А.И. Матяшевская, Е.В. Тиден

ILLUMINATING PHYSICS:

part 4

Учебное пособие

Саратов

2019

Составители - А.И. Матяшевская, Е.В. Тиден

Illuminating physics: part 4: Учебное пособие по иностранному языку для магистрантов /Сост. А.И. Матяшевская, Е.В. Тиден. — Саратов, 2019. — 83 с.

Рецензент:

Кандидат философских наук Шилова С.А.

Table of Contents

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, Quanta Magazine, The Atlantic, 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. Why things happen

Exercise I.

Say what Russian words help to guess the meaning of the following words: cosmos, naïve, illusion, regularities, sorts, central, dilemma, ignore, statistical, thermodynamics

Exercise II.

Make sure you know the following words and word combinations.

repercussion, wavelet, to surpass, to assert, coherently, pervasive, superfluous, to stipulate, interferometry

Why things happen

Either cause and effect are the very glue of the cosmos, or they are a naive illusion due to insufficient math. But which?

For our judgments to be much use to us, we have to distinguish between causal relations and mere correlations. A working knowledge of the way in which causes and effects relate to one another seems indispensible to our ability to make our way in the world. Yet there is a long and venerable tradition in philosophy, dating back at least to David Hume in the 18th century, that finds the notions of causality to be dubious. And that might be putting it kindly.

Hume argued that when we seek causal relations, all we are able to see are regularities – the 'constant conjunction' of certain sorts of observation. He concluded from this that any talk of causal powers is illegitimate. Which is not to say that he was ignorant of the central importance of causal reasoning; indeed, he said that it was only by means of such inferences that we can 'go beyond the evidence of our memory and senses'. Causal reasoning was somehow both indispensable and illegitimate. We appear to have a dilemma. Hume's remedy for such quandaries was quite sensible, as far as it went: try to put it out of your mind. But in the late 19th and 20th centuries, his causal anxieties were reinforced by another problem, harder to ignore. According to this new line of thought, causal notions seemed peculiarly out of place in our most fundamental science – physics. There were two reasons for this. First, causes seemed too vague for a mathematically precise science. If you can't observe them, how can you measure them? If you can't measure them, how can you put them in your equations? Second, causality has a definite direction in time: causes have to happen before their effects. Yet the basic laws of physics (as distinct from such higher-level statistical generalisations as the laws of thermodynamics) appear to be time-symmetric: if a certain process is allowed under the basic laws of physics, a video of the same process played backwards will also depict a process that is allowed by the laws. The 20th-century English philosopher Bertrand Russell concluded from these considerations that, since cause and effect play no fundamental role in physics, they should be removed from the philosophical vocabulary altogether. Neo-Russellians in the 21st century express their rejection of causes with no less vigour. The philosopher of science John Earman maintains that the wooliness of causal notions makes them inappropriate for physics: 'A putative fundamental law of physics must be stated as a mathematical relation without the use of escape clauses or words that require a PhD in philosophy to apply (and two other PhDs to referee the application, and a third referee to break the tie of the inevitable disagreement of the first two).' This is all very puzzling. Is it OK to think in terms of causes or not? If so, why, given the apparent hostility to causes in the underlying laws? And if not, why does it seem to work so well? A clearer look at the physics might help us to find our way. Even though (most of) the basic laws are symmetrical in time, there are many non-thermodynamic physical phenomena that can happen only one way. Imagine a stone thrown into a still pond: after the stone breaks the surface, waves spread concentrically from the point of impact. A common enough sight.

Now, imagine a video clip of the spreading waves played backwards. What we would see are concentrically converging waves. For some reason this second process, which is the time-reverse of the first, does not seem to occur in nature. The process of waves spreading from a source looks irreversible. And yet the underlying physical law describing the behaviour of waves – the wave equation – is as time-symmetric as any law in physics. It allows for both diverging and converging waves. So, given that the physical laws equally allow phenomena of both types, why do we frequently observe organised waves diverging from a source but never coherently converging waves? Physicists and philosophers disagree on the correct answer to this question – which might be fine if it applied only to stones in ponds. But the problem also crops up with electromagnetic waves and the emission of light or radio waves: anywhere, in fact, that we find radiating waves. What to say about it? On the one hand, many physicists (and some philosophers) invoke a causal principle to explain the asymmetry. Consider an antenna transmitting a radio signal. Since the source causes the signal, and since causes precede their effects, the radio waves diverge from the antenna after it is switched on simply because they are the repercussions of an initial disturbance, namely the switching on of the antenna. Imagine the time-reverse process: a radio wave steadily collapses into an antenna before the latter has been turned on. On the face of it, this conflicts with the idea of causality, because the wave would be present before its cause (the antenna) had done anything. David Griffiths, Emeritus Professor of Physics at Reed College in Oregon and the author of a widely used textbook on classical electrodynamics, favours this explanation, going so far as to call a time-asymmetric principle of causality 'the most sacred tenet in all of physics'. On the other hand, some physicists (and many philosophers) reject appeals to causal notions and maintain that the asymmetry ought to be explained statistically. The reason why we find coherently diverging waves but never coherently converging ones, they maintain, is not that wave sources cause waves, but that a converging wave would require the co-ordinated behaviour of 'wavelets' coming in from multiple different directions of space – delicately co-ordinated behaviour so improbable that it would strike us as nearly miraculous. It so happens that this wave controversy has quite a distinguished history. In 1909, a few years before Russell's pointed criticism of the notion of cause, Albert Einstein took part in a published debate concerning the radiation asymmetry. His opponent was the Swiss physicist Walther Ritz, a name you might not recognise. It is in fact rather tragic that Ritz did not make larger waves in his own career, because his early reputation surpassed Einstein's. The physicist Hermann Minkowski, who taught both Ritz and Einstein in Zurich, called Einstein a 'lazy dog' but had high praise for Ritz. When the University of Zurich was looking to appoint its first professor of theoretical physics in 1909, Ritz was the top candidate for the position. According to one member of the hiring committee, he possessed ‘an exceptional talent, bordering on genius’. But he suffered from tuberculosis, and so, due to his failing health, he was passed over for the position, which went to Einstein instead. Ritz died that very year at age 31. Months before his death, however, Ritz published a joint letter with Einstein summarising their disagreement. While Einstein thought that the irreversibility of radiation processes could be explained probabilistically, Ritz proposed what amounted to a causal explanation. He maintained that the reason for the asymmetry is that an elementary source of radiation has an influence on other sources in the future and not in the past. This joint letter is something of a classic text, widely cited in the literature. What is less well-known is that, in the very same year, Einstein demonstrated a striking reversibility of his own. In a second published letter, he appears to take a position very close to Ritz’s – the very view he had dismissed just months earlier. According to the wave theory of light, Einstein now asserted, a wave source ‘produces a spherical wave that propagates outward. The inverse process does not exist as elementary process’. The only way in which converging waves can be produced, Einstein claimed, was by combining a very large number of coherently operating sources. He appears to have changed his mind. Given Einstein’s titanic reputation, you might think that such a momentous shift would occasion a few ripples in the history of science. But I know of only one significant reference to his later statement: a letter from the philosopher

