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ILLUMINATING PHYSICS:

part 3

Учебное пособие

Саратов

2019

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Illuminating physics: part 3: Учебное пособие по иностранному языку для магистрантов /Сост. А.И. Матяшевская, Е.В. Тиден. — Саратов, 2019. — 85 с.

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PREFACE

Настоящее учебное пособие включает актуальные тексты (2018-2019гг.) учебно-познавательной тематики для магистрантов физического факультета (направление 03.04.02 «Физика»).

Целью данного пособия является формирование навыков научной речи, в основе которых лежит владение характерными для научного стиля лексикограмматическими структурами. Ставится задача подготовить магистрантов к основным формам как письменного (аннотация, теоретический обзор, статья), так и устного научного общения (доклад, дискуссия).

Пособие состоит из 5 разделов, рассматривающих проблемы и достижения в сфере информационных технологий в современном мире. Каждый из них содержит аутентичные материалы (источники: *Aeon, Discover Magazine, Quanta Magazine, Scientific American*) и упражнения к ним. Раздел “Supplementary reading“ служит материалом для расширения словарного запаса и дальнейшего закрепления навыков работы с текстами по специальности.

Пособие может успешно использоваться как для аудиторных занятий, так и для внеаудиторной практики.

1. Is the Universe a conscious mind?

Exercise I.

Say what Russian words help to guess the meaning of the following words: fact, standard, hypothesis, objective, process, selection, absolutely, paradox, typical, astronomically

Exercise II.

Make sure you know the following words and word combinations.
Robust, to posit, albeit, incoherent, to render, to detract, ensemble, disposition, commitment, ludicrously

Is the Universe a conscious mind?

Cosmopsychism might seem crazy, but it provides a robust explanatory model for how the Universe became fine-tuned for life

In the past 40 or so years, a strange fact about our Universe gradually made itself known to scientists: the laws of physics, and the initial conditions of our Universe, are fine-tuned for the possibility of life. It turns out that, for life to be possible, the numbers in basic physics – for example, the strength of gravity, or the mass of the electron – must have values falling in a certain range. And that range is an incredibly narrow slice of all the possible values those numbers can have. It is therefore incredibly unlikely that a universe like ours would have the kind of numbers compatible with the existence of life. But, against all the odds, our Universe does. Some take the fine-tuning to be simply a basic fact about our Universe: fortunate perhaps, but not something requiring explanation. But like many scientists and philosophers, I find this implausible. In The Life of the Cosmos (1999), the physicist Lee Smolin has estimated that, taking into account all of the fine-tuning examples considered, the chance of life existing in the Universe is 1 in 10229, from which he concludes: In my opinion, a probability this tiny is not something we can let go unexplained. Luck will certainly not do here; we need some rational explanation of how something this unlikely turned out to be the case. The two standard explanations of the fine-tuning are theism and the multiverse hypothesis. Theists postulate an all-powerful and perfectly good supernatural creator of the Universe, and then explain the fine-tuning in terms of the good intentions of this creator. Life is something of great objective value; God in Her goodness wanted to bring about this great value, and hence created laws with constants compatible with its physical possibility. The multiverse hypothesis postulates an enormous, perhaps infinite, number of physical universes other than our own, in which many different values of the constants are realised. Given a sufficient number of universes realising a sufficient range of the constants, it is not so improbable that there will be at least one universe with fine-tuned laws. Both of these theories are able to explain the fine-tuning. The problem is that, on the face of it, they also make false predictions. For the theist, the false prediction arises from the problem of evil. If one were told that a given universe was created by an all-loving, all-knowing and all-powerful being, one would not expect that universe to contain enormous amounts of gratuitous suffering. One might not be surprised to find it contained intelligent life, but one would be surprised to learn that life had come about through the gruesome process of natural selection. Why would a loving God who could do absolutely anything choose to create life that way? The flaws of our Universe count strongly against the existence of God. Turning to the multiverse hypothesis, the false prediction arises from the so-called Boltzmann brain problem, named after the 19th-century Austrian physicist Ludwig Boltzmann who first formulated the paradox of the observed universe. Assuming there is a multiverse, you would expect our Universe to be a fairly typical member of the universe ensemble, or at least a fairly typical member of the universes containing observers (since we couldn't find ourselves in a universe in which observers are impossible). However, in The Road to Reality (2004), the physicist and mathematician Roger Penrose has calculated that in the kind of multiverse most favoured by contemporary physicists – based on inflationary cosmology and string theory – for every observer who observes a smooth, orderly universe as big as ours, there are 10 to the power of 10123 who observe a smooth, orderly universe that is just 10 times smaller. And by far the most common kind of observer would be a 'Boltzmann's brain': a functioning brain that has by sheer fluke emerged from a disordered universe for a brief period of time. If Penrose is right, then the odds of an observer in the multiverse theory finding itself in a large, ordered universe are astronomically small. And hence the fact that we are ourselves such observers is powerful evidence against the multiverse theory.

Neither of these are knock-down arguments. Theists can try to come up with reasons why God would allow the suffering we find in the Universe, and multiverse theorists can try to fine-tune their theory such that our Universe is less unlikely. However, both of these moves feel ad hoc, fiddling to try to save the theory rather than accepting that, on its most natural interpretation, the theory is falsified. I think we can do better. In the public mind, physics is on its way to giving us a complete account of the nature of space, time and matter. We are not there yet of course; for one thing, our best theory of the very big – general relativity – is inconsistent with our best theory of the very small – quantum mechanics. But it is standardly assumed that one day these challenges will be overcome and physicists will proudly present an eager public with the Grand Unified Theory of everything: a complete story of the fundamental nature of the Universe. In fact, for all its virtues, physics tells us precisely nothing about the nature of the physical Universe. Consider Isaac Newton's theory of universal gravitation: The variables m1 and m2 stand for the masses of two objects that we want to work out the gravitational attraction between; F is the gravitational attraction between those two masses, G is the gravitational constant (a number we know from observation); and r is the distance between m1 and m2. Notice that this equation doesn't provide us with definitions of what 'mass', 'force' and 'distance' are. And this is not something peculiar to Newton's law. The subject matter of physics are the basic properties of the physics world: mass, charge, spin, distance, force. But the equations of physics do not explain what these properties are. They simply name them in order to assert equations between them. If physics is not telling us the nature of physical properties, what is it telling us? The truth is that physics is a tool for prediction. Even if we don't know what 'mass' and 'force' really are, we are able to recognise them in the world. They show up as readings on our instruments, or otherwise impact on our senses. And by using the equations of physics, such as Newton's law of gravity, we can predict what's going to happen with great precision. It is this predictive capacity that has enabled us to manipulate the natural world in extraordinary ways, leading to the technological revolution that has transformed our planet. We are now living through a period of history in which people are so blown away by the success of physical science, so moved by the wonders of technology, that they feel strongly inclined to think that the mathematical models of physics capture the whole of reality. But this is simply not the job of physics. Physics is in the business of predicting the behaviour of matter, not revealing its intrinsic nature. Given that physics tell us nothing of the nature of physical reality, is there anything we do know? Are there any clues as to what is going on 'under the bonnet' of the engine of the Universe? The English astronomer Arthur Eddington was the first scientist to confirm general relativity, and also to formulate the Boltzmann brain problem discussed above (albeit in a different context). Reflecting on the limitations of physics in The Nature of the Physical World (1928), Eddington argued that the only thing we really know about the nature of matter is that some of it has consciousness; we know this because we are directly aware of the consciousness of our own brains: We are acquainted with an external world because its fibres run into our own consciousness; it is only our own ends of the fibres that we actually know; from those ends, we more or less successfully reconstruct the rest, as a palaeontologist reconstructs an extinct monster from its footprint. We have no direct access to the nature of matter outside of brains. But the most reasonable speculation, according to Eddington, is that the nature of matter outside of brains is continuous with the nature of matter inside of brains. Given that we have no direct insight into the nature of atoms, it is rather 'silly', argued Eddington, to declare that atoms have a nature entirely removed from mentality, and then to wonder where mentality comes from. In my book Consciousness and Fundamental Reality (2017), I developed these considerations into an extensive argument for panpsychism: the view that all matter has a consciousness-involving nature.

There are two ways of developing the basic panpsychist position. One is micropsychism, the view that the smallest parts of the physical world have consciousness. Micropsychism is not to be equated with the absurd view that quarks have emotions. In human beings, consciousness is a sophisticated thing, involving subtle and complex emotions, thoughts and sensory experiences. But there seems nothing incoherent with the idea that consciousness might exist in some extremely basic forms. We have good reason to think that the conscious experience of a horse is much less complex than that of a human being, and the experiences of a chicken less complex than those of a horse. As organisms become simpler, perhaps at some point the light of consciousness suddenly switches off, with simpler organisms having no experience at all. But it is also possible that the light of consciousness never switches off entirely, but rather fades as organic complexity reduces, through insects, plants and bacteria. For the micropsychist, this fading-while-never-turning-off continuum further extends into inorganic matter, with fundamental physical entities – perhaps electrons and quarks – possessing extremely rudimentary forms of consciousness, to reflect their extremely simple nature. However, a number of scientists and philosophers of science have recently argued that this kind of 'bottom-up' picture of the Universe is outdated, and that contemporary physics suggests that in fact we live in a 'top-down' Universe, in which complex wholes are more fundamental than their parts. According to holism, the table in front of you does not derive its existence from the sub-atomic particles that compose it; rather, those sub-atomic particles derive their existence from the table. Ultimately, everything that exists derives its existence from the ultimate complex system: the Universe as a whole. Holism has a somewhat mystical association, in its commitment to a single unified whole being the ultimate reality. But there are strong scientific arguments in its favour. The American philosopher Jonathan Schaffer argues that the phenomenon of quantum entanglement is good evidence for holism. Entangled particles behave as a whole, even if they are separated by such large distances that it is impossible for any kind of signal to travel between them. According to Schaffer, we can make sense of this only if, in general, we are in a Universe in which complex systems are more fundamental than their parts. If we combine holism with panpsychism, we get cosmopsychism: the view that the Universe is conscious, and that the consciousness of humans and animals is derived not from the consciousness of fundamental particles, but from the consciousness of the Universe itself. This is the view I ultimately defend in Consciousness and Fundamental Reality. The cosmopsychist need not think of the conscious Universe as having human-like mental features, such as thought and rationality. Indeed, in my book I suggested that we think of the cosmic consciousness as a kind of 'mess' devoid of intellect or reason. However, it now seems to me that reflection on the fine-tuning might give us grounds for thinking that the mental life of the Universe is just a little closer than I had previously thought to the mental life of a human being. The Canadian philosopher John Leslie proposed an intriguing explanation of the fine-tuning. What strikes us as so incredible about the fine-tuning is that, of all the values the constants in our laws had, they ended up having exactly those values required for something of great value: life, and ultimately intelligent life. If the laws had not, against huge odds, been fine-tuned, the Universe would have had infinitely less value; some say it would have had no value at all. Leslie proposes that this proper understanding of the problem points us in the direction of the best solution: the laws are fine-tuned because their being so leads to something of great value. He posits no entities whatsoever other than the observable Universe. But it is not clear that it is intelligible. Values don't seem to be the right kind of things to have a causal influence on the workings of the world, at least not independently of the motives of rational agents. It is rather like suggesting that the abstract number 9 caused a hurricane. But the cosmopsychist has a way of rendering it intelligible, by proposing that the mental capacities of the Universe mediate between value facts and cosmological facts. On this view, which we can call 'agentive cosmopsychism', the Universe itself fine-tuned the laws in response to considerations of value. When was this done? In the first 10-43 seconds, known as the Planck epoch, our current physical theories, in which the fine-tuned laws are embedded, break down. The cosmopsychist can propose that during this early stage of cosmological history, the Universe itself ‘chose’ the fine-tuned values in order to make possible a universe of value.

Making sense of this requires two modifications to basic cosmopsychism. Firstly, we need to suppose that the Universe acts through a basic capacity to recognise and respond to considerations of value. This is very different from how we normally think about things, but it is consistent with everything we observe. The Scottish philosopher David Hume long ago noted that all we can really observe is how things behave – the underlying forces that give rise to those behaviours are invisible to us. We standardly assume that the Universe is powered by a number of non-rational causal capacities, but it is also possible that it is powered by the capacity of the Universe to respond to considerations of value. How are we to think about the laws of physics on this view? I suggest that we think of them as constraints on the agency of the Universe. Unlike the God of theism, this is an agent of limited power, which explains the manifest imperfections of the Universe. The Universe acts to maximise value, but is able to do so only within the constraints of the laws of physics. The beneficence of the Universe does not much reveal itself these days; the cosmopsychist might explain this by holding that the Universe is now more constrained than it was in the unique circumstances of the first split second after the Big Bang, when currently known laws of physics did not apply.

Ockham’s razor is the principle that, all things being equal, more parsimonious theories – that is to say, theories with relatively few postulations – are to be preferred. Is it not a great cost in terms of parsimony to ascribe fundamental consciousness to the Universe? Not at all. The physical world must have some nature, and physics leaves us completely in the dark as to what it is. It is no less parsimonious to suppose that the Universe has a consciousness-involving nature than that it has some non-consciousness-involving nature. If anything, the former proposal is more parsimonious insofar as it is continuous with the only thing we really know about the nature of matter: that brains have consciousness. Having said that, the second and final modification we must make to cosmopsychism in order to explain the fine-tuning does come at some cost. If the Universe, way back in the Planck epoch, fine-tuned the laws to bring about life billions of years in its future, then the Universe must in some sense be aware of the consequences of its actions. This is the second modification: I suggest that the agentive cosmopsychist postulate a basic disposition of the Universe to represent the complete potential consequences of each of its possible actions. In a sense, this is a simple postulation, but it cannot be denied that the complexity involved in these mental representations detracts from the parsimony of the view. However, this commitment is less profligate than the postulations of the theist or the multiverse theorist. The theist postulates a supernatural agent while the agentive cosmopsychist postulates a natural agent. The multiverse theorist postulates an enormous number of distinct, unobservable entities: the many universes. The agentive cosmopsychist merely adds to an entity that we already believe in: the physical Universe. And most importantly, agentive cosmopsychism avoids the false predictions of its two rivals. The idea that the Universe is a conscious mind that responds to value strikes us a ludicrously extravagant cartoon. But we must judge the view not on its cultural associations but on its explanatory power. Agentive cosmopsychism explains the fine-tuning without making false predictions; and it does so with a simplicity and elegance unmatched by its rivals. It is a view we should take seriously.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) This seems to be the least ________________ of the applications but still worth a mention.

2) It sounds unlikely, ______________, that the two positions can be reconciled.

3) Furthermore, the idea of affirmative action for conservatives seems ______________.

4) Those are not the only instances where _____________ members make an impressive mark.

5) Scientific theories can always be defended by the addition of ___________ hypotheses.

6) The natural experiments that might help ___________ theories do not come around often.

7) Students and superiors tout her teaching technique and ____________ expertise.

8) _____________ also does not say that the simplest account is to be preferred regardless of its capacity to explain outliers, exceptions, or other phenomena in question.

9) Further improvements can be obtained by the technique of ____________ propagation.

10) The educated Confucian elite in China were of an entirely different ________________.

Exercise IV.

Make up sentences of your own with the following word combinations: psychism and panpsychism, on the face of it, ad hoc, to fiddle, to falsify, it turns out that, against all the odds, taking into account, let go unexplained, to bring about this great value

Exercise V.

Match the words to the definitions in the column on the right:

gratuitous	recognizably different in nature from something else of a similar type
gruesome	unwilling to spend money or use resources; stingy or frugal
asset	doing good; feeling beneficent
capture	recklessly extravagant or wasteful in the use of resources
rudimentary	causing repulsion or horror; grisly
constraint	a useful or valuable thing, person, or quality
profligate	lacking good reason
distinct	take into one's possession or control by force

beneficence	involving or limited to basic principles
parsimonious	a limitation or restriction

Exercise VI.

Identify the part of speech the words belong to: holism, cosmopsychism, initial, conditions, possibility, possible, strength, gravity, electron, compatible

Exercise VII.

Match the words to make word combinations:

powerful	matter
multiverse	explanation
subject	creator
Ockham's	conditions
knock-down	evidence
supernatural	examples
rational	razor
fine-tuning	theory
conscious	arguments
initial	mind

Exercise VIII.

Summarize the article “Is the Universe a conscious mind?”

2. Beauty ≠ truth

Exercise I.

Say what Russian words help to guess the meaning of the following words: test, archetype, phenomenon, energy, topography, classical, intuition, nervous, experiment, discourse

Exercise II.

