A theory of everything?

In his later years, Einstein sought a unified theory that would extend general relativity and provide an alternative to quantum theory. There is now talk of a 'theory of everything' (although Einstein himself never used the phrase). Fifty years after his death, how close are we to such a theory?

I have learned from the history of physics that the most spectacular developments usually come when the existing theoretical insights create conflict, when observed phenomena seem to defy logic. This happened when Max Planck investigated a problem in the statistical features of radiation — which led to the foundation of quantum mechanics. It also happened when Einstein asked questions about observers moving at the speed of light — which led to the theory of relativity. On a more modest scale, a problem with neutral currents in the weak interactions of particles led to the prediction of the charm quark.

History has a habit of repeating itself, but not in a predictable manner. So, even if we are facing similar problems today, where will they lead us? Now, our most prominent difficulty is the reconciliation of the general theory of relativity with quantum mechanics. And one of the real paradoxes is the tiny value of the cosmological constant. There are also conceptual difficulties with black holes, or, more precisely, with what happens when the gravitational force exhibits its notorious instability.

I once planned to write a paper entitled '200 incorrect theories to explain the cosmological constant', with 200 references, but I never had the patience to read all those papers. I am convinced that this problem, and that of the black holes, will require a much more revolutionary approach. Many of my colleagues, in particular string theorists, expect that the ultimate laws of physics will contain a kind of logic that is even more mysterious and alien than that of quantum mechanics. I, however, will only be content if the logic is found to be completely straightforward. I suspect that the favoured interpretation of quantum mechanics will have to be revised. I am not saying that quantum mechanics is wrong or incomplete. But I do think that an ultimate theory will not have any stochastic elements: I side with Albert Einstein, who always suspected that nature's true equations would not allow for gambling. **Gerard 't Hooft**

Physics as we know it is undergoing a profound transformation. The focus of twentieth-century physics — the structure of matter — is shifting to the structure of the Universe. Physicists are asking (and hoping to answer) new kinds of questions. Instead of asking what the laws or equations of physics are and how we solve them, we ponder why the laws of physics are as they are, and ask whether they could be otherwise. Could things be different in other parts of a much bigger universe than any we have ever imagined? Why are the laws and constants of nature so well-tuned to the existence of life? Is it accident or is there a pattern?

There are contrasting views on these questions. Theoretical physicists have always hoped that the underlying laws of physics — the laws of particle physics — would be uniquely determined by the internal consistency of some particularly simple mathematical theory. Not only would the theory explain why the proton and neutron are about 1,800 times heavier than the electron, but the theory would also explain itself: no other theory is possible. Moreover, according to this view the fantastic coincidences that seem incredibly fine tuned, just so that life can exist, are exactly that that — just lucky coincidences.

Many physicists hoped that string theory would be the mathematical 'silver bullet' that would uniquely explain our world. But the more we learn about cosmology and the more we learn about string theory, the less likely this seems. Experimental cosmology has given us reasons to believe two things: that the Universe is vastly bigger than the 10 billion light-years that we can see with our astronomical instruments; and that at least one constant of nature, the so-called cosmological constant, is absurdly fine tuned (to more than one hundred decimal places) to be in the range where galaxies, stars and life can form. And, in a reversal of fortune that stunned string theorists, it seems that their own theory has so many solutions that there is an incredible 'landscape' of possibilities.

The competing view — that physicists generally hate, but might have to take seriously — is that the Universe is tremendously big and filled with smaller 'pocket universes', each with its own peculiar elementary particles, forces and constants of nature. This seems to be both what observational cosmology and string theory are pushing us towards. If so, the explanation of some aspects of nature would then be that life as we know it can only exist in those regions where the conditions are suitable. Who is right? Hopefully time will tell. **Leonard Susskind**

Einstein famously devoted the second half of his career to attempting to unify the forces of nature. To Einstein, this meant unifying electromagnetism and gravitation, the only forces he regarded as truly fundamental. Nowadays, we include weak interactions and the strong force as coequal partners. We aim to unify general relativity — Einstein's theory of gravity — with quantum field theory, the framework in which we understand the other three forces.

Does such a unified theory exist? Can we find it? Or could the search go on forever — with each step forward raising a new riddle? If there is a unified field theory and we find it, can we do enough decisive experiments and calculations to confirm that it is right? Can a unified field theory be used to compute the dimensionless constants that we observe in nature, or do the values of these constants depend on the choice of a solution of the unified field theory? Are they different in different parts of the Universe?

One of the few things we do know is that, with string theory, theoretical physicists have stumbled upon a theory that looks like it might be the unified field theory. It modifies the notions of quantum field theory and forces upon us the unification of gravity and quantum theory. It can naturally encompass the standard model of particle physics. And it always seems to defy full understanding, no matter how much progress is made. In thirty-something years of intense work, string theory has generated an amazing panoply of rich ideas, with wide influence in different areas of physics and mathematics. But it continues to baffle its practitioners. **Edward Witten**

Cosmologists have already reached a reasonable understanding of the global evolution of the Universe and the formation of cosmic structure — notwithstanding three fundamental yet hypothetical components of the theory, namely dark matter, the cosmological constant and inflation (or the scalar field that induces inflation). How then might we be concerned with a 'theory of everything'?