Karl Popper to the journal Nature in 1956. In this letter, Popper describes the wave asymmetry in terms very similar to Einstein's. And he also makes one particularly interesting remark, one that might help us to unpick the riddle. Coherently converging waves, Popper insisted, 'would demand a vast number of distant coherent generators of waves the co-ordination of which, to be explicable, would have to be shown as originating from the centre'. This is, in fact, a particular instance of a much broader phenomenon. Consider two events that are spatially distant yet correlated with one another. If they are not related as cause and effect, they tend to be joint effects of a common cause. If, for example, two lamps in a room go out suddenly, it is unlikely that both bulbs just happened to burn out simultaneously. So we look for a common cause – perhaps a circuit breaker that tripped. Common-cause inferences are so pervasive that it is difficult to imagine what we could know about the world beyond our immediate surroundings without them. Hume was right: judgments about causality are absolutely essential in going 'beyond the evidence of the senses'. In his book The Direction of Time, the philosopher Hans Reichenbach formulated a principle underlying such inferences: 'If an improbable coincidence has occurred, there must exist a common cause.' To the extent that we are bound to apply Reichenbach's rule, we are all like the hard-boiled detective who doesn't believe in coincidences.

This gives us a hint at the power of causal inferences: they require only very limited, local knowledge of the world as input. Nevertheless, causal skeptics have argued that such inferences are superfluous in physics, which is supposed to proceed in a very different way. In this rather majestic vision of scientific inference, we simply feed the laws a description of the complete state of a system at one time, and then they ‘spit out’ the state of the system at any other time. The laws are a kind of smoothly humming engine, generating inferences from one time to another – and given this magnificent machine, the skeptics claim, causal principles are practically irrelevant. It’s an appealing idea. However, a moment’s reflection tells us that very few investigations could actually proceed in this manner. For one thing, we rarely (if ever) have access to the complete initial data required for the laws to deliver an unequivocal answer. Suppose we wanted to calculate the state of the world just one second from now. If the laws are relativistic – that is, if they stipulate that no influence can travel faster than light – our initial state description would need to cover a radius of 300,000 km. Only then could we account for any possible influences that might reach our location within one second. For all practical purposes this is, of course, impossible. And so we find that, even in physics, we need inferences that require much less than complete states as input. Astronomical observations provide a particularly stark example. How do we know that the points of light in the night sky are stars? The approach using laws and initial (or, in this case, final) conditions to calculate backward in time to the existence of the star would require data on the surface of an enormous sphere of possibly many light years in diameter. Stuck here on Earth as we are, that just isn’t going to happen. So what do we do? Well, we can make use of the fact that we observe points of light at the same celestial latitude and longitude at different moments in time, or at different spatial locations, and that these light points are highly correlated with one another. (These correlations can, for example, be exploited in stellar interferometry.) From these correlations we can infer the existence of the star as common cause of our observations. Causal inference may be superfluous in some idealised, superhuman version of physics, but if you actually want to find out how the Universe works, it is vital.

It can sometimes seem as if the debate over wave asymmetry hasn't advanced much since 1909. And yet, doesn't the comparison with other common-cause inferences show that Ritz and then later Einstein were right and the earlier Einstein was wrong? Indeed, if we take Popper's remark seriously, it seems as if the probabilistic explanation itself relies on implicit causal assumptions. Let's think again about a wave coherently diverging from a source compared with a wave coherently converging into a source. Both scenarios involve 'delicately set up' correlations among different parts of the wave; after all, each of the two processes is simply the other one run backwards in time. But then, contrast our familiar experience with that of the narrator in Martin Amis' time-flipped novel Time's Arrow , who takes a boat journey across the Atlantic: John is invariably to be found on the stern, looking at where we're headed. The ship's route is clearly delineated on the surface of the water and is violently consumed by our advance. Thus we leave no mark on the ocean, as if we are successfully covering our tracks. That the ship's wake pattern should be laid out before the ship, so that it is made to disappear as the ship advances, seems miraculous and all but impossible. And yet the correlations are the very same ones that exist between a ship and its familiar wake-pattern in the real world. Why on earth should that be? Why does a wave coherently converging into a source strike us as miraculous, while a wave coherently diverging from a source is completely ordinary? The answer must be that, in the case of the diverging wave, there is an obvious explanation for the 'delicate' correlations: the source acts as common cause. This is in sharp contrast with a converging wave, for which the correlations cannot be explained by appealing to the source into which the wave converges. Since the two processes are the time-reverse of each other, the only possible difference between the two cases, it seems, concerns their different causal structures. I think this answer is essentially correct. And so, as far as it goes, perhaps we can declare victory for Ritz. However, victory might prove rather hollow. Formal advances in causal modelling in the past two decades suggest that the difference between the two explanatory strategies – causal and probabilistic – is much smaller than it first appears. As the computer scientist Judea Pearl and others have shown, causal structures can in fact be represented with mathematical precision. This answers Earman's vagueness worry: one PhD is more than enough to be able to apply them coherently, and it might even help if the degree is not in philosophy.