Make sure you know the following words and word combinations.

sheer, pledge, tangible, arbiter, crude, shibboleth, bewildering, disarray, to amend, hand-picked

Beauty ≠ truth

Scientists prize elegant theories, but a taste for simplicity is a treacherous guide. And it doesn’t even look good

Albert Einstein’s theory of general relativity is a century old next year and, as far as the test of time is concerned, it seems to have done rather well. For many, indeed, it doesn’t merely hold up: it is the archetype for what a scientific theory should look like. Einstein’s achievement was to explain gravity as a geometric phenomenon: a force that results from the distortion of space-time by matter and energy, compelling objects – and light itself – to move along particular paths, very much as rivers are constrained by the topography of their landscape. General relativity departs from classical Newtonian mechanics and from ordinary intuition alike, but its predictions have been verified countless times. In short, it is the business. Einstein himself seemed rather indifferent to the experimental tests, however. The first came in 1919, when the British physicist Arthur Eddington observed the Sun's gravity bending starlight during a solar eclipse. What if those results hadn't agreed with the theory? (Some accuse Eddington of cherry-picking the figures anyway, but that's another story.) 'Then,' said Einstein, 'I would have been sorry for the dear Lord, for the theory is correct.' That was Einstein all over. As the Danish physicist Niels Bohr commented at the time, he was a little too fond of telling God what to do. But this wasn't sheer arrogance, nor parental pride in his theory. The reason Einstein felt general relativity must be right is that it was too beautiful a theory to be wrong. This sort of talk both delights today's physicists and makes them a little nervous. After all, isn't experiment – nature itself – supposed to determine truth in science? What does beauty have to do with it? 'Aesthetic judgments do not arbitrate scientific discourse,' the string theorist Brian Greene reassures his readers in The Elegant Universe. 'Ultimately, theories are judged by how they fare when faced with cold, hard, experimental facts.' Einstein, Greene insists, didn't mean to imply otherwise – he was just saying that beauty in a theory is a good guide, an indication that you are on the right track. Einstein isn't around to argue, of course, but I think he would have done. It was Einstein, after all, who said that 'the only physical theories that we are willing to accept are the beautiful ones'. And if he was simply defending theory against too hasty a deference to experiment, there would be plenty of reason to side with him – for who is to say that, in case of a discrepancy, it must be the theory and not the measurement that is in error? But that's not really his point. Einstein seems to be asserting that beauty trumps experience come what may. He wasn't alone. Here's the great German mathematician Hermann Weyl: 'My work always tries to unite the true with the beautiful; but when I had to choose one or the other, I usually chose the beautiful.' So much, you might be tempted to conclude, for scientists' devotion to truth: here were some of its greatest luminaries, pledging obedience to a different calling altogether. Was this kind of talk perhaps just the spirit of the age? It would be nice to think so. In fact, the discourse about aesthetics in scientific ideas has never gone away. Even Lev Landau and Evgeny Lifshitz, in their seminal Course of Theoretical Physics, were prepared to call general relativity 'probably the most beautiful of all existing theories'. Today, popularisers such as Greene are keen to make beauty a selling point of physics. The quantum theorist Adrian Kent speculated that the very uglinessof certain modifications of quantum mechanics might count against their credibility. After all, he wrote, here was a field in which 'elegance seems to be a surprisingly strong indicator of physical relevance'. We have to ask: what is this beauty they keep talking about? The Nobel Prize-winning physicist Paul Dirac agreed with Einstein, saying in 1963 that 'it is more important to have beauty in one's equations than to have them fit experiment'. Yet faced with the question of what this all-important beauty is, Dirac threw up his hands. Mathematical beauty, he said, 'cannot be defined any more than beauty in art can be defined' – though he added that it was something 'people who study mathematics usually have no difficulty in appreciating'.

Given this history of evasion, it was refreshing to hear the theoretical physicist Nima Arkani-Hamed spell out what 'beauty' really means for him and his colleagues. It’s not fashion, it’s not sociology. It’s not something that you might find beautiful today but won’t find beautiful 10 years from now. The things that we find beautiful today we suspect would be beautiful for all eternity. And the reason is, what we mean by beauty is really a shorthand for something else. The laws that we find describe nature somehow have a sense of inevitability about them. There are very few principles and there’s no possible other way they could work once you understand them deeply enough. So that’s what we mean when we say ideas are beautiful. Does this bear any relation to what beauty means in the arts? Arkani-Hamed had a shot at that. Take Ludwig van Beethoven, he said, who strove to develop his Fifth Symphony in ‘perfect accordance to its internal logical structure’.Beethoven is indeed renowned for the way he tried out endless variations and directions in his music. But you notice this quality precisely because it is so rare. What generally brings a work of art alive is not its inevitability so much as the decisions that the artist made. We gasp not because the words, the notes, the brushstrokes are ‘right’, but because they are revelatory: they show us not a deterministic process but a sensitive mind making surprising and delightful choices. In fact, pure mathematicians often say that it is precisely this quality that delights them in a great proof: not that it is correct but that it shows a personal, tangibly human genius taking steps in a direction we’d never have guessed. Why shouldn’t scientists be allowed their own definition of beauty? Perhaps they should. Yet isn’t there a narrowness to the standard that they have chosen? Even that might not be so bad, if their cult of ‘beauty’ didn’t seem to undermine the credibility of what they otherwise so strenuously assert:

the sanctity of evidence. It doesn't matter who you are, they say, how famous or well-published: if your theory doesn't match up to nature, it's history. But if that's the name of the game, why on earth should some vague notion of beauty be brought into play as an additional arbiter? Because of experience, they might reply: true theories are beautiful. Well, general relativity might have turned out OK, but plenty of others have not. It's not hard to mine science history for theories and proofs that were beautiful and wrong, or complicated and right. No one has ever shown a correlation between beauty and 'truth'. But it is worse than that, for sometimes 'beauty' in the sense that many scientists prefer – an elegant simplicity, to put it in crude terms – can act as a fake trump card that deflects inquiry. In one little corner of science that I can claim to know reasonably well, an explanation from 1959 for why water-repelling particles attract when immersed in water (that it's an effect of entropy, there being more disordered water molecules when the particles stick together) was so neat and satisfying that it continues to be peddled today, even though the experimental data show that it is untenable and that the real explanation probably lies in a lot of devilish detail. The idea that simplicity, as distinct from beauty, is a guide to truth – the idea, in other words, that Occam's Razor is a useful tool – seems like something of a shibboleth in itself. It is a logical assumption, all else being equal. But it is rare in science that all else is equal. More often, some experiments support one theory and others another. Ironically, the quest for a 'final theory' of nature's deepest physical laws has meant that the inevitability and simplicity now look more remote than ever. For we are now forced to contemplate no fewer than 10500 permissible variants of string theory. It’s always possible that 10500 minus one of them might vanish at a stroke, thanks to the insight of some future genius. Right now, though, the dream of elegant fundamental laws lies in bewildering disarray.

I don’t want scientists to abandon their talk of beauty. Anything that inspires scientific thinking is valuable, and if a quest for beauty – a notion of beauty peculiar to science, removed from art – does that, then bring it on. If, on the other hand, we want beauty in science to make contact with aesthetics in art, I believe we should seek it precisely in the human aspect: in ingenious experimental design, elegance of theoretical logic, gentle clarity of exposition, imaginative leaps of reasoning. These things are not vital for a theory that works, an experiment that succeeds, an explanation that enchants and enlightens. But they are rather lovely. Beauty, unlike truth or nature, is something we make ourselves. Who doesn’t like a pretty idea? Physicists certainly do. In the foundations of physics, it has become accepted practice to prefer hypotheses that are aesthetically pleasing. Physicists believe that their motivations don’t matter because hypotheses, after all, must be tested. But most of their beautiful ideas are hard or impossible to test. And whenever an experiment comes back empty-handed, physicists can amend their theories to accommodate the null results. This has been going on for about 40 years. In these 40 years, aesthetic arguments have flourished into research programmes – such as supersymmetry and the multiverse – that now occupy thousands of scientists. In these 40 years, society spent billions of dollars on experiments that found no evidence to support the beautiful ideas. And in these 40 years, there has not been a major breakthrough in the foundations of physics. My colleagues arguethat criteria of beauty are experience-based. The most fundamental theories we currently have – the standard model of particle physics and Albert Einstein's general relativity – are beautiful in specific ways. I agree it was worth a try to assume that more fundamental theories are beautiful in similar ways. But, well, we tried, and it didn't work. Nevertheless, physicists continue to select theories based on the same three criteria of beauty: simplicity, naturalness, and elegance. With simplicity I don't mean Occam's razor, which demands that among two theories that achieve the same thing, you pick the one that's simpler. No, I mean absolute simplicity: a theory should be simple, period. When theories are not simple enough for my colleagues' tastes, they try to make them simpler – by unifying several forces or by postulating new symmetries that combine particles in orderly sets. The second criterion is naturalness. Naturalness is an attempt to get rid of the human element by requiring that a theory should not use assumptions that appear hand-picked. This criterion is most often applied to the values of constants without units, such as the ratios of elementary particles' masses. Naturalness demands that such numbers should be close to one or, if that's not the case, the theory explains why that isn't so. Then there's elegance, the third and most elusive aspect of beauty. It's often described as a combination of simplicity and surprise that, taken together, reveals new connections. We find elegance in the 'Aha effect', the moment of insight when things fall into place. Physicists currently consider a theory promising if it's beautiful according to these three criteria. This led them to predict, for example, that protons should be able to decay. Experiments have looked for this since the 1980s, but so far nobody has seen a proton decay. Theorists also predicted that we should be able to detect dark matter particles, such as weakly interacting massive particles (WIMPs). We have commissioned dozens of experiments but haven't found any of the hypothetical particles – at least not so far. The same criteria of symmetry and naturalness led many physicists to believe that the Large Hadron Collider (LHC) should see something new besides the Higgs boson, for example so-called 'supersymmetric' particles or additional dimensions of space. But none have been found so far. How far can you push this programme before it becomes absurd? Well, if you make a theory simpler and simpler it will eventually become unpredictive, because the theory no longer contains enough information to even carry through calculations. What you get then is what theorists now call a 'multiverse' – an infinite collection of universes with different laws of nature. For example, if you use the law of gravity without fixing the value of Newton's constant by measurement, you could say that your theory contains a universe for any value of the constant. Of course, you then have to postulate that we live in the one universe that has the value of Newton's constant that we happen to measure. So it might look like you haven't gained much. Except that theorists can now write papers about that large number of new universes. Even better, the other universes aren't observable, hence multiverse theories are safe from experimental test.

I think it's time we take a lesson from the history of science. Beauty does not have a good track record as a guide for theory-development. Many beautiful hypotheses were just wrong, like Johannes Kepler's idea that planetary orbits are stacked in regular polyhedrons known as ‘Platonic solids’, or that atoms are knots in an invisible aether, or that the Universe is in a ‘steady state’ rather than undergoing expansion. And other theories that were once considered ugly have stood the test of time. When Kepler suggested that the planets move on ellipses rather than circles, that struck his contemporaries as too ugly to be true. And the physicist James Maxwell balked at his own theory involving electric and magnetic fields, because in his day the beauty standard involved gears. Paul Dirac chided a later version of Maxwell’s theory as ugly, because it required complicated mathematical gymnastics to remove infinities. Nevertheless, those supposedly ugly ideas were correct. They are still in use today. And we no longer find them ugly. History has a second lesson. Even though beauty was a strong personal motivator for many physicists, the problems that led to breakthroughs were not merely aesthetic misgivings – they were mathematical contradictions. Einstein, for example, abolished absolute time because it was in contradiction with Maxwell’s electromagnetism, thereby creating special relativity. He then resolved the conflict between special relativity and Newtonian gravity, which gave him general relativity. Dirac later removed the disagreement between special relativity and quantum mechanics, which led to the development of the quantum field theories which we still use in particle physics today. The Higgs boson, too, was born out of need for logical consistency. Found at the LHC in 2012, the Higgs boson is necessary to make the standard model work. Without the Higgs, particle physicists’ calculations return probabilities larger than 1, mathematical nonsense that cannot describe reality. Granted, the mathematics didn't tell us it had to be the Higgs boson, it could have been something else. But we knew that something new had to happen at the LHC, before it was even built. This was reasoning built on solid mathematical ground. Supersymmetric particles, on the other hand, are pretty but not necessary. They were included to fix an aesthetic shortcoming of the current theory, a lack of naturalness. There's nothing mathematically wrong with a theory that's not supersymmetric, it's just not particularly pretty. Particle physicists used supersymmetry to remedy this perceived shortfall, thereby making the theory much more beautiful. The predictions that supersymmetric particles should be seen at the LHC, therefore, were based on hope rather than sound logic. And the particles have not been found. My conclusion from this long line of null results is that when physics tries to rectify a perceived lack of beauty, we waste time on problems that aren't really problems. Physicists must rethink their methods, now – before we start discussing whether the world needs a next larger particle collider or yet another dark matter search. The answer can't be that anything goes, of course. The idea that new theories should solve existing problems is good in principle – it's just that, currently, the problems themselves aren't sharply formulated enough for that criterion to be useful. The conceptual and philosophical basis of reasoning in the foundations of physics is weak, and this must improve. It's no use, and not good scientific practice, to demand that nature conform to our ideals of beauty. We should let evidence lead the way to new laws of nature. I am pretty sure beauty will await us there.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) Their function is to enforce laws, legislate new ones, and _____________ conflicts.

2) If you prefer to pretend that there is no _______________, you are welcome to do so.

3) The driving force for the last 40 years has been to reduce costs ______________.

4) Tech_____________ Esther Dyson and Slide founder Max Levchin are board members.

5) Since I see no ______________, I have no clue what the interviewer is hoping to hear.

6) At first glance, there's nothing hugely _______________ about the letters and memos.

7) As some keen observers had predicted, nothing _______________ came out of the meetings.

8) Mainstream parties once changed names, merged and split with ____________ speed.

9) An alternative is to decrease the surface area to volume ratio of the pressurized volume, by using more anvils to converge upon a higher-order _________________, such as a dodecahedron.

10) The best way to _______________ such a situation is to make sure the next test is truer.

Exercise IV.

Make up sentences of your own with the following word combinations:

all over, come what may, to have a shot at smth, name of the game, to rectify, to arbitrate, to fare, to gasp, to assert, to deflect

Exercise V.

Match the words to the definitions in the column on the right:

ellipse	a method of rapid writing by means of abbreviations and symbols, used esp. for taking dictation.
ingenious	the state or quality of being holy, sacred, or saintly
to enchant	a feeling of doubt or apprehension about the outcome or consequences of something
gear	a solid figure with many plane faces, typically more than six
revelatory	fill (someone) with great delight; charm
to contemplate	a regular oval shape, traced by a point moving in a plane so that the sum of its distances from two other points (the foci) is constant, or resulting when a cone is cut by an oblique plane that does not intersect the base
shorthand	revealing something hitherto unknown
misgiving	clever, original, and inventive
sanctity	equipment that is used for a particular purpose
polyhedron	look thoughtfully for a long time at

Exercise VI.

Identify the part of speech the words belong to.

treacherous, discrepancy, evasion, untenable, permissible, elusive, seminal, elegant, simplicity, achievement

Exercise VII.

Match the words to make word combinations:

philosophical	phenomenon
selling	basis
Platonic	eclipse
quantum	pride
seminal	solid
parental	point
solar	guide
geometric	course
general	theorist
treacherous	relativity

Exercise VIII.

Summarize the article “Beauty ≠ truth”.

3. The cold fusion horizon

Exercise I.

Say what Russian words help to guess the meaning of the following words: horizon, risk, reputation, project, apparatus, engineer, reactor, commercially, fundamental, principle

Exercise II

Make sure you know the following words and word combinations.
OPERA, racking, lone, to tenet, watertight, to rebuke, to amass, to contemplate, tainted, to deter

The cold fusion horizon

Is cold fusion truly impossible, or is it just that no respectable scientist can risk their reputation working on it?

A few years ago, a physicist friend of mine made a joke on Facebook about the laws of physics being broken in Italy. He had two pieces of news in mind. One was a claim by a team at the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) in Gran Sasso, who said they'd discovered superluminal neutrinos. The other concerned Andrea Rossi, an engineer from Bologna, who claimed to have a cold fusion reactor producing commercially useful amounts of heat. Why were these claims so improbable? The neutrinos challenged a fundamental principle of Albert Einstein's theory of special relativity, which says that nothing can travel faster than light. Meanwhile cold fusion (or LENR, for 'low-energy nuclear reaction') is the controversial idea that nuclear reactions similar to those in the Sun could, under certain conditions, also occur close to room temperature. The latter was popularised in 1989 by Martin Fleischmann and Stanley Pons, who claimed to have found evidence that such processes could take place in palladium loaded with deuterium (an isotope of hydrogen). A few other physicists, including the late Sergio Focardi at Bologna, claimed similar effects with nickel and ordinary hydrogen. But most were highly skeptical, and the field subsequently gained, as Wikipedia puts it, 'a reputation as pathological science'. It turned out that my physicist friend and I disagreed about which of these unlikely claims was most credible. He thought it was the neutrinos, because the work had been done by respectable scientists rather than a lone engineer with a somewhat chequered past. I favoured Rossi, on grounds of the physics. Superluminal neutrinos would overturn a fundamental tenet of relativity, but all Rossi needed was a previously unnoticed channel to a reservoir of energy whose existence is not in doubt. We know that huge amounts of energy are locked up in metastable nuclear configurations, trapped like water behind a dam. There's no known way to get useful access to it at low temperatures. But – so far as I knew – there was no 'watertight' argument that such methods were impossible. The neutrinos were scratched from the race, when it became apparent that someone on OPERA's team of respectable scientists had failed to tighten an optical lead correctly. Rossi, however, has been going from strength to strength. Recently, Rossi was granted a US patent for one of his devices, previously refused on the grounds that insufficient evidence had been provided that the technique worked as claimed. There are credible reports that a 1MW version of his device, producing many times the energy that it consumes, has been on trial in an industrial plant in North Carolina for months, with good results so far. There's a paper by two Swedish physicists, Rickard Lundin and Hans Lidgren, who say that the 'experimental results by Rossi and co-workers and their E-Cat reactor provide the best experimental verification' of the process they propose.