We probably do not need such a theory to answer the dark matter problem — we hope that experiments will reveal the nature of this matter directly. The existence of the cosmological constant, or vacuum energy, has fundamental implications for physics. If a theory of everything were to tell us nothing specific about this energy, that would perhaps be the most important result. We would then not need to worry about its arbitrary value (and could appeal to the anthropic principle without hesitation). Or perhaps the theory of everything contains a compromise solution, with a dynamically varying vacuum energy.

Inflation provides the seed of cosmic structure and fits recent data beautifully. But the model is still poorly understood, and this problem is most closely connected with the theory of everything. But progress here should be driven by developments in particle physics, towards a model that can predict the correct magnitude of cosmological fluctuations. Cosmology is, unfortunately, not useful in constructing a theory of everything — although a theory of everything would solve some important problems in cosmology. We watch and wait!

Masataka Fukugita

The quest for a unifying theory is an ambitious task. The ultimate goal is a simple, elegant, unifying theory — one that can be used to predict the result of any conceivable experi-ment. But nature manifests only a fraction of the simplicity that such a theory is supposed to contain. A unified theory would have to connect a spare formulation to our apparently far more compli-cated world.

This means that even if simple principles underlie physical reality, more elaborate theoretical ideas are needed to relate these principles to actual physical phenomena. That is not necessarily a bad thing: one of the most interesting challenges in physics is to figure out such relationships. But it does mean that a truly unified theory is likely to contain some complicated elements. For example, symmetry is essential to the simplicity of the beautiful theoretical description of the weak nuclear force. But that symmetry is broken by the state of the Universe in which we live. The underlying theory is simple and unifies the weak force and electromagnetism, but the reality is more complicated. We need new experimental results to complete the story.

String theory, which accommodates both quantum mechanics and gravity, aims to be a unified theory. But to derive the properties of the world in which we live, theorists need to make assumptions about various parameters. Originally, string theorists hoped string theory would dictate these parameters. But this is looking increasingly unlikely. It is far more probable that there aren't enough rules to predict all the parameters of our world.

Physics has changed dramatically over the years as we have learned about physical principles that apply at higher energies and smaller length scales. New information from upcoming experiments, such as those at the Large Hadron Collider at CERN in Switzerland, should help us discover further guiding principles. Progress will depend on relating intriguing features of the results of such experiments to the consequences of various theories, such as string theory. I don't know if we'll ever know all the answers or find a single predictive unifying theory. But I'm confident that we will continue to make progress towards a deeper understanding of nature's fundamental laws.

Lisa Randall

I dislike the phrase 'a theory of everything'. It is arrogant and suggests that all that remains to do is to tie the world, as we know it, up in a single theory. But I do believe that progress will be made in the discovery of a deeper and more unified understanding of the phenomena so far discovered.

Can quantum theory and general relativity be unified? The first step towards this goal is to invent a common language and theory in which the principles of general relativity and quantum theory work together consistently. The good news is that a theory of this description has been found: it is called loop quantum gravity. This is not to say that all questions about this theory have been answered, or that we know that it describes nature. But it is a consistent, well-defined theory that does follow from combining the principles of both quantum theory and general relativity. In particular, it realizes perfectly the basic principle embodied in Einstein's theory that space and time are dynamical, and evolve with matter, rather than being a fixed background. It makes a major new prediction which is that space, like atoms, has a discrete structure and it predicts the details of that structure. This discreteness might be tested in real experiments, which are now underway.

A further step would be to discover a common origin for the geometry of space-time and quantum phenomena, so as to truly unify them. In such a theory there would be at first nothing recognizable as either space or quantum physics: these would emerge as approximate descriptions, just as temperature and pressure emerge from the statistics of the motions of large numbers of atoms. Such a theory does not exist but some first steps have been taken towards formulating it.

Lee Smolin

Two years after Einstein completed the special theory of relativity, he was already at work on an extension of this theory which included gravitation. He quickly seized on the equivalence of gravitational and inertial mass as the key to understanding gravitation. To take account of this 'equivalence principle', the special theory of relativity had to give way to a generalized theory of relativity and gravitation, in which inertia and gravity are united and no privileged frames of reference exist.

By 1915, Einstein had a general theory in which all space-time structures become dynamical fields. This is quite a remarkable conclusion. All other successful quantum theories — in particular, non-relativistic quantum mechanics and special relativistic quantum field theory — have incorporated some kinematical background space-time structure, a stage on which the dramas of dynamics are enacted. Now, there is no kinematics independent of dynamics: in this sense, general relativity is a background-independent theory.