More importantly, it turns out that the causal asymmetry of common-cause structures and the assumption of probabilistic independence are really two sides of the same coin. More precisely, common-cause inferences need the initial inputs to the system to be probabilistically independent of one another. This makes intuitive sense: if the inputs to your model are correlated, downstream relationships between variables could be due to matches that were present from the beginning, rather than due to anything that happened inside the model. So common-cause inferences depend on an assumption of independence. And from this perspective it might seem that the early Einstein was correct after all: probability comes first. But not so fast! As we saw above, the explanatory direction can be reversed so that the assumption of probabilistic independence is taken to reflect a causal assumption about the system. And this, again, seems to indicate that Ritz was right. We face a chicken-and-egg dilemma. In fact there might not be a uniquely correct answer to the question which of the two assumptions is logically prior. This opens up a third interpretive option. Why not see both the probabilistic independence assumption and the common-cause principle as mutually dependent aspects of causal structures? We can accept that these structures have an important role to play in physics, just as they do in other sciences and in common sense, without having to commit to the metaphysical priority of either. This third view is reminiscent of the late US physicist Richard Feynman's view about physical laws. Feynman argued that the laws of physics do not exhibit a unique, logical structure, such that one set of statements is more fundamental than another. Instead of a hierarchical 'Euclidean conception' of theories, Feynman argued that physics follows what he calls the 'Babylonian tradition', according to which the principles of physics provide us with an interconnected structure with no unique, context-independent starting point for our derivations. Given such structures, Feynman said: 'I am never quite sure of where I am supposed to begin or where I am supposed to end.' I want to suggest that we should think of causal structures in physics in the very same way. Contrary to Russellian skeptics, causal structures play as indispensible a role in physics as in other sciences. And yet we do not need to take sides in the debate between Einstein and Ritz. Derivation doesn't have to start anywhere in particular. Rather, we can understand the probabilistic independence assumption and the causal asymmetry as two interrelated aspects of causal structures.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) _____________connections have to be examined, not assumed, or you'll get into trouble.

2) A study by the Kauffman Foundation found an inverse _____________ between the two.

3) The selection of a new chairman will occur in ____________ with the CEO decision.

4) I included this fact in the article without stating the _____________ from the fact.

5) After years of mutual ___________, Turkey and the Iraqi Kurds are at last talking.

6) Two or more wires may be wrapped ______________, separated by insulation, to form coaxial cable.

7) By contrast, outsiders face harsh ______________ if they speak out of turn.

8) This concept of resonance is at the core of many practical applications of ____________ theory.

9) Corruption in many forms has been one of the _____________ problems affecting India.

10) Astronomical observations tell us that all ________________ objects are made of matter.

Exercise IV.

Make up sentences of your own with the following word combinations: to crop up, circuit-breaker, hard-boiled, to spit out, to make one's way in the world, at least, dating back to, in the very same way, contrary to, to take sides in the debate between

Exercise V.

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

illegitimate	a conclusion reached on the basis of evidence and reasoning
reminiscent	a state of perplexity or uncertainty over what to do in a difficult situation
derivation	call earnestly for
momentous	leaving no doubt; unambiguous
celestial	physical strength and good health
inference	the obtaining or developing of something from a source or origin
quandary	not authorized by the law; not in accordance with accepted standards or rules

vigor	tending to remind one of something
unequivocal	(of a decision, event, or change) Of great importance or significance, esp. in its bearing on the future
invoke	positioned in or relating to the sky, or outer space as observed in astronomy

Exercise VI.

Identify the part of speech the words belong to: causal, correlation, venerable, conjunction, inference, peculiarly, distinct, putative, hostility, concentrically

Exercise VII.

Match the words to make word combinations:

defenite	generalisations
causal	phenomena
independence	illusion
still	relations
statistical	tradition
basic	assumption
mere	pond
causal	laws
naive	direction
venerable	correlations

Exercise VIII.

Summarize the article “Why things happen”

2. Time after time

Exercise I.

Say what Russian words help to guess the meaning of the following words: comfort, planet, globe, moment, melancholy, motivated, acceleration, orbit, demonstrated, system

Exercise II.

Make sure you know the following words and word combinations.

Fleeting, to retrace, precept, to engender, to ascend, to plummet, conjunction, crank, to exhaust, reservoir

Time after time

The question of whether time moves in a loop or a line has occupied human minds for millenia. Has physics found the answer?

Imprisoned in the fortress of Taureau, the French revolutionary Louis-Auguste Blanqui gazed toward the stars. As Blanqui looked up at the night sky, he found comfort in the possibility of other worlds. While life on Earth is fleeting, he wrote in Eternity by the Stars(1872), we might take solace in the notion that myriad replicas of our planet are brimming with similar creatures – that all events, he said, ‘that have taken place or that are yet to take place on our globe, before it dies, take place in exactly the same way on its billions of duplicates'. Might certain souls be imprisoned on these faraway worlds, too? Perhaps. But Blanqui held out hope that, through chance mutations, those who are unjustly jailed down here on Earth might there walk free. Blanqui's vision of replica worlds might seem fanciful – wishful thinking born of a prolonged confinement, perhaps. Yet it reflects an age-old conundrum that continues to baffle physicists and cosmologists to this day. Does the Universe repeat itself in space or time? Or are we barrelling endlessly forward, never to repeat this moment or arrangement of matter, never to retrace our steps? While Blanqui imagined human history replicating itself in space, the 19th-century German philosopher Friedrich Nietzsche envisioned repetition over time. He called this 'eternal recurrence', also known as 'eternal return'. Nietzsche prided himself on the 'discovery' that he, and everyone else in the world, would relive their lives, again and again, in perpetuity. This was not necessarily a cause for celebration. 'What if some day or night a demon were to steal after you into your loneliest loneliness,' he wrote, 'and say to you: "This life as you now live it and have lived it, you will have to live once again and innumerable times again; and there will be nothing new in it, but every pain and every joy and every thought and sigh?"' Still, immortality – returning to Earth throughout the aeons – was something of a recompense for the horror of having to re-experience melancholy, sickness and despair.