As I say, I don't claim that this evidence is conclusive. It's still conceivable that there is fraud involved, as many skeptics have claimed; or some large and persistent measurement error. Yet these alternatives are becoming increasingly unlikely. Rossi is not even the only person claiming commercially relevant results from LENR. Another prominent example is Robert Godes, of the California-based Brillouin Energy. Imagine that someone had a working hot-fusion reactor in Florida – assembled, as Rossi's 1MW device is reported to be, in a couple of shipping containers, and producing several hundred kilowatts of excess power, month after month, in apparent safety. That would be huge news. As several people have noticed, a new clean source of energy would be really, really useful right about now. But if the potential news is this big, why haven't most of you heard about Rossi or any of the other people who have been working in the area (for many years, in some cases)? This is where, from a philosopher of science's point of view, things get interesting. As a question about sociology, the answer is obvious. Cold fusion is dismissed as pseudoscience, the kind of thing that respectable scientists and science journalists simply don't talk about (unless to remind us of its disgrace). The term cold fusion has become almost synonymous with scientific chicanery. Ever since 1989, in fact, the whole subject has been largely offlimits in mainstream scientific circles. Authors who do put their head above the parapet are ignored or rebuked. Sociology is one thing, but rational explanation another. It is very hard to extract from this history any satisfactory justification for ignoring recent work on LENR. After all, the standard line is that the rejection of cold fusion in 1989 turned on the failure to replicate the claims of Fleischmann and Pons. Yet if that were the real reason, then the rejection would have to be provisional. Failure to replicate couldn't possibly be more than provisional – empirical science is a fallible business, as any good scientist would acknowledge. In that case, well-performed experiments claiming to overturn the failure to replicate would certainly be of great interest. What if the failure to replicate wasn't crucial after all? What if we already knew, on theoretical grounds alone, that cold fusion was impossible? But this would make a nonsense of the fuss over the failure to reproduce Fleischmann and Pons' findings. And in any case, it is simply not true. As I said at the beginning, what physicists actually say (in my experience) is that although LENR is highly unlikely, we cannot say that it is impossible. We know that the energy is in there, after all.

No doubt one could find some physicists who would claim it was impossible. But they might like to recall the case of the great nuclear physicist Lord Rutherford, who claimed in 1933 that 'anyone who expects a source of power from transformation of… atoms is talking moonshine' – only days before Leo Szilard, prompted by newspaper reports of Rutherford's remarks, figured out the principles of the chain reaction that makes nuclear fission useable as an energy source, peaceful or otherwise. This is not to deny that there is truth in the principle popularised by Carl

Sagan, that extraordinary claims require extraordinary evidence. We should certainly be very cautious about such surprising claims, unless and until we amass a great deal of evidence. But this is not a good reason for ignoring such evidence in the first place, or refusing to contemplate the possibility that it might exist. ('It is sad that such people say that science should be driven by data and results, but at the same time refuse to look at the actual results.') Again, there's a sociological explanation why few people are willing to look at the evidence. They put their reputations at risk by doing so. Cold fusion is tainted, and the taint is contagious – anyone seen to take it seriously risks contamination. So the subject is stuck in a place that is largely inaccessible to reason – a reputation trap, we might call it. People outside the trap won't go near it, for fear of falling in. People inside the trap are already regarded as disreputable, an attitude that trumps any efforts that they might make to argue their way out, by reason and evidence.

Outsiders might be surprised to learn how well-populated the trap actually is, in the case of cold fusion and LENR. The field never entirely went away, nor vanished from the laboratories of respected institutions. To anyone willing to listen, the community will say that they have amassed a great deal of evidence of excess heat, not explicable in chemical terms, and of various markers of nuclear processes. Some, including a team at one of Italy's leading research centres, say that they have many replications of the Fleischmann and Pons results. Again, the explanation for ignoring these claims cannot be that other attempts failed 25 years ago. That makes no sense at all. Rather, it's the reputation trap. The results are ignored because they concern cold fusion, which we ‘know’ to be pseudoscience – we know it because attempts to replicate these experiments failed 25 years ago! The reasoning is still entirely circular, but the reputation trap gives its conclusion a convincing mask of respectability. That’s how the trap works. Fifty years ago, Thomas Kuhn taught us that this is the usual way for science to deal with paradigm-threatening anomalies. The borders of dominant paradigms are often protected by reputation traps, which deter all but the most reckless or brilliant critics. If LENR were an ordinary piece of science (or proposed science), the challenge posed by Rossi and others would promise fascinating spectator sport for philosophers and historians of science. We could take our seats on the sidelines and wait to see whether walls fall – whether distinguished skeptics end up with egg on their faces. But there’s more, much more. None of us, not even philosophers, are mere spectators in this case. We all have skin in the game, and parts, indeed a planet, quite seriously in peril. There may be a huge cost to a false negative. If Rossi, Godes, Lundin, Lidgren and others do turn out to have something useful – something that can make some useful contribution to meeting our desperate need for clean, cheap energy – we will have wasted a generation of progress. What we should have done instead is to have engineered the exact opposite of a reputation trap – perhaps an X Prize-like reward for the first reliable replication of the Fleischmann and Pons results.

I suspect it’s too late to dismantle the trap for LENR. If Rossi and Godes et al are actually on to something, then the field is going to be mainstream soon anyway. But we could try to learn from our mistakes.

There might be other potential cases with a similar payoff structure (a high cost for false negatives, with a low cost for false positives). I suspect there are some in the area of emerging extreme risks.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) This means that you're ______________ up some data usage anytime your smartphone is on.

2) This ultra-dense form of ______________ may facilitate achieving laser-induced fusion.

3) Altogether, the _______________ will save up to 228 billion gallons of water per year.

4) Today, the theory behind the concept has been tested and found to be _______________.

5) People born under that sign are said to be hardworking, tolerant and __________________.

6) I suspect that your company's policy is meant to thwart that sort of ___________________.

7) Possible penalties range from an official ___________ to expulsion from the Senate.

8) It would all be better if people admitted they are _________________ and mistakes happen.

9) All nuclear reactors rely on nuclear ______________, a process discovered in the 1930s.

10) If that had happened, the scale of the __________________ would be that of Chernobyl.

Exercise IV.

Make up sentences of your own with the following word combinations: optical lead, false negative, payoff , close to room temperature, on grounds of physics, to overturn a fundamental tenet of relativity, is not in doubt, to be locked up in, to be trapped like water behind a dam, to get useful access to

<u>Exercise V</u>.

Match the words to the definitions in the column on the right:

reservoir	capable of making mistakes or being erroneous
peril	illicitly distilled or smuggled liquor
spectator	serious and immediate danger
parapet	a large natural or artificial lake used as a source of water supply
fission	the use of trickery to achieve a political, financial, or legal purpose
excess	a person who watches at a show, game, or other event
fuss	a low, protective wall along the edge of a roof, bridge, or balcony
fallible	the action of dividing or splitting something into two or more parts

moonshine	an amount of something that is more than necessary, permitted, or desirable
chicanery	a display of unnecessary or excessive excitement, activity, or interest

Exercise VI.

Identify the part of speech the words belong to.

persistent, provisional, contamination, deuterium, fusion, horizon, impossible, respectable, scientist, reputation

Exercise VII.

Match the words to make word combinations:

room	configurations
superluminal	reactor
fundamental	evidence
industrial	temperature
insufficient	principle
nuclear	idea
controversial	neutrinos
fusion	reaction

Exercise VIII.

Summarize the article “The cold fusion horizon”

4. Future Wear

Exercise I.

Say what Russian words help to guess the meaning of the following words: technological, laboratory, machine, stabilize, active, version, industrial, optic, polymer, cylinder

Exercise II.

Make sure you know the following words and word combinations.

subterranean, to mutter, to align, to augment, arduous, to coax, to endow, quip, versatile, barcode

Future Wear

If one MIT researcher has his way, our fabric could be the next great technological frontier.

In a cluttered subterranean laboratory at MIT, Jung Tae Lee is attempting to make a battery as long and thin as a fishing line. With a focused gaze, the researcher adjusts the knobs on an imposing blue machine that heats up and stretches out filament. “Must stabilize before making active fiber,” he mutters. Benjamin Grena is more loquacious. The grad student explains that the blue machine, which stands nearly twice his height, is a draw tower, a custom version of an industrial appliance used to extrude glass rods into fiber-optic cable. Lee will make his device by elongating, or drawing, a fat polymer cylinder that has been embedded with electrodes and injected with battery fluids. The trick is to keep the metals and liquids aligned, as Lee heats and stretches the cylinder until its diameter is ideally a mere 1/200th its original size — a high-precision variation on pulling saltwater taffy. “And then,” Grena says, “you’ll have a power source that can be woven together with sensors and other functional fibers.” These resulting electronic textiles could be worn as garments, implanted in a body or blanketed across a city. For Yoel Fink — Grena and Lee’s MIT adviser and supervisor, respectively, and the mastermind behind the high-tech threads — the textiles represent nothing less than a turning point in human civilization. “Fabrics have remained sort of immutable since the Late Stone Age,” Fink says. “That’s because they’re made of fibers that are made of a single material, and so long as you make fibers of a single material, they’re not going to be highly functional.” With a method for crafting fibers that integrate everything from polymers to metals and fluids — and then controlling the internal arrangement of these materials — Fink envisions vast new possibilities for fabrics. And given the ubiquity of textiles in our world, he believes the fibers he’s working on will profoundly augment technology as a whole.

Fink’s vision is attracting a following well beyond the basements of MIT. He founded an institute called Advanced Functional Fabrics of America (AFFOA), a public-private consortium comprising more than two dozen major research institutions, including Drexel University in Philadelphia and Carnegie Mellon University in Pittsburgh. The consortium also includes influential technology companies such as Tesla and Corning, as well as the U.S. Department of Defense. As CEO, Fink commands a total budget of $317 million, with which he intends to create an institutional network with expansive expertise that can efficiently push fiber innovations beyond lab experiments and into consumer products. He has already built a 20,000-square-foot prototyping facility, which began operating in the Boston area last June. Far from resisting Fink's assault on millennia of spinning and weaving, the traditional textile industry is a committed ally. "I've been around textile people my whole life, and I've never heard anybody talk about putting electronics into a textile," says Norman Chapman, president of Inman Mills, a yarn-spinning and fabric-weaving company in South Carolina. Together with other industry mainstays such as Milliken and Warwick Mills, Inman has enthusiastically joined AFFOA. In the frenzy of revolution, only Fink's students seem unflappable. Fiber drawing cannot be hurried.

Fink sits in his spacious MIT office, cradling an army helmet wrapped in camo-patterned fabric. "You see these golden fibers?" he asks, pointing at some barely visible metallic threads. "This was produced a few years ago at Natick." He's referring to the U.S. Army's Soldier Research, Development and Engineering Center, an early collaborator that helped him to demonstrate that functional fibers could be woven into standard gear. Ultimately, the Army is interested in preventing battlefield friendly fire by developing threads with special optical qualities that respond to laser sights. Fink and his collaborators have addressed this by weaving filaments with different reflective qualities into a kind of plaid pattern that's instantly visible through a comrade's laser sight. It's a clear signal not to shoot. Enrolled in materials science, Fink drifted in search of a research project, interviewing with dozens of professors across a broad spectrum of fields. One of them was Ned Thomas, a materials scientist who was involved in a secret multimillion-dollar program for the Defense Advanced Research Projects Agency (DARPA) to create a mechanism that would reflect light from any direction. Thomas invited Fink to attend a meeting where MIT scientists would discuss a plan for tackling this problem. As Fink prepared, he started to look at dielectric materials — insulators and semiconductors that are layered to make high-precision mirrors — and a very simple question came into his head. “I knew from my optics studies that layered systems reflect, but the angle is limited,” he says. What he couldn’t find was a theoretical basis for this rule of thumb. So at the meeting, he naively asked if anybody knew a formula to determine the angle at which multilayered dielectrics stop reflecting. “I was sure one of them was going to say, ‘There’s this optics course I’m giving next term,’ ” Fink recalls. “But the room was silent.” He immediately started to work on the problem, and several weeks and analyses later, he found there is no physical limit. By layering the right thicknesses of certain dielectric materials, he could make a mirror that reflected light from any angle — a perfect mirror. The physics community was agog. Fink decided to keep working on the idea anyway, hoping to expand the use of his mirror into a high-efficiency alternative to fiber-optic cable for telecommunications. A conventional optical fiber is limited by the materials it’s made of, because they don’t perfectly reflect the light waves inside: The cord gradually absorbs the photons running through it, weakening the signal. Fink’s plan was to fabricate a hollow tube with multilayered dielectric walls that would perfectly reflect the light passing through. “I actually needed to ask around how fibers were made,” he admits. But he’d successfully earned his doctorate and transitioned to MIT faculty in 2000, giving him the freedom to acquire a small draw tower and start experimenting, along with several grad students. He had no idea he was breaking the most basic industrywide rules. Until Fink came along, everyone assumed any materials you'd use to make a filament needed to have matching viscosities, thermal properties and other traits in order to extrude them together; you also needed to draw them at low tension and high temperature. Through trial and error, Fink figured out how to draw at high tension and low temperature. And the "OmniGuide," as Fink calls his invention, became his first functional fiber. However, the telecommunications field wasn't prepared for a revolution. The industry was shrinking in the early 2000s, and cheap optical fiber was overabundant. Instead, Fink co-founded a company that put the OmniGuide to use in medicine. "We made a scalpel for minimally invasive surgery," he says. The bladeless tool uses the intense light of a carbon dioxide laser to cut through soft tissue. The CO2 wavelength is ideal for surgery because the water in fat and muscle absorbs it efficiently, making for easy cutting. And doctors have long favored CO2 lasers for procedures in tight spaces where metal tools would get in the way. Before Fink got involved, CO2 laser procedures were arduous. Because glass won't transmit light at the CO2 wavelength, surgeons couldn't use conventional optical fiber to guide the laser beam; instead, they had to painstakingly and precisely aim the whole unwieldy laser unit at the patient to hit just the right spot, and they could only cut tissue in the laser's line of sight. However, with a flexible omniguide putting the laser beam right at the doctor's fingertips, surgeons can maneuver the light exactly where it's needed. Fink's invention has now been used in more than 200,000 procedures. It's also served as a paradigm for Fink's subsequent approach to engineering, which combines experimental openness with interdisciplinary reach, stretching fiber technology into every domain he encounters. “He is visionary, he’s rebellious, and he’s incredibly scientifically brave,” observes Polina Anikeeva, an MIT professor of materials science and engineering, and a frequent collaborator. “He goes after big questions without any fear.” Fink’s relentless effort has vastly increased the uses of high-tech fibers. He’s also found that many of his techniques for fabricating these kinds of fibers could be used to make electronics.

In a subterranean laboratory several twists and turns away from Fink’s draw tower, Tural Khudiyev, another postdoctoral team member, is gently coaxing a fiber to sing. He has exposed metal conductors on one end of the strand and connected them to a high-voltage amplifier. Holding the tip of the filament in a vice, he switches on the amp and cups his ear. The cord softly hums. “This,” Khudiyev says, “is the piezoelectric effect. It converts an electrical signal into a sound. The opposite is also possible. The fiber can be a microphone as well.” Scientists have known about the piezoelectric effect since 1880 and have exploited the phenomenon in electronics for a century, not only for sound but also to exert and detect pressure. By introducing piezoelectricity into a thread that can be woven into a garment, Fink’s group is transplanting a hundred years of innovation into a new domain, endowing fabrics with capabilities that could be achieved previously only with devices that people strap on or carry. Those devices, such as health and fitness wearables, are limited by the fact that they’re accessories. “Stuff we wear is called clothes,” quips Fink. He believes this is more than a trivial distinction. Our clothing has as much as

20 square feet of external surface area, touching nearly every part of the body. That means a piezoelectric textile could potentially hear our surroundings, sense our movements and monitor internal organs, such as our heart and lungs, with unprecedented fidelity. It could also generate energy as we walk. And piezoelectricity is only one of many electronic capacities Fink's lab is systematically mastering. Michael Rein, a former grad student of Fink's and now a senior product engineer at AFFOA, has been drawing fibers that contain tiny diodes, semiconductors that can alternately emit or detect light. Woven into a fabric, they'll be able to electronically change a garment's appearance or allow for remote communication. In his thesis work, Rein demonstrated that these functional fibers are washable — an important milestone on the road from lab to marketplace. As with any electronics, multiple components will be able to do far more collectively. For instance, by combining Rein's diode fibers with Khudiyev's piezoelectrics, "you could communicate at a distance," observes Fink's grad student Grena. The diodes could detect a voice-controlled laser beam and make the piezoelectric fabric vibrate so that troops could hear their commander's orders on a chaotic battlefield. Conversely, vital signs measured by piezoelectric fibers could be relayed to a medic by light-emitting diodes (LEDs) on a wounded soldier's uniform. Grena also foresees advantages in terms of scale, especially for sensor networks. Fibrous electronics can be stretched very thin to extend over vast distances. A piezoelectric mesh could take large-scale measurements, like bridge strain or ocean currents.

At the opposite extreme, Anikeeva is applying Fink's fiber-drawing technique to neuroscience. Her flexible filaments take advantage of the miniaturization afforded by fiber drawing, combining optical waveguides with conductive electrodes and fluid channels to create a probe thinner than a human hair. A single probe can deliver drugs and measure neural activity in a brain or spinal cord without damaging tissue. It can even stimulate neurons that have had their DNA modified to respond to light, making it a powerful and versatile tool in the emerging field of optogenetics. “The fiber-drawing process,” says Anikeeva, “is the enabling capability.”

At MIT’s Computer Science and Artificial Intelligence Lab, Fink shows off some of the first products developed by AFFOA. He presents backpacks with unique barcode-like patterns woven into the fabric; an ordinary iPhone camera can scan the pack from across a room to bring up information, like a quote or a song, through a program the wearer can enable and use with a phone. He also shows off baseball caps woven with diodes that sense signals from overhead lights. The signals are sent by flickering the lighting more quickly than our eyes can perceive — a system that could help future wearers navigate disorienting buildings like hospitals and airports. “Most university intellectual property is sitting on a shelf,” Fink explains. “And the reason is there’s a gap between where research ends and production begins.” With AFFOA and its approach to projects like these, the gap is eliminated. As groundbreaking as the materials coming out of Fink’s lab may be, Dion believes their adoption will depend on addressing real human needs in ways that people find appealing, issues that are more readily taken up by designers and sociologists than engineers. The obvious place to start using functional fibers and fabrics is in health care, especially for people with conditions that need constant monitoring and treatment. Functional fabrics might not only provide better support, but they could also eliminate the stigma of looking different. We'll be successful with wearable technology as medical devices when nobody can tell you're wearing them. People ask, how's this fabric going to look like? Actually it's not going to look any different, but it's going to do a whole lot more.