Attempts to create a quantum theory of gravity are thus faced with the following problem: must we give up background independence to quantize gravity? This has been the choice made (so far, at least) by perturbative string theorists, who introduce a background — flat space-time of ten, eleven or however many dimensions — and then apply a variant of the procedures used in (special relativistic) quantum field theory to quantize the string in this background (the excited states of the quantized string represent particles).

But loop quantum gravity theorists maintain that it is not only possible, but mandatory to formulate a background-independent quantum theory of gravity, if the most important feature of general relativity is not to be lost. If this approach proves possible and physically fruitful, then I believe that the formulation of the first background-independent physical theory will rank as Einstein's greatest achievement.

John Stachel

In the history of physics, the opinion that almost everything is known, or that the 'theory of the world' is at hand, has often been widespread; after the work of Newton and after Maxwell, for example. Clearly, this was always nonsense. Personally, I find the idea that we are near to the final 'theory of everything' close to fantasy.

The big theoretical question is how to formulate quantum field theory consistently with what we have learned from general relativity, namely with background independence.

The tentative theories we have, such as loop gravity, strings or noncommutative geometry, are courageous attempts that are worth pursuing but badly incomplete. Loop gravity has no ambition of being a theory of everything: it is just a background-independent theory of quantum space-time. In string theory, a background-independent formulation seems as far away as ever. More crucially, none of these speculative theories has received any empirical support from experiment. Worse, phenomena such as proton decay, supersymmetric particles and signs of extra dimensions were predicted, but haven't shown up.

Rarely have we been so far from a theory of everything. Thinking that we might be close to it is the common error of those who mistake their own expectations for the ultimate truth. **Carlo Rovelli**

One must distinguish a theory of fundamental forces, fields and particles that unites gravity with all other forces from a true theory of everything. The key question is what requirements of the former make it a theory of everything in the true sense — a theory that will explain both fundamental physics and how entities of genuine complexity, including human beings, can arise out of this fundamental physics.

It has been suggested that only five of the 20 parameters of the standard model determine whether complexity can arise. The problem for any underlying more fundamental theory is to explain why these five parameters lie in the part of parameter space favourable for life. The key tension is as follows: the ultimate aim of the 'theory of forces and particles' enterprise is to uniquely derive an underlying fundamental theory with no free parameters at all. However, there is no reason why any such theory will lead to physics lying in the small part of possibility space that allows life to exist. If this were to happen, then this most extraordinary coincidence (fundamental physics symmetries and variational principles inevitably leading to the existence of life) would cry out for an even more fundamental explanation. How one would attain such an explanation from within the domain of physics is completely unclear.

It may indeed be helpful if there exists no parameter-free fundamental physics theory, but rather a family of theories with varying effective parameters (perhaps because of a vast array of possible vacuum states). Then one could try to explain the anthropic coincidence as either an observational selection effect (observers only exist in universes that allow life), or a physical selection effect concerning what kinds of universes are most likely to occur, as in Lee Smolin's proposal of a quasi-darwinian evolutionary process affecting which cosmological outcome is most likely. **George Ellis**

I don't like the term 'theory of everything' because it suggests that there is some theory that when discovered will immediately solve all scientific problems. Clearly there isn't any such thing. I do think that we may find what I like to call a 'final theory'; that is, a single simple theory that pushes all our explanations as far as they can go. I could be wrong about this, but we'll never know without trying to find it. **Steven Weinberg**

The terminology 'theory of everything' has always worried me. There is a certain physicist's arrogance about it that suggests that knowing all the physical laws would tell us everything about the world, at least in principle. Does a physical theory of 'everything' include a theory of consciousness? Does it include a theory of morality, or of human behaviour, or of aesthetics? Even if our idea of science could be expanded to incorporate these things, would we still think of it as 'physics', or would it even be reducible to physics?

As for myself, I perhaps have enough of the physicist's arrogance about me to believe that a physical 'theory of everything' should at least contain the seeds of an explanation of the phenomenon of consciousness. It seems to me that this phenomenon is such a fundamental one that it cannot be simply an accidental concomitant of the complexity of brain action. It must be of such sophistication that the brain is enabled to dig more deeply into the fundamental workings of the Universe than are more commonplace physical systems. And if this is so, then we are very much farther from a proper understanding of the laws of nature than most physicists seem to believe.

Indeed, irrespective of the consciousness issue, in my opinion, we are nowhere close to an accurate, purely physical theory of everything. I find it remarkable how many physicists will express the view that, despite some missing details and unifying concepts, we know virtually all we need to know to describe the fully detailed physical behaviour of systems — at least in principle. Yet, there is at least one glaring omission in present physical theory. This is how small-scale quantum processes can add up, for large and complicated systems, to the almost classical behaviour of macroscopic bodies. Indeed, it is not just an omission but an actual fundamental inconsistency, sometimes referred to as the measurement paradox (or Schrödinger's cat). In my view, until this paradox is resolved we must necessarily remain very far from a physical theory of everything — whether or not such a theory exists. **Roger Penrose**

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