Both Blanqui and Nietzsche were motivated, at least in part, by Isaac Newton's laws of motion and the principle of the conservation of mechanical energy. These principles show how the gravitational forces that govern the acceleration of objects also steer the planets into orbit around the Sun. In 1814, the French scientist Pierre-Simon Laplace demonstrated that Newtonian physics, applied to a closed system, allows you to predict to near-perfection what will happen next. ‘We may regard the present state of the Universe as the effect of its past and the cause of its future,’ Laplace wrote in A Philosophical Essay on Probabilities (1814). If you could have perfect knowledge of the positions, velocities and forces that apply to ‘the greatest bodies of the Universe and those of the tiniest atom’, Laplace said, ‘for such an intellect nothing would be uncertain, and the future just like the past would be present before its eyes.’ This determinism, however, ends up eating its own tail. In Newtonian physics, space is a static theatre within which objects move and shift. But suppose those objects are themselves composed of a finite quantity and variety of constituents – any chunk of ice, for example, is made up of hydrogen and oxygen atoms. Given enough time, the possible combinations of constituents would be bound to repeat themselves, both in time and space. The situation is a bit like an endless tournament of noughts and crosses. Because there is a finite playing field (an array of nine squares) and a finite number of elements (noughts and crosses), eventually any given outcomes must reoccur. Any region of space, of course, would have vastly more components than a game of noughts and crosses, but the principle still holds: the time cycles or spatial repetitions might be inordinately spread out, but chance recombinations would make them inevitable nonetheless.

Conservation of mechanical energy follows directly from Newton’s laws. This precept states that in the absence of friction and air resistance, energy freely converts from one type, potential energy (the energy of an object held in position), into another type, kinetic (the energy of motion). It's a natural form of recycling. So the pendulum driving a grandfather clock would swing back and forth, turning the potential energy at the highest point of the swing into kinetic energy at the lowest point, over and over. (Of course, in practice, air resistance would gradually slow down that process, unless it were externally restarted.) The relatively steady motion of the Moon in its orbit around Earth testifies to the regularity and repetition engendered by conservation laws. In this way, science and a sort of mysticism can join hands. Both Blanqui and Nietzsche were materialists, in that they believed human thoughts and feelings were byproducts of chemical mechanisms. All things are fundamentally made of atoms, including whatever mechanisms create the illusion of souls. Consequently, they believed that physical cycles would inevitably lead to a recurrence of ideas and emotions.

Materialism is closely linked to atomism, the notion that everything is composed of a finite array of unbreakable components. While some ancient philosophers embraced atomism, there was a much stronger consensus around the idea that time runs in cycles. Unlike Nietzsche's eternal recurrence, however, the classical view of cycles was much less precise. In most versions, human lives would not recur exactly. Rather, history in general – both human and cosmic – would pass through endless cycles of creation and destruction, like a great wheel of destiny. Many of the ancients believed that Earthly civilisations would ascend from the ashes of previous societies, ascend to golden eras of great power and fortune, turn toward decadence, and plummet into disaster, only to be replaced by other cultures on the rise. In later centuries, plotting cycles played a pivotal role in observational astronomy, one of the few exact sciences in the ancient world. Astronomers were able to anticipate celestial events such as eclipses and conjunctions (when two or more planets are aligned). Yet until the early 19th century, physics mandated no particular direction for time. Newton's laws, for example, run exactly the same forward and backward – which meant, in principle, that machines should be able to run forever. At the height of the Industrial Revolution, manufacturers hoped to achieve this perfect efficiency by constructing flawless engines, which would not lose energy via friction and heat. Surely some clever-enough inventor could eliminate waste? Meanwhile, the rise of railways and factories demanded more accurate timekeeping, standardised machinery, and an accelerated pace of life. It was almost as if history was necessarily advancing toward progress and precision, onward and upward – never back. In the quest for perfect efficiency, however, waste remained a persistent bugbear. The French physicist Sadi Carnot addressed the problem of the perpetual motion machine in his influential book Reflections on the Motive Power of Fire (1824). He considered the workings of a steam engine: a device that used the expansion and compression of water, as it is respectively heated and allowed to cool, to drive a piston up and down. Rods attached to the moving piston were typically connected to cranks or wheels, setting those, in turn, into motion. This allowed the engine to do work, which is a measure of the ability of a force to move something from one point to another. Steam engines draw water from a cold basin, heat it up in a boiler, and expel the hot water and steam into a hot basin, where it would be allowed to cool. The larger the temperature difference between the basins, Carnot found, the greater the amount of work performed by the engine. Still, there would always be a significant quantity of waste energy involved. In other words, no matter how savvy the designer, he or she could never develop a perfectly efficient machine: there would always be unusable energy, which would increase over time. In the 1850s and ’60s, the German physicist Rudolf Clausius generalised Carnot’s results about waste energy into a principle known as the second law of thermodynamics, also called the law of nondecreasing entropy. Entropy measures how much of the energy of any system is unavailable to do work. For example, heat dissipating into the atmosphere from the exhaust of a car cannot be collected and used to power a motorbike. Over time, the second law broadly states, the amount of entropy must naturally increase or, at best, stay the same; it can never decrease. Entropy has an inverse relationship with temperature differences. Heat flows naturally from a hot reservoir into a cold reservoir, potentially doing work in the process (such as driving a turbine). Hence stark temperature differences match efficient, low-entropy situations. On the other hand, if there was no temperature difference between components of a system – a situation known as thermal equilibrium – no work could be performed. Therefore, entropy would be very high. For instance, while the ocean has an abundance of energy due to the motions of the molecules within it, that energy can be converted into work only if heat can flow from the ocean into something colder. At the time, that wasn’t a realistic solution, and therefore most of the ocean’s energy had little chance of being extracted. The second law of thermodynamics means that natural processes tend to get less and less efficient over time, because any process that exchanges heat between hot and cold reservoirs tends to equalise their temperatures. That is, their entropy tends to rise. Eventually, when the temperatures even out, the state of thermal equilibrium is reached, and no further work can be done. Another way of stating the second law, then, is that closed systems naturally tend toward thermal equilibrium. This behaviour defines a distinct arrow of time. If you place an ice cube in a mug of hot tea, you would observe the temperatures balancing out, leading to a lukewarm drink. But you would never see an ice cube spontaneously emerge from lukewarm tea, ceding energy to the liquid and making it steaming hot. If you saw a film of such a strange occurrence, you'd rightly conclude that it was being played in reverse. In this way, the second law dictates that time has a distinct direction: it is linear, rather than cyclical. Clausius's conclusions addressed closed systems, such as an engine. But what about the Universe itself? In 1852 the British physicist Lord Kelvin suggested that the Universe as a whole would eventually reach a state of uniform temperature, once all the stars within it had burned out. Once this 'heat death' had been reached, no further work could be done anywhere in space. Back then, no one knew about the processes of nuclear fusion that powered the stars, so estimates of stellar lifetimes were much lower – and the imminent prospect of heat death very frightening indeed. Today, we know that stars can shine for billions of years. Even after their demise, stars leave behind relics, such as white dwarves, neutron stars and black holes, which radiate at various rates (black holes, admittedly, extremely slowly). Nevertheless, eventually – in a time frame far longer than Lord Kelvin envisioned – the Universe, if it keeps going the way it has been, would reach a quiescent state. Time's arrow of non-decreasing entropy, in other words, seems to be universal. With the benefit of contemporary instruments and methods, modern science is now striving to unravel the nature of time. It has identified new ways of understanding the arrow of time that supplement the law of non-decreasing entropy. The American astronomer Edwin Hubble and others in the 1920s showed that the Universe is expanding. This fact suggests that cosmological time is marching forward, in step with cosmic growth. Findings by several teams of astronomers in the 1990s demonstrated that cosmic growth is speeding up, apparently due to an unobserved entity known as dark energy. In some theories, dark energy is conceived as strengthening over time. Eventually, it would become so powerful that it should overwhelm all of the other forces of nature and tear apart the fabric of the Universe, well before heat death, in a condition called the Big Rip.