Adapted from Discover Magazine

Exercise III.

Fill in the gaps.

1) Despite those expenses, ________________ storage is expected to cost only $1 per sq.

2) Governments make money by exercising control and ______________ taxes, fees and fines.

3) The normally ______________ Olmert summed up his resignation in two sentences.

4) The tweezers are made from a _______________ tapered to a tip measuring 3 microns across, with metal electrodes on either side.

5) This cannot only ______________ the duration of your cold, but even make you sicker.

6) For example, consider the claim to truth held by the ______________ laws of physics.

7) The global housing boom has been unusual in its strength, duration and ____________.

8) They measure the ________________, or thickness, of oil as it comes out of the ground.

9) The result was less ________________ and held together better than a conventional braise.

10) Researchers have created a new kind of _____________ that uses DNA origami technology.

<u>Exercise IV</u>.

Make up sentences of your own with the following word combinations: twists and turns, with a focused gaze, to heat up, to stand nearly twice its height, to keep the metals and liquids aligned, to be woven together with sensors, turning point in, real human needs, to be taken up by designers, in health care

<u>Exercise V</u>.

Match the words to the definitions in the column on the right:

frontier	a state formally cooperating with another for a military or other purpose, typically by treaty
to elongate	force (something unwelcome or unfamiliar) to be accepted or put in place
hollow	thrust or force out
to flicker	having a hole or empty space inside
expertise	tension
imposing	make (something) longer, esp. unusually so in relation to its width

strain	a line or border separating two countries
to extrude	expert skill or knowledge in a particular field
ally	shine unsteadily; vary rapidly in brightness

Exercise VI.

identify the part of speech the words belong to: immutable, loquacious, viscosity, relentless, fiber-optic, consortium, unwieldy, fibrous, ubiquity

Exercise VII.

Match the words to make word combinations:

battery	appliance
glass	cylinder
draw	fiber
custom	cable
subterranean	rod
active	tower
industrial	frontier
polymer	version
fiber-optic	fluids
technological	laboratory

Exercise VIII .

Summarize the article “Future Wear.”

SUPPLEMENTARY READING

Cosmologists Debate How Fast the Universe Is Expanding

New measurements could upend the standard theory of the cosmos that has reigned since the discovery of dark energy 21 years ago.

In 1998, two teams of cosmologists observed dozens of distant supernovas and inferred that they’re racing away from Earth faster and faster all the time. This meant that — contrary to expectations — the expansion of the universe is accelerating, and thus the fabric of space must be infused with a repulsive “dark energy” that comprises more than two-thirds of everything. For this discovery, the team leaders, Saul Perlmutter of the Supernova Cosmology Project and Brian Schmidt and Adam Riess of the High-Z Supernova Search Team, won the 2011 Nobel Prize in Physics. Fast forward to July of this year.

On a Monday morning three weeks ago, many of the world’s leading cosmologists gathered in Santa Barbara, California, to discuss a major predicament. Riess, now 49, strolled to the front of a seminar room to give the opening talk. A bulldog of a man in a short-sleeved box-check shirt, Riess laid out the evidence, gathered by himself and others, that the universe is currently expanding too fast — faster than theorists predict when they extrapolate from the early universe to the present day. “If the late and early universe don’t agree, we have to be open to the possibility of new physics,” he said.

At stake is the standard theory of the cosmos that has reigned since the discovery of dark energy. The theory, called ΛCDM, describes all the visible matter and energy in the universe, along with dark energy (represented by the Greek letter Λ, or lambda) and cold dark matter (CDM), showing how they evolve according to Albert Einstein’s theory of gravity. ΛCDM perfectly captures features of the early universe — patterns best seen in ancient microwaves coming from a critical moment when the cosmos was 380,000 years old. Since the Planck Space Telescope’s first map of this “cosmic microwave background” was released in 2013, scientists have been able to precisely infer a distance scale in the young universe and use ΛCDM to fast-forward from the 380,000-year-mark to now, to predict the current rate of cosmic expansion — known as the Hubble constant, or H0.

The Planck team predicts that the universe should expand at a rate of 67.4 kilometers per second per megaparsec. That is, as you look farther into space, space should be receding 67.4 kilometers per second faster for each megaparsec of distance, just as two Sharpie marks on an expanding balloon separate faster the farther apart they are. Measurements of other early-universe features called “baryon acoustic oscillations" yield exactly the same prediction: H0 = 67.4. Yet observations of the actual universe by Riess's team have suggested for six years that the prediction is off. That July morning in a room with an obstructed view of the Pacific, Riess seemed to have a second Nobel Prize in his sights. Among the 100 experts in the crowd — invited representatives of all the major cosmological projects, along with theorists and other interested specialists — nobody could deny that his chances of success had dramatically improved the Friday before.

Ahead of the conference, a team of cosmologists calling themselves H0LiCOW had published their new measurement of the universe's expansion rate. By the light of six distant quasars, H0LiCOW pegged H0 at 73.3 kilometers per second per megaparsec — significantly higher than Planck's prediction. What mattered was how close H0LiCOW's 73.3 fell to measurements of H0 by SH0ES — the team led by Riess. SH0ES measures cosmic expansion using a "cosmic distance ladder," a stepwise method of gauging cosmological distances. SH0ES' latest measurement in March pinpointed H0 at 74.0, well within H0LiCOW's error margins.

"My heart was aflutter," Riess told me, of his early look at H0LiCOW's result two weeks before Santa Barbara. For six years, the SH0ES team claimed that it had found a discrepancy with predictions based on the early universe. Now, the combined SH0ES and H0LiCOW measurements have crossed a statistical threshold known as "five sigma," which typically signifies a discovery of new physics. If the Hubble constant is not 67 but actually 73 or 74, then ΛCDM is missing something — some factor that speeds up cosmic expansion. This extra ingredient added to the familiar mix of matter and energy would yield a richer understanding of cosmology than the rather bland ΛCDM theory provides.

During his talk, Riess said of the gulf between 67 and 73, "This difference appears to be robust." "I know we've been calling this the 'Hubble constant tension,'" he added, "but are we allowed yet to call this a problem?" He put the question to fellow Nobel laureate David Gross, a particle physicist and the former director of the Kavli Institute for Theoretical Physics (KITP), where the conference took place. "We wouldn't call it a tension or problem, but rather a crisis," Gross said. "Then we're in crisis."

To those trying to understand the cosmos, a crisis is the chance to discover something big. Lloyd Knox, a member of the Planck team, spoke after Riess. "Maybe the Hubble constant tension is the exciting breakdown of ΛCDM that we've all been, or many of us have been, waiting and hoping for," he said.

When talks ended for the day, many attendees piled into a van bound for the hotel. We drove past palm trees with the ocean on the right and the Santa Ynez Mountains to the distant left. Wendy Freedman, a decorated Hubble constant veteran, perched in the second row. A thin, calm woman of 62, Freedman led the team that made the first measurement of H0 to within 10% accuracy, arriving at a result of 72 in 2001.

The driver, a young, bearded Californian, heard about the Hubble trouble and the issue of what to call it. Instead of tension, problem or crisis, he suggested “surd,” meaning nonsensical or irrational. The Hubble constant surd.

Freedman, however, seemed less giddy than the average conferencegoer about the apparent discrepancy and wasn’t ready to call it real. “We have more work to do,” she said quietly, almost mouthing the words.

Freedman spent decades improving H0 measurements using the cosmic distance ladder method. For a long time, she calibrated her ladder’s rungs using cepheid stars — the same pulsating stars of known brightness that SH0ES also uses as “standard candles” in its cosmic distance ladder. But she worries about unknown sources of error. “She knows where all the skeletons are buried,” said Barry Madore, Freedman’s white-whiskered husband and close collaborator, who sat up front next to the driver.

Freedman said that’s why she, Madore and their Carnegie-Chicago Hubble Program (CCHP) set out several years ago to use “tip of the red giant branch” stars (TRGBs) to calibrate a new cosmic distance ladder. TRGBs are what stars like our sun briefly turn into at the end of their lives. Bloated and red, they grow brighter and brighter until they reach a characteristic peak brightness caused by the sudden igniting of helium in their cores. Freedman, Madore and Myung Gyoon Leefirst pointed out in 1993 that these peaking red giants can serve as standard candles. Now Freedman had put them to work. As we unloaded from the van, I asked her about her scheduled talk. “It’s the second talk after lunch tomorrow,” she said.

“Be there,” said Madore, with a gleam in his eye, as we parted ways.

When I got to my hotel room and checked Twitter, I found that everything had changed. Freedman, Madore and their CCHP team’s paper had just dropped. Using tip-of-the-red-giant-branch stars, they’d pegged the Hubble constant at 69.8 — notably short of SH0ES’ 74.0 measurement using cepheids and H0LiCOW’s 73.3 from quasars, and more than halfway to Planck’s 67.4 prediction. “The Universe is just messing with us at this point, right?” one astrophysicist tweeted. Things were getting surd.

Dan Scolnic, a bespectacled young member of SH0ES based at Duke University, said that he, Riess and two other team members had gotten together, “trying to figure out what was in the paper. Adam and I then went out to dinner and we were pretty perplexed, because in what we had seen up to this point, the cepheids and TRGBs were in really good agreement.”

They soon homed in on the key change in the paper: a new way of measuring the effects of dust when gauging the intrinsic brightness of TRGBs — the first rung of the cosmic distance ladder. “We had a bunch of questions about this new method,” Scolnic said. Like other participants scattered throughout the Best Western Plus, they eagerly awaited Freedman’s talk the next day. Scolnic tweeted, “Tomorrow is going to be interesting.”

Tension, problem, crisis, surd — there has been a Hubble constantsomething for 90 years, ever since the American astronomer Edwin Hubble’s plots of the distances and recessional speeds of galaxies showed that space and everything in it is receding from us (Hubble's own refusal to accept this conclusion notwithstanding). One of the all-time greatest cosmological discoveries, cosmic expansion implies that the universe has a finite age.

The ratio of an object's recessional speed to its distance gives the Hubble constant. But whereas it's easy to tell how fast a star or galaxy is receding — just measure the Doppler shift of its frequencies, an effect similar to a siren dropping in pitch as the ambulance drives away — it's far harder to tell the distance of a pinprick of light in the night sky.

It was Henrietta Leavitt, one of the human "computers" at the Harvard College Observatory, who discovered in 1908 that cepheid stars pulsate with a frequency that's proportional to their luminosity. Big, bright cepheids pulsate more slowly than small, dim ones (just as a big accordion is harder to compress than a tiny one). And so, from the pulsations of a distant cepheid, you can read off how intrinsically bright it is. Compare that to how faint the star appears, and you can tell its distance — and the distance of the galaxy it's in.

In the 1920s, Hubble used cepheids and Leavitt's law to infer that Andromeda and other "spiral nebulae" (as they were known) are separate galaxies, far beyond our Milky Way. This revealed for the first time that the Milky Way isn't the whole universe — that the universe is, in fact, unimaginably vast. Hubble then used cepheids to deduce the distances to nearby galaxies, which, plotted against their speeds, revealed cosmic expansion.

Hubble overestimated the rate as 500 kilometers per second per megaparsec, but the number dropped as cosmologists used cepheids to calibrate evermore accurate cosmic distance ladders. From the 1970s on, the eminent observational cosmologist and Hubble protégé Allan Sandage argued that H0 was around 50. His rivals claimed a value around 100, based on different astronomical observations. The vitriolic 50-versus-100 debate was raging in the early '80s when Freedman, a young Canadian working as a postdoc at the Carnegie Observatories in Pasadena, California, where Sandage also worked, set out to improve cosmic distance ladders.

To build a distance ladder, you start by calibrating the distance to stars of known luminosity, such as cepheids. These standard candles can be used to gauge the distances to fainter cepheids in farther-away galaxies. This gives the distances of "Type 1a supernovas" in the same galaxies — predictable stellar explosions that serve as much brighter, though rarer, standard candles. You then use these supernovas to gauge the distances to hundreds of farther-away supernovas, in galaxies that are freely moving in the current of cosmic expansion, known as the "Hubble flow." These are the supernovas whose ratio of speed to distance gives H0.

But although a standard candle's faintness is supposed to tell its distance, dust also dims stars, making them look farther away than they are. Crowding by other stars can make them look brighter (and thus closer). Furthermore, even supposed standard-candle stars have inherent variations due to age and metallicity that must be corrected for. Freedman devised new methods to deal with many sources of systematic error.

When she started getting H0 values higher than Sandage's, he became antagonistic. "To him, I was a young upstart," she told me in 2017. Nevertheless, in the '90s she assembled and led the Hubble Space Telescope Key Project, a mission to use the new Hubble telescope to measure distances to cepheids and supernovas with greater accuracy than ever before. The H0 value of 72 that her team published in 2001 split the difference in the 50-versus-100 debate.

Freedman was named director of Carnegie Observatories two years later, becoming Sandage's boss. She was gracious and he softened. But "until his dying day," she said, "he believed that the Hubble constant had a very low value."

A few years after Freedman's measurement of 72 to within 10% accuracy, Riess, who is a professor at Johns Hopkins University, got into the cosmic distance ladder game, setting out to nail H0 within 1% in hopes of better understanding the dark energy he had co-discovered. Since then, his SH0ES team has steadily tightened the ladder's rungs — especially the first and most important: the calibration step. As Riess put it, "How far away is anything? After that, life gets easier; you're measuring relative things." SH0ES currently uses five independent ways of measuring the distances to their cepheid calibrators. "They all agree quite well, and that gives us a lot of confidence," he said. As they collected data and improved their analysis, the error bars around H0 reduced to 5% in 2009, then 3.3%, then 2.4%, then 1.9% as of March.

Meanwhile, since 2013, the Planck team's increasingly precise iterations of its cosmic microwave background map have enabled it to extrapolate the value for H0 evermore precisely. In its 2018 analysis, Planck found H0 to be 67.4 with 1% accuracy. With Planck and SH0ES more than "four sigma" apart, a desperate need arose for independent measurements.

Tommaso Treu, one of the founders of H0LiCOW and a professor at the University of California, Los Angeles, had dreamed ever since his student days in Pisa of measuring the Hubble constant using time-delay cosmography — a method that skips the rungs of the cosmic distance ladder altogether. Instead, you directly determine the distance to quasars — the flickering, glowing centers of faraway galaxies — by painstakingly measuring the time delay between different images of a quasar that form as its light bends around intervening matter.

But while Treu and his colleagues were collecting quasar data, Freedman, Madore and their graduate students and postdocs were pivoting to tip-of-the-red-giant-branch stars. Whereas cepheids are young and found in the crowded, dusty centers of galaxies, TRGBs are old and reside in clean galactic outskirts. Using the Hubble Space Telescope to observe TRGB stars in 15 galaxies that also contain Type 1a supernovas, Freedman's CCHP team was able to extend their ladder to supernovas in the Hubble flow and measure H0, as an additional point of comparison for Planck's 67.4 and SH0ES' 74.0.

"At some level I guess the expectation in your own head is, 'OK, you're going to come out one way or the other,' right?" Freedman told me. "And you sort of … fall in the middle. And, 'Oh! That's interesting. OK.' And that's where we came out."

My seatmate on the van the morning after Freedman's paper dropped was a theorist named Francis-Yan Cyr-Racine, of the University of New Mexico. Earlier this year, he, Lisa Randall of Harvard University, and others proposed a possible solution to the Hubble constant tension. Their idea — a new, short-lived field of repulsive energy in the early universe — would speed up cosmic expansion, matching predictions to observations, though this and all other proposed fixes strike experts as a bit contrived. When I brought up Freedman's paper, Cyr-Racine seemed unsurprised. "It's probably 70," he said of H0 — meaning he thinks early-universe predictions and present-day observations might ultimately converge in the middle, and ΛCDM will turn out to work fine. (He later said he was half kidding.)

In the seminar room, Barry Madore sat down by me and another reporter and asked, "So, where do you think all this is heading?" To the middle, apparently. "You know that song, 'Stuck in the middle with you?'" he said. "Do you know the lyrics before? 'Clowns to the left of me, jokers to the right. Here I am, stuck in the middle with you.'"

Another curveball came before lunch. Mark Reid of the Harvard-Smithsonian Center for Astrophysics presented new measurements of four masers — laserlike effects in galaxies that can be used to determine distances — that he had performed in the preceding weeks. Combined, the masers pegged H0 at 74.8, give or take 3.1. Adam Riess took a picture of the slide. Scolnic tweeted, "This week is too much. Go home H0, you're drunk."

When I spoke with Riess during the midday break, he seemed overwhelmed by all the new measurements. For several years, he said, he and his SH0ES colleagues had their "necks stuck out" in claiming a discrepancy with Planck's Hubble constant value. "At that time, it was tension, and it was discrepancy, and, you know, we also got a lot of grief about it," he said. But in two weeks, he had gone from "feeling fairly lonely" to having three new numbers to consider. Overall, Riess said, "the tension is getting greater because, you know, nobody is coming out below the Planck value." If it was all a mistake, why didn't some teams measure an expansion rate of 62 or 65? As for that 69.8, Riess had questions about Freedman's method of calibrating the first rung of her distance ladder using TRGBs in the Large Magellanic Cloud. "Now the Large Magellanic Cloud is not a galaxy; it's a cloud. It's a dusty, amorphous thing," Riess said. "This is the great irony of it. They went to TRGBs to escape dust," but they have to calibrate them somewhere — "that is, they have to pick some TRGBs where they say we know the distance by some other method. And the only place that they have done that in is the Large Magellanic Cloud."

