to the sum of its parts. In a nonlinear theory the whole is more (or less) than the sum of its parts. All classical theories are fundamentally nonlinear (friction, gravity, turbulence, etc.), while quantum physics is exactly linear (superposition, Schr¨odinger's cat, quantum entanglement, etc.). The possibility therefore exists that the answers to some, or all, of the riddles will be obtained from a (future) universal theory for the transition between linear and non-linear, i.e. between quantum and classical.

Complexity arises in systems with nonlinear "feedback". And the same may well apply for particle masses [14].

Dark energy might not be needed to explain cosmological data. Matter in the universe is in reality not evenly distributed in contrast to the basic assumption in the standard model of cosmology (an idealized universe; perfectly homogeneous and isotropic) designed to make Einstein's strongly nonlinear equations much simpler and analytically soluble. There are aggregations of matter (galaxies, etc.) that violate this idealized image, also the difference between the voids and the lumps automatically grows as the universe is expanding, i.e. the non-linearity increases with time. These lumps in the real universe provide an effect that mimics acceleration in a completely evenly smeared-out, idealized universe [15].

So far there is no fundamental explanation of friction, again because the fundamental understanding of the transition linear → nonlinear is missing. Similarly with the riddle of turbulence - as flow increases a laminar (almost linear) behavior turns into a severely turbulent (strongly nonlinear).

There is even a chance to link everything to perhaps the greatest mystery of all - the quantum measurement problem; how, when and why the ghostly and indeterminate quantum world generates our concrete, definite macroscopic world, i.e. how what we call reality really arises [16]. When a certain type of helium is cooled to almost absolute zero temperature it becomes superfluid and flows completely without friction; raise the temperature a bit and it behaves like a normal (non-linear) liquid. Would it not be cool, in the literal sense, if in this transition one could study and solve the mysteries of friction, turbulence, the arrow of time, complexity, and the quantum measurement problem ... several fat birds with one stone? The principle is linear → nonlinear, and I say like Wolfgang Pauli who in a letter to George Gamow wrote: "Only technical details are missing ..." on an otherwise blank page.

However, we should also remember Freeman Dyson's cautionary words: "People are often asking me what's going to happen next in science that's important, and of course, the whole point is that if it's important, it's some- thing we didn't expect. All the really important things come as a big surprise. Anything I mention will be something that, obviously, is not a surprise."

"We are not to tell nature what she's gotta be... She's always got better imagination than we have."

Richard Feynman

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