The majority of scientists think that cosmic expansion is irreversible – although a minority, such as Paul Steinhardt, Neil Turok and Roger Penrose have envisioned ways in which the Universe might be renewed in fresh cycles of time. Each of their models is extremely hypothetical. Steinhardt and Turok's approach, called the 'cyclic universe', pictures a periodic collision along a higher dimension (posited in certain theoretical models) of our three-dimensional space with another such space – like two slices of bread smacked together to form a sandwich. Each higher-dimensional collision supplies an energy blast that wipes out evidence of the previous cycle. Penrose's vision, called 'conformal cyclic cosmology' involves a special mathematical transformation called a conformal mapping that twists the beginning and end of the Universe together like a Mobius strip. Observations and analysis of cosmic microwave background (CMB) radiation have proved vital as a way of understanding cosmology. The CMB is relic radiation that was released some 380,000 years after the Big Bang, and varies slightly in temperature from point to point throughout the sky map. By applying powerful statistical methods to the temperature distribution of the CMB, depicted in colours and sometimes nicknamed 'the baby picture of the Universe', such minuscule fluctuations have yielded the data about the nature of space and time. For one thing, the analysed data has helped astrophysicists pin down the age and geometry of the Universe with greater precision. Scientists are now looking at the CMB for telltale clues of earlier cosmic cycles, and scars from primordial collisions between different sectors of the Universe. If such scars were found, they would lend credibility to 'bubble universe' models that suggest that the observable Universe emerged from a kind of bubble bath of myriad other expanding parts of space. Each bubble grew up into its own sector of the Universe, including the segment that we see around us. So instead of one Big Bang, there might have been numerous bursts at the same time, spawned from the cosmic froth wherever conditions were right. Scars from such primordial collisions would offer evidence that our region of space is not alone.

When it comes to the subatomic realm of quantum physics, researchers once believed that all processes were completely reversible in time, such as the scattering of electrons from each other, which appears the same if run backward or forward. However, in 1964, the American physicists James Cronin and Val Fitch demonstrated that in rare cases, certain modes of decay of elementary particles, called neutral kaons, violate a condition, called Charge-Parity or CP-invariance, that is equivalent to time symmetry. Briefly, this means that if you switch all the charges of particles in an interaction (from positive to negative, and vice-versa) and reverse the process spatially, as if it's reflected in a mirror, the resulting picture would have features similar to the original interaction – except that it would be reversed in time. After such a transformation, a negative electron moving to the right toward a positive proton would appear like a positive positron (the antimatter counterpart of an electron) moving to the left away from a negative antiproton. Reverse the latter process in time, and you'd see the positron and antiproton attract each other, in a perfectly legitimate process. Both the time-forward and time-reversed processes would be equally plausible. However, try the same steps with Cronin and Fitch's kaons (in that case, a decay process) and you would see a discrepancy between the likelihood of the time-forward and time-reversed processes. That is, one would be more common than the other. Nature, even at its deepest level, might have a preference for a single temporal direction. The arrows of time we have observed in nature – due to growing entropy, cosmic expansion and certain physical processes in particle physics – make it extremely unlikely that human events will recur in time. As far as we can see, the Universe is ageing; Nietzsche's eternal recurrence seems at odds with the world's fundamental rules. On the other hand, if the Universe is infinite in space, there's still a chance that planets nearly identical to Earth exist, untold light-years away. If we contemplate an endless cosmos, a spatial repetition of worlds could happen by mere chance. Perhaps on one of them, so far away that we could never hope to observe it, a replica of Blanqui walks free.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) With the bankruptcy looming at home, the only place USA can seek _______________ is Asia.

2) The nature of the condition continues to __________________ doctors, as does its exact cause.

3) From castle, ________________ your route, and at the Victoria Hotel turn into Ingram Road.

4) How can we inoculate ourselves against a ______________ of this whole awful cycle?

5) The mood swings like a ______________ between desperate optimism and morbid pessimism.

6) The _____________ gains in gene mapping are leading to new uses for the technology.

7) In 1869, he introduced a horse-drawn ________________ to power the threshing machines.

8) Is the death of the PC __________________ and if so what does it mean for the key players?

9) Though well-studied, the molecular details of membrane______________ remain mysterious.

10) Another equally ________________ suggestion is that she suffered from manic depression.

Exercise IV.