An hour later, Freedman, looking serene in a flower-print skirt, made her case. "If we put all our eggs in the cepheid basket, we will never uncover the unknown unknowns," she said.

She explained that she and her colleagues had used TRGBs in the Large Magellanic Cloud as their calibrators because the cloud's distance has been measured extremely precisely in multiple ways. And they employed a new approach to correct for the effect of dust on the brightness of the TRGBs — one that utilized the stars themselves, leveraging their changes in brightness as a function of color. She noted that her paired TRGBs and supernovas, on the second rung of her distance ladder, show less variation than Riess's paired cepheids and supernovas, suggesting that her dust measurement may be more accurate.

Freedman stressed during the discussion that better measurements are still needed to rule out systematic errors. "I think that's where we are," she said. "That's just reality."

From here, the discussion turned into a sparring contest between Freedman and Riess. "Wendy, to answer your question," Riess said, though she hadn't asked one, "there have been five fairly independent results presented so far. The dream of getting there is — getting there."

Scolnic, the SH0ES scientist and Riess collaborator, suggested we go outside. We sat on a sunny bench near the peach stucco building. A salty breeze blew in from the Pacific. "Definitely a day unlike any day I've experienced," he said.

H0LiCOW's new result felt to him like a year ago, what with Freedman's TRGBs and Reid's masers. "That's three big hits all within the last week. And I don't really know where we stand," he said. Even if the discrepancy is real, "there's no good story now which explains everything, on the theory or the observation side. And that's what makes this so puzzling."

"In 'Hamilton'-speak," he said, "this is the room where it happens right now."

Freedman appeared from the direction of the bluffs overlooking the ocean.

"Hey, Wendy," Scolnic said. "Wendy, I was just saying, doesn't this feel like the room where it happens, in 'Hamilton'-speak? Like, as a little kid, wouldn't you want to be in this room?"

"Isn't this where we want to be?" Freedman said. "We're working on pretty amazing data. Things that are telling us something about how the universe is evolving." "And the numbers are this close; we're arguing about a few percent," Scolnic said. "For all the sociological drama, it's funny that it's about 3 kilometers per second per megaparsec." "You have the right attitude," Freedman said. It was time to attend the conference dinner, so they went to figure out how to get back in the building, which was locked after hours.

Day three brought two new measurements of the Hubble constant: A cosmic distance ladder calibrated with "Mira" stars gave 73.6, and galactic surface brightness fluctuations gave 76.5, both plus or minus 4. Adam Riess took more photos, and by the end of the day a plot had been created reflecting all the existing measurements.

The two early-universe predictions studded the left side of the plot, with tight error bars around 67.4. Five late-universe measurements lined up on the right, around 73 or 74. And there in the middle was Freedman's 69.8, the wrench in the works, the hole in the narrative, the painful conciliatory suggestion that all the measurements might come together in the end, leaving us with the mysteries of ΛCDM and nothing new to say about nature.

Then again, all the late-universe measurements of H0, even Freedman's, fall to the right of 67.4. Erroneous measurements should come out low as well as high. So maybe the discrepancy is real. The last speaker, Cyr-Racine, held a vote about what the discrepancy should be called. Most people voted for “tension” or “problem.”Graeme Addison, an expert on baryon acoustic oscillations, said in an email after the conference, “My feeling is that the Hubble discrepancy is a real problem, and that we are missing some important physics somewhere. But the solutions people have put together so far are not super convincing.”

Addison finds the consistency of H0LiCOW and SH0ES especially compelling. And although Freedman’s paper suggested “that uncertainties associated with the SH0ES cepheids may have been underestimated,” he said there are also questions about the TRGB calibration in the Large Magellanic Cloud. Freedman claims to have improved the dust measurement, but Riess and colleagues contest this. This past Monday, in a paper posted on arxiv.org, Riess and company argued that Freedman and her team’s calibration of TRGBs relied on some low-resolution telescope data. They wrote that swapping it out for higher-resolution data would increase the H0 estimate from 69.8 to 72.4 — in range of SH0ES, H0LiCOW and the other late-universe measurements. In response, Freedman said, “There seem to be some very serious flaws in their interpretation” of her team’s calibration method. She and her colleagues have redone their own analysis using the newer data and, she wrote in an email, “We DO NOT find what [Riess and coauthors] are claiming.”

If the four new H0 measurements on the right can’t quite seem to overcome Freedman’s middle value in some people’s minds, it’s due partly to her usual equanimity. Additionally, “she is extremely well respected, and has a reputation for doing meticulous and thorough work,” said Daniel Holz, a Chicago astrophysicist who uses neutron star collisions as “standard sirens,” a promising new technique for measuring H0.

Meanwhile, the next data release from the Gaia space telescope, due in two or three years, will enable researchers to calibrate cepheids and TRGBs geometrically based on their parallax, or how far apart they look from different positions in the sky. The James Webb Space Telescope, Hubble’s successor, will also yield a wellspring of new and better data when it launches in 2021. Cosmologists will know the value of H0 — probably within the decade — and if there is still a discrepancy with predictions, by decade’s end they could be well on their way to discovering why. They’ll know it’s a tension or a crisis and not a surd.

Adapted from Quanta Magazine

Where Quantum Probability Comes From

There are many different ways to think about probability. Quantum mechanics embodies them all.

In A Philosophical Essay on Probabilities, published in 1814, Pierre-Simon Laplace introduced a notorious hypothetical creature: a “vast intelligence” that knew the complete physical state of the present universe. For such an entity, dubbed “Laplace’s demon” by subsequent commentators, there would be no mystery about what had happened in the past or what would happen at any time in the future.

According to the clockwork universe described by Isaac Newton, the past and future are exactly determined by the present.

Laplace's demon was never supposed to be a practical thought experiment; the imagined intelligence would have to be essentially as vast as the universe itself. And in practice, chaotic dynamics can amplify tiny imperfections in the initial knowledge of the system into complete uncertainty later on. But in principle, Newtonian mechanics is deterministic.

A century later, quantum mechanics changed everything. Ordinary physical theories tell you what a system is and how it evolves over time. Quantum mechanics does this as well, but it also comes with an entirely new set of rules, governing what happens when systems are observed or measured. Most notably, measurement outcomes cannot be predicted with perfect confidence, even in principle. The best we can do is to calculate the probability of obtaining each possible outcome, according to what's called the Born rule: The wave function assigns an "amplitude" to each measurement outcome, and the probability of getting that result is equal to the amplitude squared. This feature is what led Albert Einstein to complain about God playing dice with the universe.

Researchers continue to argue over the best way to think about quantum mechanics. There are competing schools of thought, which are sometimes referred to as "interpretations" of quantum theory but are better thought of as distinct physical theories that give the same predictions in the regimes we have tested so far. All of them share the feature that they lean on the idea of probability in a fundamental way. Which raises the question: What is "probability," really?

Like many subtle concepts, probability starts out with a seemingly straightforward, commonsensical meaning, which becomes trickier the closer we look at it. You flip a fair coin many times; whether it comes up heads or tails on any particular trial is completely unknown, but if we perform many trials we expect to get heads 50% of the time and tails 50% of the time. We therefore say that the probability of obtaining heads is 50%, and likewise for tails.

We know how to handle the mathematics of probability, thanks to the work of the Russian mathematician Andrey Kolmogorov and others. Probabilities are real numbers between zero and one, inclusive; the probabilities of all independent events add up to one; and so on. But that's not the same as deciding what probability actually is.

There are numerous approaches to defining probability, but we can distinguish between two broad classes. The "objective" or "physical" view treats probability as a fundamental feature of a system, the best way we have to characterize physical behavior. An example of an objective approach to probability is frequentism, which defines probability as the frequency with which things happen over many trials, as in our coin-tossing example.

Alternatively, there are "subjective" or "evidential" views, which treat probability as personal, a reflection of an individual's credence, or degree of belief, about what is true or what will happen. An example is Bayesian probability, which emphasizes Bayes' law, a mathematical theorem that tells us how to update our credences as we obtain new information. Bayesians imagine that rational creatures in states of incomplete information walk around with credences for every proposition you can imagine, updating them continually as new data comes in. In contrast with frequentism, in Bayesianism it makes perfect sense to attach probabilities to one-shot events, such as who will win the next election, or even past events that we're unsure about.

Interestingly, different approaches to quantum mechanics invoke different meanings of probability in central ways. Thinking about quantum mechanics helps illuminate probability, and vice versa. Or, to put it more pessimistically: Quantum mechanics as it is currently understood doesn't really help us choose between competing conceptions of probability, as every conception has a home in some quantum formulation or other.

Let's consider three of the leading approaches to quantum theory. There are "dynamical collapse" theories, such as the GRW modelproposed in 1985 by Giancarlo Ghirardi, Alberto Rimini and Tullio Weber. There are "pilot wave" or "hidden variable" approaches, most notably the de Broglie-Bohm theory, invented by David Bohm in 1952 based on earlier ideas from Louis de Broglie. And there is the "many worlds" formulation suggested by Hugh Everett in 1957.

Each of these represents a way of solving the measurement problem of quantum mechanics. The problem is that conventional quantum theory describes the state of a system in terms of a wave function, which evolves smoothly and deterministically according to the Schrödinger equation. At least, it does unless the system is being observed; in that case, according to the textbook presentation, the wave function suddenly "collapses" into some particular observational outcome. The collapse itself is unpredictable; the wave function assigns a number to each possible outcome, and the probability of observing that outcome is equal to the value of the wave function squared. The measurement problem is simply: What constitutes a "measurement"? When exactly does it occur? Why are measurements seemingly different from ordinary evolution?

Dynamical-collapse theories offer perhaps the most straightforward resolution to the measurement problem. They posit that there is a truly random component to quantum evolution, according to which every particle usually obeys the Schrödinger equation, but occasionally its wave function will spontaneously localize at some position in space. Such collapses are so rare that we would never observe one for a single particle, but in a macroscopic object made of many particles, collapses happen all the time. This prevents macroscopic objects — like the cat in Schrödinger's infamous thought experiment — from evolving into an observable superposition. All the particles in a large system will be entangled with each other, so that when just one of them localizes in space, the rest are brought along for the ride.

Probability in such models is fundamental and objective. There is absolutely nothing about the present that precisely determines the future. Dynamical-collapse theories fit perfectly into an old-fashioned frequentist view of probability. What happens next is unknowable, and all we can say is what the long-term frequency of different outcomes will be. Laplace's demon wouldn't be able to exactly predict the future, even if it knew the present state of the universe exactly.

Pilot-wave theories tell a very different story. Here, nothing is truly random; the quantum state evolves deterministically, just as the classical state did for Newton. The new element is the concept of hidden variables, such as the actual positions of particles, in addition to the traditional wave function. The particles are what we actually observe, while the wave function serves merely to guide them.

In a sense, pilot-wave theories bring us back to the clockwork universe of classical mechanics, but with an important twist: When we're not making an observation, we don't, and can't, know the actual values of the hidden variables. We can prepare a wave function so that we know it exactly, but we only learn about the hidden variables by observing them. The best we can do is to admit our ignorance and introduce a probability distribution over their possible values.

Probability in pilot-wave theories, in other words, is entirely subjective. It characterizes our knowledge, not an objective frequency of occurrences over time. A full-powered Laplace demon that knew both the wave function and all the hidden variables could predict the future exactly, but a hobbled version that only knew the wave function would still have to make probabilistic predictions.

Then we have many-worlds. This is my personal favorite approach to quantum mechanics, but it's also the one for which it is most challenging to pinpoint how and why probability enters the game.

Many-worlds quantum mechanics has the simplest formulation of all the alternatives. There is a wave function, and it obeys Schrödinger's equation, and that's all. There are no collapses and no additional variables. Instead, we use Schrödinger's equation to predict what will happen when an observer measures a quantum object in a superposition of multiple possible states. The answer is that the combined system of observer and object evolves into an entangled superposition. In each part of the superposition, the object has a definite measurement outcome and the observer has measured that outcome.

Everett's brilliant move was simply to say, "And that's okay" — all we need to do is recognize that each part of the system subsequently evolves separately from all of the others, and therefore qualifies as a separate branch of the wave function, or "world." The worlds aren't put in by hand; they were lurking in the quantum formalism all along.

The idea of all those worlds might seem extravagant or distasteful, but those aren't respectable scientific objections. A more legitimate question is the nature of probability within this approach. In many-worlds, we can know the wave function exactly, and it evolves deterministically. There is nothing unknown or unpredictable. Laplace's demon could predict the entire future of the universe with perfect confidence. How is probability involved at all?

An answer is provided by the idea of "self-locating," or "indexical," uncertainty. Imagine that you are about to measure a quantum system, thus branching the wave function into different worlds (for simplicity, let’s just say there will be two worlds). It doesn’t make sense to ask, “After the measurement, which world will I be on?” There will be two people, one on each branch, both descended from you; neither has a better claim to being “really you” than the other.

But even if both people know the wave function of the universe, there is now something they don’t know: which branch of the wave function they are on. There will inevitably be a period of time after branching occurs but before the observers find out what outcome was obtained on their branch. They don’t know where they are in the wave function. That’s self-locating uncertainty, as first emphasized in the quantum context by the physicist Lev Vaidman.

You might think you could just look at the experimental outcome really quickly, so that there was no noticeable period of uncertainty. But in the real world, the wave function branches incredibly fast, on timescales of 10−21 seconds or less. That’s far quicker than a signal can even reach your brain. There will always be some period of time when you’re on a certain branch of the wave function, but you don’t know which one. Can we resolve this uncertainty in a sensible way? Yes, we can, asCharles Sebens and I have argued, and doing so leads precisely to the Born rule: The credence you should attach to being on any particular branch of the wave function is just the amplitude squared for that branch, just as in ordinary quantum mechanics. Sebens and I needed to make a new assumption, which we called the “epistemic separability principle”: Whatever predictions you make for experimental outcomes, they should be unaltered if we only change the wave function for completely separate parts of the system. Self-locating uncertainty is a different kind of epistemic uncertainty from that featured in pilot-wave models. You can know everything there is to know about the universe, and there’s still something you’re uncertain about, namely where you personally are within it. Your uncertainty obeys the rules of ordinary probability, but it requires a bit of work to convince yourself that there’s a reasonable way to assign numbers to your belief. You might object that you want to make predictions now, even before branching happens. Then there’s nothing uncertain; you know exactly how the universe will evolve. But included in that knowledge is the conviction that all the future versions of yourself will be uncertain, and they should use the Born rule to assign credences to the various branches they could be on. In that case, it makes sense to act precisely as if you live in a truly stochastic universe, with the frequency of various outcomes given by the Born rule. (David Deutsch and David Wallace have made this argument rigorous using decision theory.) In one sense, all of these notions of probability can be thought of as versions of self-locating uncertainty. All we have to do is consider the set of all possible worlds — all the different versions of reality one could possibly conceive. Some such worlds obey the rules of dynamical-collapse theories, and each of these is distinguished by the actual sequence of outcomes for all the quantum measurements ever performed. Other worlds are described by pilot-wave theories, and in each one the hidden variables have different values. Still others are many-worlds realities, where agents are uncertain about which branch of the wave function they are on. We might think of the role of probability as expressing our personal credences about which of these possible worlds is the actual one.

The study of probability takes us from coin flipping to branching universes. Hopefully our understanding of this tricky concept will progress hand in hand with our understanding of quantum mechanics itself.

Adapted from Quanta Magazine

The Simple Idea Behind Einstein's Greatest Discoveries

Lurking behind Einstein's theory of gravity and our modern understanding of particle physics is the deceptively simple idea of symmetry. But physicists are beginning to question whether focusing on symmetry is still as productive as it once was.

The flashier fruits of Albert Einstein's century-old insights are by now deeply embedded in the popular imagination: Black holes, time warps and wormholes show up regularly as plot points in movies, books, TV shows. At the same time, they fuel cutting-edge research, helping physicists pose questions about the nature of space, time, even information itself.

Perhaps ironically, though, what is arguably the most revolutionary part of Einstein's legacy rarely gets attention. It has none of thesplash of gravitational waves, the pull of black holes or even the charm of quarks. But lurking just behind the curtain of all these exotic phenomena is a deceptively simple idea that pulls the levers, shows how the pieces fit together, and lights the path ahead.

The idea is this: Some changes don't change anything. The most fundamental aspects of nature stay the same even as they seemingly shape-shift in unexpected ways. Einstein's 1905 papers on relativity led to the unmistakable conclusion, for example, that the relationship between energy and mass is invariant, even though energy and mass themselves can take vastly different forms. Solar energy arrives on Earth and becomes mass in the form of green leaves, creating food we can eat and use as fuel for thought. ("What is this mind of ours: what are these atoms with consciousness?" asked the late Richard Feynman. "Last week's potatoes!") That's the meaning of E = mc2. The "c" stands for the speed of light, a very large number, so it doesn't take much matter to produce an enormous amount of energy; in fact, the sun turns millions of tons of mass into energy each second.

This endless morphing of matter into energy (and vice versa) powers the cosmos, matter, life. Yet through it all, the energy-matter content of the universe never changes. It's strange but true: Matter and energy themselves are less fundamental than the underlying relationships between them.

We tend to think of things, not relationships, as the heart of reality. But most often, the opposite is true. "It's not the stuff," said the Brown University physicist Stephon Alexander.