Make up sentences of your own with the following word combinations: to steal after, to move in a loop, to move in a line, to look up at the sky, to take solace in the notion, to take place on our globe, held out, to jail down, to baffle physicists and cosmologists to this day. in perpetuity

Exercise V.

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

solace	deprive (someone) of membership of or involvement in a school or other organization
aeon	in a state or period of inactivity or dormancy
pendulum	only moderately warm; tepid
plausible	totally bewilder or perplex
telltale	a weight hung from a fixed point so that it can swing freely backward and forward, esp. a rod with a weight at the end that regulates the mechanism of a clock
demise	comfort or consolation in a time of distress or sadness
to expel	the longest division of geological time
to baffle	seeming reasonable or probable

lukewarm	revealing, indicating, or betraying something
quiescent	a person's death

Exercise VI.

Identify the part of speech the words belong to.

conundrum, recurrence, perpetuity, inordinately, recompense, efficiency, perpetual, imminent, fusion, primordial

Exercise VII.

Match the words to make word combinations:

Big	worlds
Conformal	mutations
Möbius	vision
steam	replicas
Blanqui's	sky
chance	map
faraway	Rip
myriad	strip
night	engine
human	minds

Exercise VIII.

Summarize the article “Time after time”.

3. Why the Many-Worlds Interpretation Has Many Problems

Exercise I.

Say what Russian words help to guess the meaning of the following words: interpretation, idea, popular, extraordinary, isolated, illustrates, arguments, extreme, invested, orthodox

Exercise II.

Make sure you know the following words and word combinations.

Incoherent, alluring, thought-provoking, traverse, attribute, to hinge, to scramble, undue, to conceive, exuberant

Why the Many-Worlds Interpretation Has Many Problems

The idea that the universe splits into multiple realities with every measurement has become an increasingly popular proposed solution to the mysteries of quantum mechanics. But this “many-worlds interpretation” is incoherent.

It is the most extraordinary, alluring and thought-provoking of all the ways in which quantum mechanics has been interpreted. In its most familiar guise, the many-worlds interpretation (MWI) suggests that we live in a near-infinity of universes, all superimposed in the same physical space but mutually isolated and evolving independently. In many of these universes there exist replicas of you and me, all but indistinguishable yet leading other lives. The MWI illustrates just how peculiarly quantum theory forces us to think. It is an intensely controversial view. Arguments about the interpretation of quantum mechanics are noted for their passion, as disagreements that can't be settled by objective evidence are wont to be. But when the MWI is in the picture, those passions can become so extreme that we must suspect a great deal more invested in the matter than simply the resolution of a scientific puzzle. The MWI is qualitatively different from the other interpretations of quantum mechanics, although that's rarely recognized or admitted. For the interpretation speaks not just to quantum mechanics itself but to what we consider knowledge and understanding to mean in science. It asks us what sort of theory, in the end, we will demand or accept as a claim to know the world. After the Danish physicist Niels Bohr refined what became known as the Copenhagen interpretation — widely regarded as the orthodox view of quantum mechanics — in the 1930s and '40s, it seemed that the central problem for quantum mechanics was the mysterious rupture created by observation or measurement, which was packaged up into the rubric of "collapse of the wave function." The wave function is a mathematical expression that defines all possible observable states of a quantum system, such as the various possible locations of a particle. Up until a measurement is made and the wave function collapses (whatever that means), there is no reason to attribute any greater a degree of reality to any of the possible states than to any other. It's not that the quantum system is actually in one or other of these states but we don't know which; we can confidently say that it is not in any one of these states, but is properly described by the wave function itself, which in some sense "permits" them all as observational outcomes. Where, then, do they all go, when the wave function collapses? At first glance, the many-worlds interpretation looks like a delightfully simple answer to that mysterious vanishing act. It says that none of the states vanishes at all, except to our perception. This solution was proposed by the young physicist Hugh Everett III in his 1957 doctoral thesis at Princeton, where he was supervised by John Wheeler. It purported to solve the "measurement problem" using only what we know already: that quantum mechanics works. But Bohr and colleagues didn't bring wave function collapse into the picture just to make things difficult. They did it because that's what seems to happen. When we make a measurement, we really do get just one result out of the many that quantum mechanics offers. Wave function collapse seemed to be demanded in order to connect quantum theory to reality. So what Everett was saying was that it's our concept of reality that's at fault. We only think that there's a single outcome of a measurement. But in fact all of them occur. We only see one of those realities, but the others have a separate physical existence too. In effect, this implies that the entire universe is described by a gigantic wave function that contains within it all possible realities. This "universal wave function," as Everett called it in his thesis, begins as a combination, or superposition, of all possible states of its constituent particles. As it evolves, some of these superpositions break down, making certain realities distinct and isolated from one another. In this sense, worlds are not exactly "created" by measurements; they are just separated. This is why we shouldn't, strictly speaking, talk of the "splitting" of worlds (even though Everett did), as though two have been produced from one. Rather, we should speak of the unraveling of two realities that were previously just possible futures of a single reality. (The many-worlds interpretation is distinct from the multiverse hypothesis, which envisions other universes, born in separate Big Bangs, that have always been physically disconnected from our own.)

When Everett presented his thesis, and at the same time published the idea in a respected physics journal, it was largely ignored. It wasn't until 1970 that people began to take notice, after an exposition on the idea was presented in the widely read magazine Physics Today by the American physicist Bryce DeWitt. This scrutiny forced the question that Everett's thesis had somewhat skated over. If all the possible outcomes of a quantum measurement have a real existence, where are they, and why do we see (or think we see) only one? This is where the many worlds come in. DeWitt argued that the alternative outcomes of the measurement must exist in a parallel reality: another world. You measure the path of an electron, and in this world it seems to go this way, but in another world it went that way. That requires a parallel, identical apparatus for the electron to traverse. More, it requires a parallel you to observe it — for only through the act of measurement does the superposition of states seem to "collapse." Once begun, this process of duplication seems to have no end: you have to erect an entire parallel universe around that one electron, identical in all respects except where the electron went. You avoid the complication of wave function collapse, but at the expense of making another universe. The theory doesn't exactly predict the other universe in the way that scientific theories usually make predictions. It's just a deduction from the hypothesis that the other electron path is real too. This picture gets really extravagant when you appreciate what a measurement is. In one view, any interaction between one quantum entity and another — a photon of light bouncing off an atom — can produce alternative outcomes, and so demands parallel universes. As DeWitt put it, “Every quantum transition taking place on every star, in every galaxy, in every remote corner of the universe is splitting our local world on earth into myriads of copies.” In this “multiverse,” says the physicist and many-worlds proponent Max Tegmark, “all possible states exist at every instant” — meaning, at least in the popular view, that everything that is physically possible is (or will be) realized in one of the parallel universes. In particular, after a measurement takes place, there are two (or more) versions of the observer where before there was one. “The act of making a decision,” says Tegmark — a decision here counting as a measurement, generating a particular outcome from the various possibilities — “causes a person to split into multiple copies.” Both copies are in some sense versions of the initial observer, and both of them experience a unique, smoothly changing reality that they are convinced is the “real world.” At first these observers are identical in all respects except that one observed this path of the electron (or whatever is being measured) and the other that path. But after that, who can say? Their universes go their separate ways, launched on a trajectory of continual unraveling.

You can probably see why the MWI is the interpretation of quantum mechanics that wins all the glamour and publicity. It tells us that we have multiple selves, living other lives in other universes, quite possibly doing all the things that we dream of but will never achieve (or never dare to attempt). There is no path not taken. For every tragedy, there is salvation and triumph. Who could resist that idea? There are, of course, some questions to be asked. For starters, about this business of bifurcating worlds. How does a split actually happen? That is now seen to hinge on the issue of how a microscopic quantum event gives rise to macroscopic, classical behavior through a process called "decoherence," in which the wavelike states of a quantum system become uncoordinated and scrambled by their interactions with their environment. Parallel quantum worlds have split once they have decohered, for by definition decohered wave functions can have no direct, causal influence on one another. For this reason, the theory of decoherence developed in the 1970s and '80s helped to revitalize the MWI by supplying a clear rationale for what previously seemed a rather vague contingency. In this view, splitting is not an abrupt event. It evolves through decoherence and is only complete when decoherence has removed all possibility of interference between universes. It's then meaningless to ask how many worlds there are — as the philosopher of physics David Wallace aptly puts it, the question is rather like asking, "How many experiences did you have yesterday?" You can identify some of them, but you can't enumerate them. What we can say a little more precisely is what kind of phenomenon causes splitting. In short, it must happen with dizzying profusion. Just within our own bodies, there must be at least as many splitting events affecting each of us every second as there are encounters between our molecules in the same space of time. Those numbers are astronomical. The main scientific attraction of the MWI is that it requires no changes or additions to the standard mathematical representation of quantum mechanics. There is no mysterious, ad hoc and abrupt collapse of the wave function. But if we take what it says seriously, it soon becomes clear that the conceptual and metaphysical problems with quantum mechanics aren’t banished by virtue of this apparent parsimony of assumptions - far from it.

The MWI is surely the most polarizing of interpretations. Some physicists consider it almost self-evidently absurd; “Everettians,” meanwhile, are often unshakable in their conviction that this is the most logical, consistent way to think about quantum mechanics. My own view is that the problems with the MWI are overwhelming — not because they show it must be wrong, but because they render it incoherent. It simply cannot be articulated meaningfully. I’ll attempt to summarize the problems, but first, let’s dispense with a wrong objection. Some criticize the MWI on aesthetic grounds: People object to all those countless other universes, multiplying by the trillion every nanosecond, because it just doesn’t seem proper. Other copies of me? Other world histories? Worlds where I never existed? This objection is rightly dismissed by saying that an affront to one’s sense of propriety is no grounds for rejecting a theory. Who are we to say how the world should behave? A stronger objection to the proliferation of worlds is the idea that every little quantum “measurement” spawns a world gives an undue importance to the little differences generated by quantum events, as if each of them were vital to the universe. This is contrary to what we generally learn from physics: that most of the fine details make no difference at all to what happens at larger scales. But one of the most serious difficulties with the MWI is what it does to the notion of self. What can it mean to say that splittings generate copies of me? In what sense are those other copies “me?” Brian Greene, a well-known physics popularizer with Everettian inclinations, insists simply that “each copy is you.” You just need to broaden your mind beyond your idea of what “you” means. Each of these individuals has its own consciousness, and so each believes he or she is “you” — but the real “you” is their sum total. The physicist Lev Vaidman has thought rather carefully about this matter of quantum youness. “At the present moment there are many different ‘Levs’ in different worlds,” he says, “but it is meaningless to say that now there is another ‘I.’ There are, in other words, beings identical to me (at the time of splitting) in these other worlds, and all of us came from the same source — which is ‘me’ right now.” The “I” at each moment of time, he says, is defined by a complete classical description of the state of his body and brain. But such an “I” could never be conscious of its existence. Consciousness relies on experience, and experience is not an instantaneous property: It takes time, not least because the brain’s neurons themselves take a few milliseconds to fire. You can’t “locate” consciousness in a universe that is frantically splitting countless times every nanosecond, any more than you can fit a summer into a day. If consciousness — or mind, call it what you will — were somehow able to snake along just one path in the quantum multiverse, then we’d have to regard it as some nonphysical entity immune to the laws of (quantum) physics. For how can it do that when nothing else does? If the MWI sacrifices the possibility of thinking meaningfully about selfhood, we should at least acknowledge that this is so. What this boils down to is the interpretation of probabilities in the MWI. There is a huge and unresolved literature on this question, and some researchers see it as the issue on which the idea stands or falls. But much of the discussion assumes, I think wrongly, that the matter is independent of questions about the notion of selfhood. What the MWI really denies is the existence of facts at all. It replaces them with an experience of pseudo-facts (we think that this happened, even though that happened too). In so doing, it eliminates any coherent notion of what we can experience, or have experienced, or are experiencing right now. We might reasonably wonder if there is any value — any meaning — in what remains, and whether the sacrifice has been worth it. Every scientific theory (at least, I cannot think of an exception) is a formulation for explaining why things in the world are the way we perceive them to be. This assumption that a theory must recover our perceived reality is generally so obvious that it is unspoken. MWI claims to explain why it looks as though "you" are here observing that the electron spin is up, not down. But actually it is not returning us to this fundamental ground truth at all. Properly conceived, it is saying that there are neither facts nor a you who observes them. It says that our unique experience as individuals is not simply a bit imperfect and unreliable, but is a complete illusion. If we really pursue that idea, rather than pretending that it gives us quantum siblings, we find ourselves unable to say anything about anything that can be considered a meaningful truth. The MWI — if taken seriously — is unthinkable. Its implications undermine a scientific description of the world far more seriously than do those of any of its rivals.Yet I have pushed hard against the MWI not so much to try to demolish it as to show how its flaws, once brought to light, are instructive. Like the Copenhagen interpretation (which also has profound problems), it should be valued for forcing us to confront some tough philosophical questions. What quantum theory seems to insist is that at the fundamental level the world cannot supply clear “yes/no” empirical answers to all the questions that seem at face value as though they should have one. The MWI is an exuberant attempt to rescue the “yes/no” by admitting both of them at once. But in the end, if you say everything is true, you have said nothing. We needn’t fear a scientific idea that changes our view of macroscopic reality. But an idea that, when we pursue it seriously, makes that view inchoate and unspeakable doesn’t fulfill the function of science. The value of the many worlds, then, is that they close off an easy way out. It was worth admitting them in order to discover that they are a dead end. But there is no point then sitting there insisting we have found the way out. We need to go back and keep searching.