The same is true, Einstein showed, for "stuff" like space and time, seemingly stable, unchangeable aspects of nature; in truth, it's the relationship between space and time that always stays the same, even as space contracts and time dilates. Like energy and matter, space and time are mutable manifestations of deeper, unshakable foundations: the things that never vary no matter what.

"Einstein's deep view was that space and time are basically built up by relationships between things happening," said the physicist Robbert Dijkgraaf, director of the Institute for Advanced Study in Princeton, New Jersey, where Einstein spent his final decades.

The relationship that eventually mattered most to Einstein's legacy was symmetry. Scientists often describe symmetries as changes that don't really change anything, differences that don't make a difference, variations that leave deep relationships invariant. Examples are easy to find in everyday life. You can rotate a snowflake by 60 degrees and it will look the same. You can switch places on a teeter-totter and not upset the balance. More complicated symmetries have led physicists to the discovery of everything from neutrinos to quarks — they even led to Einstein's own discovery that gravitation is the curvature of space-time, which, we now know, can curl in on itself, pinching off into black holes.

Over the past several decades, some physicists have begun to question whether focusing on symmetry is still as productive as it used to be. New particles predicted by theories based on symmetries haven't appeared in experiments as hoped, and the Higgs boson that was detected was far too light to fit into any known symmetrical scheme. Symmetry hasn't yet helped to explain why gravity is so weak, why the vacuum energy is so small, or why dark matter remains transparent.

"There has been, in particle physics, this prejudice that symmetry is at the root of our description of nature," said the physicist Justin Khoury of the University of Pennsylvania. "That idea has been extremely powerful. But who knows? Maybe we really have to give up on these beautiful and cherished principles that have worked so well. So it's a very interesting time right now."

Light

Einstein wasn't thinking about invariance or symmetry when he wrote his first relativity papers in 1905, but historians speculate that his isolation from the physics community during his employment in the Swiss patent office might have helped him see past the unnecessary trappings people took for granted.

Like other physicists of his time, Einstein was pondering several seemingly unrelated puzzles. James Clerk Maxwell's equations revealing the intimate connection between electric and magnetic fields looked very different in different frames of reference — whether an observer is moving or at rest. Moreover, the speed at which electromagnetic fields propagated through space almost precisely matched the speed of light repeatedly measured by experiments — a speed that didn't change no matter what. An observer could be running toward the light or rushing away from it, and the speed didn't vary.

Einstein connected the dots: The speed of light was a measurable manifestation of the symmetrical relationship between electric and magnetic fields — a more fundamental concept than space itself. Light didn't need anything to travel through because it was itself electromagnetic fields in motion. The concept of "at rest" — the static “empty space” invented by Isaac Newton — was unnecessary and nonsensical. There was no universal “here” or “now”: Events could appear simultaneous to one observer but not another, and both perspectives would be correct.

Chasing after a light beam produced another curious effect, the subject of Einstein’s second relativity paper, “Does the Inertia of a Body Depend Upon Its Energy Content?” The answer was yes. The faster you chase, the harder it is to go faster. Resistance to change becomes infinite at the speed of light. Since that resistance is inertia, and inertia is a measure of mass, the energy of motion is transformed into mass. “There is no essential distinction between mass and energy,” Einstein wrote.

It took several years for Einstein to accept that space and time are inextricably interwoven threads of a single space-time fabric, impossible to disentangle. “He still wasn’t thinking in a fully unified space-time sort of way,” said David Kaiser, a physicist and historian of science at the Massachusetts Institute of Technology.

Unified space-time is a difficult concept to wrap our minds around. But it begins to make sense if we think about the true meaning of “speed.” The speed of light, like any speed, is a relationship — distance traveled over time. But the speed of light is special because it can’t change; your laser beam won’t advance any faster just because it is shot from a speeding satellite. Measurements of distance and time must therefore change instead, depending on one’s state of motion, leading to effects known as “space contraction” and “time dilation.” The invariant is this: No matter how fast two people are traveling with respect to each other, they always measure the same “space-time interval.” Sitting at your desk, you hurtle through time, hardly at all through space. A cosmic ray flies over vast distances at nearly the speed of light but traverses almost no time, remaining ever young. The relationships are invariant no matter how you switch things around.

Gravity

Einstein’s special theory of relativity, which came first, is “special” because it applies only to steady, unchanging motion through space-time — not accelerating motion like the movement of an object falling toward Earth. It bothered Einstein that his theory didn’t include gravity, and his struggle to incorporate it made symmetry central to his thinking. “By the time he gets full-on into general relativity, he’s much more invested in this notion of invariants and space-time intervals that should be the same for all observers,” Kaiser said.

Specifically, Einstein was puzzled by a difference that didn’t make a difference, a symmetry that didn’t make sense. It’s still astonishing to drop a wad of crumped paper and a set of heavy keys side by side to see that somehow, almost magically, they hit the ground simultaneously — as Galileo demonstrated (at least apocryphally) by dropping light and heavy balls off the tower in Pisa. If the force of gravity depends on mass, then the more massive an object is, the faster it should sensibly fall. Inexplicably, it does not.

The key insight came to Einstein in one of his famous thought experiments. He imagined a man falling off a building. The man would be floating as happily as an astronaut in space, until the ground got in his way. When Einstein realized that a person falling freely would feel weightless, he described the discovery as the happiest thought of his life. It took a while for him to pin down the mathematical details of general relativity, but the enigma of gravity was solved once he showed that gravity is the curvature of space-time itself, created by massive objects like the Earth. Nearby "falling" objects like Einstein's imaginary man or Galileo's balls simply follow the space-time path carved out for them.

When general relativity was first published, 10 years after the special version, a problem arose: It appeared that energy might not be conserved in strongly curved space-time. It was well-known that certain quantities in nature are always conserved: the amount of energy (including energy in the form of mass), the amount of electric charge, the amount of momentum. In a remarkable feat of mathematical alchemy, the German mathematician Emmy Noether proved that each of these conserved quantities is associated with a particular symmetry, a change that doesn't change anything.

Noether showed that the symmetries of general relativity — its invariance under transformations between different reference frames — ensure that energy is always conserved. Einstein's theory was saved. Noether and symmetry have both occupied center stage in physics ever since.

Matter

Post Einstein, the pull of symmetry only became more powerful. Paul Dirac, trying to make quantum mechanics compatible with the symmetry requirements of special relativity, found a minus sign in an equation suggesting that "antimatter" must exist to balance the books. It does. Soon after, Wolfgang Pauli, in an attempt to account for the energy that seemed to go missing during the disintegration of radioactive particles, speculated that perhaps the missing energy was carried away by some unknown, elusive particle. It was, and that particle is the neutrino.

Starting in the 1950s, invariances took on a life of their own, becoming ever more abstract, "leaping out," as Kaiser put it, from the symmetries of space-time. These new symmetries, known as "gauge" invariances, became extremely productive, "furnishing the world," Kaiser said, by requiring the existence of everything from W and Z bosons to gluons. "Because we think there's a symmetry that's so fundamental it has to be protected at all costs, we invent new stuff," he said. Gauge symmetry "dictates what other ingredients you have to introduce." It's roughly the same kind of symmetry as the one that tells us that a triangle that's invariant under 120-degree rotations must have three equal sides.

Gauge symmetries describe the internal structure of the system of particles that populates our world. They indicate all the ways physicists can shift, rotate, distort and generally mess with their equations without varying anything important. "The symmetry tells you how many ways you can flip things, change the way the forces work, and it doesn't change anything," Alexander said. The result is a peek at the hidden scaffolding that supports the basic ingredients of nature.

The abstractness of gauge symmetries causes a certain unease in some quarters. “You don’t see the whole apparatus, you only see the outcome,” Dijkgraaf said. “I think with gauge symmetries there’s still a lot of confusion.”

To compound the problem, gauge symmetries produce a multitude of ways to describe a single physical system — a redundancy, as the physicist Mark Trodden of the University of Pennsylvania put it. This property of gauge theories, Trodden explained, renders calculations “fiendishly complicated.” Pages and pages of calculations lead to very simple answers. “And that makes you wonder: Why? Where does all that complexity in the middle come from? And one possible answer to that is this redundancy of description that gauge symmetries give you.”

Such internal complexity is the opposite of what symmetry normally offers: simplicity. With a tiling pattern that repeats itself, “you only need to look at one little bit and you can predict the rest of it,” Dijkgraaf said. You don’t need one law for the conservation of energy and another for matter where only one will do. The universe is symmetrical in that it’s homogeneous on large scales; it doesn’t have a left or right, up or down. “If that weren’t the case, cosmology would be a big mess,” Khoury said.

Broken Symmetries

The biggest problem is that symmetry as it’s now understood seems to be failing to answer some of the biggest questions in physics. True, symmetry told physicists where to look for both the Higgs boson andgravitational waves — two momentous discoveries of the past decade. At the same time, symmetry-based reasoning predicted a slew of things that haven’t shown up in any experiments, including the “supersymmetric” particles that could have served as the cosmos’s missing dark matter and explained why gravity is so weak compared to electromagnetism and all the other forces.

In some cases, symmetries present in the underlying laws of nature appear to be broken in reality. For instance, when energy congeals into matter via the good old E = mc2, the result is equal amounts of matter and antimatter — a symmetry. But if the energy of the Big Bang created matter and antimatter in equal amounts, they should have annihilated each other, leaving not a trace of matter behind. Yet here we are.

The perfect symmetry that should have existed in the early hot moments of the universe somehow got destroyed as it cooled down, just as a perfectly symmetrical drop of water loses some of its symmetry when it freezes into ice. (A snowflake may look the same in six different orientations, but a melted snowflake looks the same in every direction.)

“Everyone’s interested in spontaneously broken symmetries,” Trodden said. “The law of nature obeys a symmetry, but the solution you’re interested in does not.” But what broke the symmetry between matter and antimatter?

It would come as a surprise to no one if physics today turned out to be burdened with unnecessary scaffolding, much like the notion of “empty space” that misdirected people before Einstein. Today’s misdirection, some think, may even have to do with the obsession with symmetry itself, at least as it’s currently understood.

Many physicists have been exploring an idea closely related to symmetry called "duality." Dualities are not new to physics. Wave-particle duality — the fact that the same quantum system is best described as either a wave or a particle, depending on the context — has been around since the beginning of quantum mechanics. But newfound dualities have revealed surprising relationships: For example, a three-dimensional world without gravity can bemathematically equivalent, or dual, to a four-dimensional world with gravity.

If descriptions of worlds with different numbers of spatial dimensions are equivalent, then "one dimension in some sense can be thought of as fungible," Trodden said. "These dualities include elements — the number of dimensions — we think about as invariant," Dijkgraaf said, "but they are not." The existence of two equivalent descriptions with all the attendant calculations raises "a very deep, almost philosophical point: Is there an invariant way to describe physical reality?"

No one is giving up on symmetry anytime soon, in part because it's proved so powerful and also because relinquishing it means, to many physicists, giving up on "naturalness" — the idea that the universe has to be exactly the way it is for a reason, the furniture arranged so impeccably that you couldn't imagine it any other way.

Clearly, some aspects of nature — like the orbits of the planets — are the result of history and accident, not symmetry. Biological evolution is a combination of known mechanisms and chance. Perhaps Max Born was right when he responded to Einstein's persistent objection that "God does not play dice" by pointing out that "nature, as well as human affairs, seems to be subject to both necessity and accident." Certain aspects of physics will have to remain intact — causality for example. "Effects cannot precede causes," Alexander said. Other things almost certainly will not.

One aspect that will surely not play a key role in the future is the speed of light, which grounded Einstein's work. The smooth fabric of space-time Einstein wove a century ago inevitably gets ripped to shreds inside black holes and at the moment of the Big Bang. "The speed of light can't remain constant if space-time is crumbling," Alexander said. "If space-time is crumbling, what is invariant?"

Certain dualities suggest that space-time emerges from something more basic still, the strangest relationship of all: What Einstein called the "spooky" connections between entangled quantum particles. Many researchers believe these long-distance links stitch space-time together. As Kaiser put it, "The hope is that something like a continuum of space-time would emerge as a secondary effect of more fundamental relationships, including entanglement relationships." In that case, he said, classical, continuous space-time would be an "illusion."

The high bar for new ideas is that they cannot contradict consistently reliable theories like quantum mechanics and relativity — including the symmetries that support them. Einstein once compared building a new theory to climbing a mountain. From a higher perspective, you can see the old theory still standing, but it's altered, and you can see where it fits into the larger, more inclusive landscape. Instead of thinking, as Feynman suggested, with last week's potatoes, future thinkers might

ponder physics using the information encoded in quantum entanglements, which weave the space-time to grow potatoes in the first place.
Adapted from Quanta magazine

In the dark

Dark matter is the commonest, most elusive stuff there is. Can we grasp this great unsolved problem in physics?

I'm sitting at my desk at the University of Washington trying to conserve energy. It isn't me who's losing it; it's my computer simulations. Actually, colleagues down the hall might say I was losing it as well. When I tell people I'm working on speculative theories about dark matter, they start to speculate about me. I don't think everyone who works in the building even believes in it. In presentations, I point out how many cosmological puzzles it helps to solve. Occam's Razor is my silver bullet: the fact that just one posit can explain so much. Then I talk about the things that standard dark matter doesn't fix. There don't seem to be enough satellite galaxies around our Milky Way. The inner shapes of small galaxies are inconsistent. I invoke Occam's Razor again and argue that you can resolve these issues by adding a weak self-interaction to standard dark matter, a feeble scattering pattern when its particles collide. Then someone will ask me if I really believe in all this stuff. Tough question. The world we see is an illusion, albeit a highly persistent one. We have gradually got used to the idea that nature's true reality is one of uncertain quantum fields; that what we see is not necessarily what is. Dark matter is a profound extension of this concept. It appears that the majority of matter in the universe has been hidden from us. That puts physicists and the general public alike in an uneasy place. Physicists worry that they can't point to an unequivocal confirmed prediction or a positive detection of the stuff itself. The wider audience finds it hard to accept something that is necessarily so shadowy and elusive. The situation, in fact, bears an ominous resemblance to the aether controversy of more than a century ago. In the late-1800s, scientists were puzzled at how electromagnetic waves (for instance, light) could pass through vacuums. Just as the most familiar sort of waves are constrained to water — it's the water that does the waving — it seemed obvious that there had to be some medium in which electromagnetic waves were ripples. Hence the notion of 'aether', an imperceptible field that was thought to permeate all of space.

The American scientists Albert Michelson and Edward Morley carried out the most famous experiment to probe the existence of aether in 1887. If light needed a medium to propagate, they reasoned, then the Earth ought to be moving through this same medium. They set up an ingenious apparatus to test the idea: a rigid optics table floating on a cushioning vat of liquid mercury such that the table could rotate in any direction. The plan was to compare the wavelengths of light beams travelling in different relative directions, as the apparatus rotated or as the Earth swung around the sun. As our planet travelled along its orbit in an opposite direction to the background aether, light beams should be impeded, compressing their wavelength. Six months later, the direction of the impedance should reverse and the wavelength would expand. But to the surprise of many, the wavelengths were the same no matter what direction the beams travelled in. There was no sign of the expected medium. Aether appeared to be a mistake.This didn’t rule out its existence in every physicist’s opinion. Disagreement about the question rumbled on until at least some of the aether proponents died. Morley himself didn’t believe his own results. Only with perfect hindsight is the Michelson-Morley experiment seen as evidence for the absence of aether and, as it turned out, confirmation of Albert Einstein’s more radical theory of relativity. Dark matter, dark energy, dark money, dark markets, dark biomass, dark lexicon, dark genome: scientists seem to add dark to any influential phenomenon that is poorly understood and somehow obscured from direct perception. The darkness, in other words, is metaphorical. At first, however, it was intended quite literally. In the 1930s, the Swiss astronomer Fritz Zwicky observed a cluster of galaxies, all gravitationally bound to each other and orbiting one another much too fast. Only the gravitational pull of a very large, unseen mass seemed capable of explaining why they did not simply spin apart. Zwicky postulated the presence of some kind of ‘dark’ matter in the most casual sense possible: he just thought there was something he couldn’t see. But astronomers have continued to find the signature of unseen mass throughout the cosmos. For example, the stars of galaxies also rotate too fast. In fact, it looks as if dark matter is the commonest form of matter in our universe. It is also the most elusive. It does not interact strongly with itself or with the regular matter found in stars, planets or us. Its presence is inferred purely through its gravitational effects, and gravity, vexingly, is the weakest of the fundamental forces. But gravity is the only significant long-range force, which is why dark matter dominates the universe’s architecture at the largest scales.

In the past half-century, we have developed a standard model of cosmology that describes our observed universe quite well. In the beginning, a hot Big Bang caused a rapid expansion of space and sowed the seeds for fluctuations in the density of matter throughout the universe. Over the next 13.7 billion years, those density patterns were scaled up thanks to the relentless force of gravity, ultimately forming the cosmic scaffolding of dark matter whose gravitational pull suspends the luminous galaxies we can see. This standard model of cosmology is supported by a lot of data, including the pervasive radiation field of the universe, the distribution of galaxies in the sky, and colliding clusters of galaxies. These robust observations combine expertise and independent analysis from many fields of astronomy. All are in strong agreement with a cosmological model that includes dark matter. Astrophysicists who try to trifle with the fundamentals of dark matter tend to find themselves cut off from the mainstream. It isn’t that anybody thinks it makes for an especially beautiful theory; it’s just that no other consistent, predictively successful alternative exists. But none of this explains what dark matter actually is. That really is a great, unsolved problem in physics. So the hunt is on. Particle accelerators sift through data, detectors wait patiently underground, and telescopes strain upwards. The current generation of experiments has already placed strong constraints on viable theories. Optimistically, the nature of dark matter could be understood within a few decades. Pessimistically, it might never be understood.We are in an era of discovery. A body of well-confirmed theory governs the assortment of fundamental particles that we have already observed. The same theory allows the existence of other, hitherto undetected particles. A few decades ago, theorists realised that a so-called Weakly Interacting Massive Particle (WIMP) might exist. This generic particle would have all the right characteristics to be dark matter, and it would be able to hide right under our noses. If dark matter is indeed a WIMP, it would interact so feebly with regular matter that we would have been able to detect it only with the generation of dark matter experiments that are just now coming on stream. The most promising might be the Large Underground Xenon (LUX) experiment in South Dakota, the biggest dark matter detector in the world. The facility opened in a former gold mine this February and is receptive to the most elusive of subatomic particles. And yet, despite LUX's exquisite sensitivity, the hunt for dark matter itself has been something of a waiting game. So far, the only particles to turn up in the detector's trap are bits of cosmic noise: nothing more than a nuisance.

The past success of standard paradigms in theoretical physics leads us to hunt for a single generic dark matter particle — the dark matter. Arguably, though, we have little justification for supposing that there is anything to be found at all; as the English physicist John D Barrow said in 1994: 'There is no reason that the universe should be designed for our convenience.' With that caveat in mind, it appears the possibilities are as follows. Either dark matter exists or it doesn't. If it exists, then either we can detect it or we can't. If it doesn't exist, either we can show that it doesn't exist or we can't. The observations that led astronomers to posit dark matter in the first place seem too robust to dismiss, so the most common argument for non-existence is to say there must be something wrong with our understanding of gravity – that it must not behave as Einstein predicted. That would be a drastic change in our understanding of physics, so not many people want to go there. On the other hand, if dark matter exists and we can't detect it, that would put us in a very inconvenient position indeed. But we are living through a golden age of cosmology. In the past two decades, we have discovered so much: we have measured variations in the relic radiation of the Big Bang, learnt that the universe's expansion is accelerating, glimpsed black holes and spotted the brightest explosions ever in the universe. In the next decades, we are likely to observe the first stars in the universe, map nearly the entire distribution of matter, and hear the cataclysmic merging of black holes through gravitational waves. Even among these riches, dark matter offers a uniquely inviting prospect, sitting at a confluence of new observations, theory, technology and (we hope) new funding. The various proposals to get its measure tend to fall into one of three categories: artificial creation (in a particle accelerator), indirect detection, and direct detection. The last, in which researchers attempt to catch WIMPs in the wild, is where the excitement is. The underground LUX detector is one of the first in a new generation of ultra-sensitive experiments. It counts on the WIMP interacting with the nucleus of a regular atom. These experiments generally consist of a very pure detector target, such as pristine elemental Germanium or Xenon, cooled to extremely low temperatures and shielded from outside particles. The problem is that stray particles tend to sneak in anyway. Interloper interactions are carefully monitored. Noise reduction, shielding and careful statistics are the only way to confirm real dark-matter interaction events from false alarms.

Theorists have considered a lot of possibilities for how the real thing might work with the standard WIMP. Actually, the first generation of experiments has already ruled out the so-called z-boson scattering interaction. What is left is Higgs boson-mediated scattering, which would involve the same particle that the Large Hadron Collider discovered in Geneva in November last year. That implies a very weak interaction, but it would be perfectly matched to the current sensitivity threshold of the new generation of experiments. Then again, science is less about saying what is than what is not, and non-detections have placed relatively interesting constraints on dark matter. They have also, in a development that is strikingly reminiscent of the aether controversy, thrown out some anomalies that need to be cleared up. Using a different detector target to LUX, the Italian DAMA (short for 'DArk MAtter') experiment claims to have found an annual modulation of their dark matter signal. Detractors dispute whether they really have any signal at all. Just like with the aether, we expected to see this kind of yearly variation, as the Earth orbits the Sun, sometimes moving with the larger galactic rotation and sometimes against it. The DAMA collaboration measured such an annual modulation. Other competing projects (XENON, CDMS, Edelweiss and ZEPLIN, for example) didn't, but these experiments cannot be compared directly, so we should probably reserve judgment. Nature can be cruel. Physicists could take non-detection as a hint to give up, but there is always the teasing possibility that we just need a better experiment. Or perhaps dark matter will reveal itself to be almost as complex as regular matter. Previous experiments imposed quite strict limitations on just how much complexity we can expect — there's no prospect of dark-matter people, or even dark-matter chemistry, really — but it could still come in multiple varieties. We might find a kind of particle that explains only a fraction of the expected total mass of dark matter.

In a sense, this has already occurred. Neutrinos are elusive but widespread (60 billion of them pass through an area the size of your pinky every second). They hardly ever interact with regular matter, and until 1998 we thought they were entirely massless. In fact, neutrinos make up a tiny fraction of the mass budget of the universe, and they do act like an odd kind of dark matter. They aren't 'the' dark matter, but perhaps there is no single type of dark matter to find.To say that we are in an era of discovery is really just to say that we are in an era of intense interest. Physicists say we would have achieved something if we determine that dark matter is not a WIMP. Would that not be a discovery? At the same time, the field is burgeoning with ideas and rival theories. Some are exploring the idea that dark matter has interactions, but we will never be privy to them. In this scenario, dark matter would have an interaction at the smallest of scales which would leave standard cosmology unchanged. It might even have an exotic universe of its own: a dark sector. This possibility is at once terrifying and entrancing to physicists. We could posit an intricate dark matter realm that will always escape our scrutiny, save for its interaction with our own world through gravity. The dark sector would be akin to a parallel universe.

It is rather easy to tinker with the basic idea of dark matter when you make all of your modifications very feeble. And so this is what all dark matter theorists are doing. I have run with the idea that dark matter might have self-interactions and worked that into supercomputer simulations of galaxies. On the largest scales, where cosmology has made firm predictions, this modification does nothing, but on small scales, where the theory of dark matter shows signs of faltering, it helps with several issues. The simulations are pretty to look at and they make acceptable predictions. There are too many free parameters, though — what scientists call fine-tuning — such that the results can seem tailored to fit the observations. That's why I reserve judgement, and you would be well advised to do the same. We will probably never know for certain whether dark matter has self-interactions. At best, we might put an upper limit on how strong such interactions could be. So, when people ask me if I think self-interacting dark matter is the correct theory, I say no. I am constraining what is possible, not asserting what is. But this is kind of disappointing, isn't it? Surely cosmology should hold some deep truth that we can hope to grasp. One day, perhaps, LUX or one of its competitors might discover just what they are looking for. Or maybe on some unassuming supercomputer, I will uncover a hidden truth about dark matter. Regardless, such a discovery will feel removed from us, mediated as it will be through several layers of ghosts in machines. The dark matter universe is part of our universe, but it will never feel like our universe. Nature plays an epistemological trick on us all. The things we observe each have one kind of existence, but the things we cannot observe could have limitless kinds of existence. A good theory should be just complex enough. Dark matter is the simplest solution to a complicated problem, not a complicated solution to simple problem. Yet there is no guarantee that it will ever be illuminated. And whether or not astrophysicists find it in a conceptual sense, we will never grasp it in our hands. It will remain out of touch. To live in a universe that is largely inaccessible is to live in a realm of endless possibilities, for better or worse.

Adapted from Aeon

What Einstein meant by 'God does not play dice'

'The theory produces a good deal but hardly brings us closer to the secret of the Old One,' wrote Albert Einstein in December 1926. 'I am at all events convinced that He does not play dice.'

Einstein was responding to a letter from the German physicist Max Born. The heart of the new theory of quantum mechanics, Born had argued, beats randomly and uncertainly, as though suffering from arrhythmia. Whereas physics before the quantum had always been about doing this and gettingthat, the new quantum mechanics appeared to say that when we do this, we get that only with a certain probability. And in some circumstances we might get the other.

Einstein was having none of it, and his insistence that God does not play dice with the Universe has echoed down the decades, as familiar and yet as elusive in its meaning as E = mc2. What did Einstein mean by it? And how did Einstein conceive of God?

Hermann and Pauline Einstein were nonobservant Ashkenazi Jews. Despite his parents' secularism, the nine-year-old Albert discovered and embraced Judaism with some considerable passion, and for a time he was a dutiful, observant Jew. Following Jewish custom, his parents would invite a poor scholar to share a meal with them each week, and from the impoverished medical student Max Talmud (later Talmey) the young and impressionable Einstein learned about mathematics and science. He consumed all 21 volumes of Aaron Bernstein's joyful Popular Books on Natural Science (1880). Talmud then steered him in the direction of Immanuel Kant's Critique of Pure Reason (1781), from which he migrated to the philosophy of David Hume. From Hume, it was a relatively short step to the Austrian physicist Ernst Mach, whose stridently empiricist, seeing-is-believing brand of philosophy demanded a complete rejection of metaphysics, including notions of absolute space and time, and the existence of atoms.

But this intellectual journey had mercilessly exposed the conflict between science and scripture. The now 12-year-old Einstein rebelled. He developed a deep aversion to the dogma of organised religion that would last for his lifetime, an aversion that extended to all forms of authoritarianism, including any kind of dogmatic atheism.

This youthful, heavy diet of empiricist philosophy would serve Einstein well some 14 years later. Mach's rejection of absolute space and time helped to shape Einstein's special theory of relativity (including the iconic equation E = mc2), which he formulated in 1905 while working as a 'technical expert, third class' at the Swiss Patent Office in Bern. Ten years later, Einstein would complete the transformation of our understanding of space and time with the formulation of his general theory of relativity, in which the force of gravity is replaced by curved spacetime. But as he grew older (and wiser), he came to reject Mach's aggressive empiricism, and once declared that 'Mach was as good at mechanics as he was wretched at philosophy.'

Over time, Einstein evolved a much more realist position. He preferred to accept the content of a scientific theory realistically, as a contingently 'true' representation of an objective physical reality. And, although he wanted no part of religion, the belief in God that he had carried with him from his brief flirtation with Judaism became the foundation on which he constructed his philosophy. When asked about the basis for his realist stance, he explained: 'I have no better expression than the term "religious" for this trust in the rational character of reality and in its being accessible, at least to some extent, to human reason.'

But Einstein's was a God of philosophy, not religion. When asked many years later whether he believed in God, he replied: 'I believe in Spinoza's God, who reveals himself in the lawful harmony of all that exists, but not in a God who concerns himself with the fate and the doings of mankind.' Baruch Spinoza, a contemporary of

Isaac Newton and Gottfried Leibniz, had conceived of God as identical with nature. For this, he was considered a dangerous heretic, and was excommunicated from the Jewish community in Amsterdam.

Einstein's God is infinitely superior but impersonal and intangible, subtle but not malicious. He is also firmly determinist. As far as Einstein was concerned, God's 'lawful harmony' is established throughout the cosmos by strict adherence to the physical principles of cause and effect. Thus, there is no room in Einstein's philosophy for free will: 'Everything is determined, the beginning as well as the end, by forces over which we have no control … we all dance to a mysterious tune, intoned in the distance by an invisible player.'

The special and general theories of relativity provided a radical new way of conceiving of space and time and their active interactions with matter and energy. These theories are entirely consistent with the 'lawful harmony' established by Einstein's God. But the new theory of quantum mechanics, which Einstein had also helped to found in 1905, was telling a different story. Quantum mechanics is about interactions involving matter and radiation, at the scale of atoms and molecules, set against a passive background of space and time.

Earlier in 1926, the Austrian physicist Erwin Schrödinger had radically transformed the theory by formulating it in terms of rather obscure 'wavefunctions'. Schrödinger himself preferred to interpret these realistically, as descriptive of 'matter waves'. But a consensus was growing, strongly promoted by the Danish physicist Niels Bohr and the German physicist Werner Heisenberg, that the new quantum representation shouldn't be taken too literally.

In essence, Bohr and Heisenberg argued that science had finally caught up with the conceptual problems involved in the description of reality that philosophers had been warning of for centuries. Bohr is quoted as saying: 'There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.' This vaguely positivist statement was echoed by Heisenberg: '[W]e have to remember that what we observe is not nature in itself but nature exposed to our method of questioning.' Their broadly antirealist 'Copenhagen interpretation' – denying that the wavefunction represents the real physical state of a quantum system – quickly became the dominant way of thinking about quantum mechanics. More recent variations of such antirealist interpretations suggest that the wavefunction is simply a way of 'coding' our experience, or our subjective beliefs derived from our experience of the physics, allowing us to use what we've learned in the past to predict the future.

But this was utterly inconsistent with Einstein's philosophy. Einstein could not accept an interpretation in which the principal object of the representation – the wavefunction – is not 'real'. He could not accept that his God would allow the 'lawful harmony' to unravel so completely at the atomic scale, bringing lawless indeterminism and uncertainty, with effects that can't be entirely and unambiguously predicted from their causes.

The stage was thus set for one of the most remarkable debates in the entire history of science, as Bohr and Einstein went head-to-head on the interpretation of quantum mechanics. It was a clash of two philosophies, two conflicting sets of metaphysical preconceptions about the nature of reality and what we might expect from a scientific representation of this. The debate began in 1927, and although the protagonists are no longer with us, the debate is still very much alive. And unresolved.

I don't think Einstein would have been particularly surprised by this. In February 1954, just 14 months before he died, he wrote in a letter to the American physicist David Bohm: 'If God created the world, his primary concern was certainly not to make its understanding easy for us.'

Adapted from Aeon

Einstein's Parable of Quantum Insanity

Einstein refused to believe in the inherent unpredictability of the world. Is the subatomic world insane, or just subtle?

"Insanity is doing the same thing over and over and expecting different results." That witticism — I'll call it "Einstein Insanity" — is usually attributed to Albert Einstein. Though the Matthew effect may be operating here, it is undeniably the sort of clever, memorable one-liner that Einstein often tossed off. And I'm happy to give him the credit, because doing so takes us in interesting directions.

First of all, note that what Einstein describes as insanity is, according to quantum theory, the way the world actually works. In quantum mechanics you can do the same thing many times and get different results. Indeed, that is the premise underlying great high-energy particle colliders. In those colliders, physicists bash together the same particles in precisely the same way, trillions upon trillions of times. Are they all insane to do so? It would seem they are not, since they have garnered a stupendous variety of results.

Of course Einstein, famously, did not believe in the inherent unpredictability of the world, saying "God does not play dice." Yet in playing dice, we act out Einstein Insanity: We do the same thing over and over — namely, roll the dice — and we correctly anticipate different results. Is it really insane to play dice? If so, it's a very common form of madness!

We can evade the diagnosis by arguing that in practice one never throws the dice in precisely the same way. Very small changes in the initial conditions can alter the results. The underlying idea here is that in situations where we can't predict precisely what's going to happen next, it's because there are aspects of the current situation that we haven't taken into account. Similar pleas of ignorance can defend many other applications of probability from the accusation of Einstein Insanity to which they are all exposed. If we did have full access to reality, according to this argument, the results of our actions would never be in doubt.

This doctrine, known as determinism, was advocated passionately by the philosopher Baruch Spinoza, whom Einstein considered a great hero. But for a better perspective, we need to venture even further back in history.

Parmenides was an influential ancient Greek philosopher, admired by Plato (who refers to "father Parmenides" in his dialogue the Sophist). Parmenides advocated the puzzling view that reality is unchanging and indivisible and that all movement is an illusion. Zeno, a student of Parmenides, devised four famous paradoxes to illustrate the logical difficulties in the very concept of motion. Translated into modern terms, Zeno's arrow paradox runs as follows:

1. If you know where an arrow is, you know everything about its physical state.
2. Therefore a (hypothetically) moving arrow has the same physical state as a stationary arrow in the same position.
3. The current physical state of an arrow determines its future physical state. This is Einstein Sanity — the denial of Einstein Insanity.
4. Therefore a (hypothetically) moving arrow and a stationary arrow have the same future physical state.
5. The arrow does not move.

Followers of Parmenides worked themselves into logical knots and mystic raptures over the rather blatant contradiction between point five and everyday experience. The foundational achievement of classical mechanics is to establish that the first point is faulty. It is fruitful, in that framework, to allow a broader concept of the character of physical reality. To know the state of a system of particles, one must know not only their positions, but also their velocities and their masses. Armed with that information, classical mechanics predicts the system's future evolution completely. Classical mechanics, given its broader concept of physical reality, is the very model of Einstein Sanity.

With that triumph in mind, let us return to the apparent Einstein Insanity of quantum physics. Might that difficulty likewise hint at an inadequate concept of the state of the world? Einstein himself thought so. He believed that there must exist hidden aspects of reality, not yet recognized within the conventional formulation of quantum theory, which would restore Einstein Sanity. In this view it is not so much that God does not play dice, but that the game he's playing does not differ fundamentally from classical dice. It appears random, but that's only because of our ignorance of certain "hidden variables." Roughly: "God plays dice, but he's rigged the game."

But as the predictions of conventional quantum theory, free of hidden variables, have gone from triumph to triumph, the wiggle room where one might accommodate such variables has become small and uncomfortable. In 1964, the physicist John Bell identified certain constraints that must apply to any physical theory that is both local — meaning that physical influences don't travel faster than light — and realistic, meaning that the physical properties of a system exist prior to measurement. But decades of experimental tests, including a "loophole-free" test published on the scientific preprint site arxiv.org last month, show that the world we live in evades those constraints.

Ironically, conventional quantum mechanics itself involves a vast expansion of physical reality, which may be enough to avoid Einstein Insanity. The equations of quantum dynamics allow physicists to predict the future values of the wave function, given its present value. According to the Schrödinger equation, the wave function evolves in a completely predictable way. But in practice we never have access to the full wave function, either at present or in the future, so this "predictability" is unattainable. If the wave function provides the ultimate description of reality — a controversial issue! — we must conclude that "God plays a deep yet strictly rule-based game, which looks like dice to us."

Einstein's great friend and intellectual sparring partner Niels Bohr had a nuanced view of truth. Whereas according to Bohr, the opposite of a simple truth is a falsehood, the opposite of a deep truth is another deep truth. In that spirit, let us introduce the concept of a deep falsehood, whose opposite is likewise a deep falsehood. It seems fitting to conclude this essay with an epigram that, paired with the one we started with, gives a nice example: "Naïveté is doing the same thing over and over, and always expecting the same result."

Adapted from Scientific American

Epic fails

Great theories can spend decades waiting for verification. Failed theories do too. Is there any way to tell them apart?

No-shows are a commonplace, though often hidden, part of the process of scientific discovery. Theories predict. That's their job. Ever since Isaac Newton and his co-conspirators in the 17th century consummated their revolutionary programme of subjecting nature to mathematics, this has come to mean that particular solutions to systems of equations can be interpreted as physical phenomena. If a given mathematical representation hasn't yet matched up with some phenomenon in the real world, it becomes a prediction waiting for its verification. But what happens when the verification never arrives – when the prediction fails to find its match in nature? When do you finally take 'no' for an answer?

These are constant issues in science. Take one recent example: for half a century, there was the mystery of something called the Higgs boson. The Higgs is the quantum, or the smallest possible change in energy, in what is known as the Higgs field. The Higgs concept was first proposed in the mid-1960s as part of what is now called the Standard Model of particle physics, a theory that describes the properties of the elementary particles out of which reality is built. Within the Standard Model, the Higgs boson accounts for how certain of those particles acquired the mass that they have in fact been seen to possess.

Over the next several decades, the Standard Model proved phenomenally successful, its predictions matching experimental results to as many decimal places as any measurement could achieve. But not the Higgs, which stubbornly refused to appear.

It finally emerged in observations made in 2012 and 2013, following the construction near Geneva of the Large Hadron Collider (LHC), an instrument powerful enough to peer into domains invisible to earlier devices. Up until the LHC produced its data, it remained an utterly open question whether the Higgs would actually show itself at the energies the machine could produce.

What if the LHC hadn't yielded its Higgs? The failure to find the result that the theory had anticipated, in a context that demanded some solution, would raise deep and (for theoretical physicists) very exciting questions. It would throw ideas, and careers, into turmoil. And it would have provided an opening for sweeping new theories that would attempt to make sense of the no-show.

The Higgs is no isolated example. Take the mysteries that remain in the account of what happened as the Universe was born. So much has been discovered about that seemingly inaccessible time and process because the Big Bang – the explosive appearance of space and time, matter and energy, essentially out of nothing – left a snapshot of itself in a flash of light called the Cosmic Microwave Background (CMB). Discovered in 1964 (the same year that the Higgs idea first emerged) as a seemingly uniform hiss of microwaves, the CMB offered the chance to do something new: to measure detailed properties of the very early Universe by extrapolating backward from that microwave glow to the Big Bang process itself.

In the decades since, the interplay of cosmological theory and ever more refined observations has yielded a series of insights about that nascent Universe, along with predictions about what kinds of features should be found in the CMB. For example: just by looking around us, it becomes obvious that the present-day Universe is lumpy, with big piles of matter collected into stars and galaxies and clusters of galaxies, and giant, mostly empty spaces in between. What we see now implies that the CMB should clump too, that there should be places in the microwave picture of the Universe that shine just a little brighter than other places: hot spots that map the slightly more matter-rich neighbourhoods that could ultimately grow into galaxy clusters.

Early surveys of the microwave sky showed a completely uniform, blank glow, however. If that were all there was, such a featureless early Universe would seem to be incompatible with what we know is out there now; this in turn would imply that what cosmologists thought they knew about the cosmological evolution was wrong.
That's how matters stood for almost three decades until 1989, when a specialised telescope called the Cosmic Background Explorer was launched into Earth orbit. By 1993, that instrument had captured enough photons to reveal exactly a broad pattern of light and dark – the first, out-of-focus glimpse of the original 'seeds' of galaxy clusters. There was a prediction based on a clearly observed fact in the contemporary Universe… and through enormous effort, it was shown to be true.

Since then, the CMB has been studied at greater and greater resolution to reveal an increasingly detailed picture of the events that turned the infant cosmos into one recognisably like our own. At the same time, theorists have made a series of predictions to be tested when and if observations of the CMB could be improved further still. One idea first proposed in the 1980s suggests that during its first instants of existence, our Universe underwent an episode called inflation, during which space itself expanded at a ferocious rate – ‘the bang of the Big Bang’, as one of its inventors, the theoretical physicist Alan Guth at the Massachusetts Institute of Technology, describes it. For more than 30 years, observations have yielded results that are consistent with inflation, but despite that growing collection of evidence, open questions remained.

The situation seemed set to change in 2014, as researchers closed in on a key expectation of the theory: that inflation’s wild ride would create what are called gravity waves, ripples in the gravitational field that would show themselves in particular (and very subtle) features that might be detectable in the CMB. There are several versions of the idea, each of which predicts somewhat different signals. In some of them, those primordial gravitational waves would leave a specific imprint on the CMB as a particular type of polarisation within the microwave background – thus revealing the first unequivocal connection between the vast, fast madness of the inflationary Universe with our own, more sedate cosmos. If such effects were found, it would be the final rung in the ladder of observations, the clinching evidence that we really do live in an inflated Universe.

That was the mission a research team set for itself with its instrument at the South Pole. The BICEP2 microwave telescope started gathering polarisation data in 2010. The team ran it for two years before beginning to study its data in earnest. It was a delicate, difficult analysis, and the stakes in the answer were so high that the researchers took every precaution they could think of to make sure they got it right. The public announcement came on 17 March 2014: a pattern known as ‘B-mode polarisation’, predicted by inflationary theory, had been observed in the CMB. The team detected the signal at a 5.9-sigma level – a scientific measure of confidence, one that is much better than the 3.5 million-to-one level of certainty required to claim discovery.

It was a thrilling moment. The result made front pages around the world. It brought Andrei Linde, a physicist at Stanford and one of inflation’s inventors, to the verge of tears. For scientists and amateurs of science alike, it was a gift: something beautiful, strange and newly intelligible about existence on the largest scale. There was a distant resonance, an echo of what those first few must have felt in 1687, when the earliest copies of Newton’s Principia came into their hands: a kind of breathlessness, sheer wonder that human minds could penetrate such incredibly deep mysteries. One of the most persuasive readings of inflation is that we dwell not in a singular cosmos, but in just one of uncounted island universes, our little village within a vast multiverse. What a thought! No wonder that a veteran researcher was overwhelmed by the good news.

But observing at the ragged edge of technology is always a tricky business. The tiny fluctuations the BICEP2 team found within their data – the signal they claimed was the signature of inflation's gravity waves – quickly drew informed scrutiny. Questions about their results became full-on doubts within a few weeks, as scientists from outside the team pressed them on the issue of foreground dust – ordinary debris common in galaxies such as our own Milky Way. By summer's end, it had become clear that the filtering of light through such nearby dust might explain all of the effects visible in BICEP2 data. Multiverse or stellar schmutz?

Many measures in the Universe behave as if inflationary theory is correct, but the latest attempts to check the BICEP2 measurement confirmed that it was impossible to distinguish a clear answer, given the confounding role of the galactic dust. What is known to date is that the BICEP2 results do not contain a reliable observation of inflation's signature in the CMB. That doesn't (yet) mean such traces don't exist. Several attempts are already underway to probe the CMB with yet more precision. Those measurements will likely settle whether the predicted gravity waves really do reveal themselves in the microwave background, and even if the hoped-for polarisation effects are not found, there are versions of inflation theory that do not require a gravity wave signature in the ancient glow of the Big Bang.

Still, even if some form of inflation remains a persuasive candidate to account for the properties we see in the Universe right now, it hasn't closed the deal. After more than three decades, the evidence in favour of inflation is strong but largely circumstantial. Theorists firmly support it, but the cosmos could see things differently. Long gaps between prediction and observation always raise the question: what finally persuades science – scientists – to abandon a once-successful idea? The conventional response in science is: right away, or at least as soon as you're confident of the evidence. But failure to validate a prediction is quite different from falsifying a prediction. Perhaps the failure was due simply to inadequate collection of data. There is plenty of room for stalling.

In a public talk delivered in 1963, the late physicist Richard Feynman said that science is simply 'a special method of finding things out'. But what makes it special? The way its answers get confirmed or denied: 'Observation is the judge' – the only judge, as the catechism goes – 'of whether something is so or not.' There is a strange magic to the term 'the scientific method'. At a minimum, it asserts a particular kind of authority: here is a systematic approach, a set of rules, that when followed will reliably advance our understanding of the material world. Such knowledge, though, is always provisional, a seeming weakness that is the real strength of science: every idea, every generalisation, every assumption is subject to question, to challenge, to refutation.

That's how the scientific method is usually taught. Every high-school student confronts some version of Feynman's description. The process of science rides down railroad tracks: you 'Construct a Hypothesis' to 'Test with an Experiment' (or an observation), and then you 'Analyse Results' and 'Draw Conclusions'. If the results fail to support the initial hypothesis, then it's back to step one.

Laid out like that, the scientific method can be seen as a kind of intellectual extruder.

Set the dials with the right question, pour data into the funnel, and pluck knowledge from the other end. And, most important: when that outcome fails to match reality, then you go back to the beginning, work the dials into some new configuration, try again.

This isn't just cartoon stuff either, a caricature told to children who might never dive more deeply into science than a Coke-Mentos volcano. Even for those who penetrate into more and more advanced ideas and approaches, the same message gets dressed up in more formal language. Here's a typical 'Introduction to the Scientific Method' aimed at college students: 'The scientific method requires that a hypothesis be ruled out or modified if its predictions are clearly and repeatedly incompatible with experimental tests' – pretty much what science-fair contestants are told. But the explanation goes on to echo Feynman's point: 'No matter how elegant a theory is, its predictions must agree with experimental results if we are to believe that it is a valid description of nature. In physics, as in every experimental science, "experiment is supreme".'

In other words, when a long-anticipated outcome fails to materialise, more than a single prediction lies in peril. If gravity waves don't show up in ever more acute CMB measurements, then at some point the strand of inflation theory that requires them will be in trouble. Within the myth of the scientific method, there should have been no choice about the next move. 'Experiment is supreme'… 'Observation is the judge.' We hold this truth to be self-evident: the hard test of nature trumps even the most beloved, battle-tested, long-standing idea. Does history behave like that? Do human beings?

No: real life and cherished fables routinely diverge. One of the starkest examples is the strange story of the planet Vulcan. In 1859, the French mathematician Urbain Le Verrier – the man who predicted the location of Neptune – calculated a property called the precession of the perihelion of Mercury's orbit. It is just a measure of how the planet's oval orbit shifts, with its point closest to the sun (perihelion) changing direction slightly from year to year. After accounting for the gravitational pull of all the known planets, Le Verrier was left with an error of 38 arcseconds per century. That is about 1/100th of a degree. Tiny, yes, but it wasn't zero. To account for the discrepancy, Le Verrier hypothesised 'a planet, or if one prefers a group of smaller planets circling in the vicinity of Mercury's orbit'. The unseen object came to be known as Vulcan.

The total eclipse of the sun observed July 29, 1878, at Creston, Wyoming Territory. From The Trouvelot Astronomical Drawings 1881-1882. A group of astronomers hoped that the eclipse would make visible an intra-mercurial planet, provisionally named Vulcan. Here was a concrete prediction, and a spectacular no-show. Vulcan refused to appear, decade after decade, even though its presence had been deduced from that icon of the scientific revolution, Newton's theory of gravity. Meanwhile, Mercury continued to misbehave. The American astronomer Simon Newcomb was the most authoritative student of the solar system in the last years of the 19th century. In 1882, he redid Le Verrier's calculation and showed that Mercury's excess perihelion advance was even slightly larger than Le Verrier had originally determined. But the dramatic failure of an 1878 eclipse observation in Wyoming, intended to look for new planets close to the Sun, left astronomers with few choices. Vulcan, whether imagined as a single planet or a flock of asteroids, was no longer plausible as the source of Mercury's anomaly. What to do?

After July 1878, almost all of the astronomical community abandoned the idea that a planet or planets of any appreciable size existed between the Sun and Mercury. But that broad consensus did not lead to any radical reassessment of Newtonian gravitation. Instead, a few researchers tried to salvage the core of the idea with ad-hoc explanations for Mercury's motion.

The historian of science N T Roseveare catalogued the struggle, dividing it into two main strands. Newcomb followed his recalculation of Mercury's orbit with a review of the 'matter' alternatives – Vulcan-like explanations that depended on coming up with a source of mass that for some good reason remained undetected but could generate enough gravitational tug to produce the perihelion advance. He took Vulcan itself as clearly refuted, but he catalogued a number of more subtle suggestions: perhaps the Sun was sufficiently oblate – fat around its middle – that such an unequal distribution of matter could solve the problem. Alas, the record of solar observation persuaded Newcomb that our star is pretty nearly spherical (as it is). Other proposals – matter rings, like those around Saturn, or enough of the dust that was known to exist near the Sun – fell to a variety of other objections.

After more than a decade of thinking about the problem, Newcomb came to his uncomfortably necessary conclusion: within the framework of the inverse square law of gravity, there was no plausible trove of matter near the Sun that could account for the motions of Mercury. With that, if science as lived matched the stories scientists tell about it, Newtonian theory should have been for the chop. In the fairytale version of the search for knowledge, Newcomb's verdict – that there was a persistent, unrepentant anomaly that current theory could not explain – would compel researchers to question its status as a valid description of nature.

In any myth there's at least a hint of some deeper truth, and so, as matter-based ideas fell, Newton's version of gravity did come under a bit of scrutiny. One astronomer suggested that Newton's law might be only an approximation: gravity could vary by masses involved and inversely with the distance between them to a power of 2, plus just a tiny amount: .0000001574. That would bring Mercury's motion into perfect agreement with the math, but there were several obvious objections. For one, it was such a messy move: why would the inverse exponent for gravity 'choose' to be so close to a perfect integer, and yet refuse to settle on exactly two?

To be sure, nature sometimes just is, in ways that can seem both arbitrary and unlovely. Even now, there are several numbers in fundamental theories of the large and small that are set by observation. In some cases they are just as odd – or weirder still – than an inverse 2.0000001574 power law. Even so, simplicity, elegance and, above all, consistency have proved to be pretty great ad-hoc measures of theoretical insight, even if they give no guarantees. An inverse-not-quite-two law was ugly enough that very few researchers took it seriously. The idea finally went away in the 1890s when it was shown to account for Mercury's motion, but not that of Earth's moon.

A few more attempts to tweak Newton followed. Some added another term to the classic inverse square law to better fit theory to nature, and others explored the idea that the speed of a body might change its gravitational attraction. None gained significant support from either physicists or astronomers, and they all would collapse under a variety of fatal flaws.

By the turn of the 20th century, most researchers had given up. There was still no explanation for Mercury's behaviour, but no one seemed to care. There was so much new to think about. X-rays and radioactivity had opened up the empire of the atom. Planck's desperate creation of the quantum theory was about to transform the study of both energy and the fundamental nature of matter. The decades-in-the-making confirmation that the speed of light (in a vacuum) was truly constant was beginning to hint that extremes of speed might produce some very interesting effects. At the Paris Exhibition of 1900, the American historian Henry Adams marvelled at the practical applications of the new science of electricity. In 1903, the Wright brothers' experiments on a beach in North Carolina would usher in an age in which, among much else, long-pondered and very difficult questions in physics – such as the motion of air over a surface – took on literally life-and-death significance.

Through it all, good old Newtonian theory worked a treat, pretty much all the time. Its laws of motion described the experience of the real world close to perfectly and, if Mercury acted up a little (so little, those few arc-seconds per century!), comets and Jupiter and falling apples and just about everything else that could be observed proceeded on their way in calm agreement with the rules laid down in the Principia. Amid all this – the tumult of the new and the excellence of the old – Vulcan itself dwindled into a mostly forgotten embarrassment, the physical sciences' crazy uncle in the attic. There it sat (or rather, didn't), hooting in the rafters, and yet no one seemed to hear.

That willful disregard eventually changed, but only after a young man in Switzerland named Albert Einstein started to think about something else entirely, nothing to do with any confrontation between a planet and an idea. He was contemplating the relationship between space, time, acceleration and gravity. He ended up by creating the general theory of relativity, and in the process finally explained the anomalous motion of Mercury's orbit: not due to another planet or asteroid, but due to the previously unknown effects of the warping of space around the Sun. The improved calculation of Mercury's orbit was, in fact, a crucial first test of Einstein's new theory.

What moral to draw, then, of the non-existence of Vulcan and the subsequent triumph of general relativity? At the least this: science is unique among human ways of knowing because it is self-correcting. Every claim is provisional, which is to say each is incomplete in some small or, occasionally, truly consequential way. But in the midst of the fray, it is impossible to be sure what any gap between knowledge and nature might mean. We know now that Vulcan could never have existed; Einstein has shown us so. But no route to such certainty existed for Le Verrier, nor for any of his successors over the next half-century. They lacked not facts, but a framework, some alternative way of seeing, through which Vulcan's absence could be understood.

Such insights do not come on command. And until they do, the only way any of us can interpret what we find is through what we already know to be true. For more than two centuries, humankind lived in the cosmos that Newton discovered. In the end, that cosmos was demolished not by a failure of prediction, but by a more complete theory. Vulcan's non-existence did not overthrow Newton's theory. Rather, it became the marker on which the theory's passing is written.

Adapted from Aeon