Adapted from Quanta Magazine

Exercise III.

Fill in the gaps.

1) But their explanations will be arbitrary and possibly even logically____________________.

2) They lend a false familiarity to this strange and ________________land and its culture.

3) Richard Behar certainly has written an intersting and _________________ article.

4) Juries should be sheltered from political or sensationalised ______________, they say.

5) The _______________ structure dominates the landscape in the eastern part of the city.

6) ________________ Army volunteers ring the bells to call attention to their red kettles.

7) The second ______________ is that purchasing a house remains surprisingly affordable.

8) It is not ______________, but it is much faster than what we thought previously.

9) Ultimately, city officials want to _______________ the buildings and redevelop the site.

10) How different was the response from this person who'd seen ________________ suffering.

Exercise IV.

Make up sentences of your own with the following word combinations:
to skate over, ad hoc, to split into, in its most familiar guise, be settled by objective evidence, to be packaged up into the rubric of, there is no reason to, at first glance, to make a measurement, to get just one result out of the many

Exercise V.

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

to refine	appear or claim to be or do something, esp. falsely; profess
rupture	(of a situation or event) too unlikely or undesirable to be considered a possibility
abrupt	pull or knock down (a building)

constituent	an action or remark that causes outrage or offense
rationale	not expressed in speech
affront	sudden and unexpected
unspoken	a set of reasons or a logical basis for a course of action or a particular belief
demolish	complicate: make more complex, intricate, or richer
to purport	break or burst suddenly
unthinkable	being a part of a whole

Exercise VI.

Identify the part of speech the words belong to.

peculiarly, gigantic, scrutiny, salvation, contingency, propriety, instantaneous, instructive, unspeakable, parsimony

Exercise VII.

Match the words to make word combinations:

Many-Worlds	function
wave	realities
Big	guise
multiple	space
objective	view
controversial	puzzle

physical	interpretation
familiar	evidence
multiverse	Bangs
scientific	hypothesis

Exercise VIII.

Summarize the article "Why the Many-Worlds Interpretation Has Many Problems"

4. Science Is Getting Less Bang for Its Buck

Exercise I.

Say what Russian words help to guess the meaning of the following words: progress, dominated, politics, economy, technology, civilization, public, investment, published, proportional

Exercise II.

Make sure you know the following words and word combinations.

paucity, bleak, to venerate, quadruple, intricate, rudimentary, inexhaustible, proliferation, ingenuity, incrementally

Science Is Getting Less Bang for Its Buck

Despite vast increases in the time and money spent on research, progress is barely keeping pace with the past. What went wrong?

The writer Stewart Brand once wrote that "science is the only news." While news headlines are dominated by politics, the economy, and gossip, it’s science and technology that underpin much of the advance of human welfare and the long-term progress of our civilization. This is reflected in an extraordinary growth in public investment in science: Today, there are more scientists, more funding for science, and more scientific papers published than ever before: On the surface, this is encouraging. But for all this increase in effort, are we getting a proportional increase in our scientific understanding? Or are we investing vastly more merely to sustain (or even see a decline in) the rate of scientific progress? It’s surprisingly difficult to measure scientific progress in meaningful ways. Part of the trouble is that it’s hard to accurately evaluate how important any given scientific discovery is.

Consider the early experiments on what we now call electricity. Many of these experiments seemed strange at the time. In one such experiment, scientists noticed that after rubbing amber on a cat’s fur, the amber would mysteriously attract objects such as feathers, for no apparent reason. In another experiment, a scientist noticed that a frog’s leg would unexpectedly twitch when touched by a metal scalpel. Even to the scientists doing these experiments, it wasn’t obvious whether they were unimportant curiosities, or a path to something deeper. Today, with the benefit of more than a century of hindsight, they look like epochal experiments, early hints of a new fundamental force of nature. But even though it can be hard to assess the significance of scientific work, it’s necessary to make such assessments. We need these assessments to award science prizes, and to decide which scientists should be hired or receive grants. In each case, the standard approach is to ask independent scientists for their opinion of the work in question. This approach isn’t perfect, but it’s the best system we have. With that in mind, we ran a survey asking scientists to compare Nobel prizewinning discoveries in their fields. We then used those rankings to determine how scientists think the quality of Nobel prizewinning discoveries has changed over the decades. As a sample survey question, we might ask a physicist which was a more important contribution to scientific understanding: the discovery of the neutron (the particle that makes up roughly half the ordinary matter in the universe) or the discovery of the cosmic microwave background radiation (the afterglow of the Big Bang). Think of the survey as a tournament, competitively matching discoveries against one another, with expert scientists judging which is better. For the physics prize, we surveyed 93 physicists from the world’s top academic physics departments, and they judged 1,370 pairs of discoveries.The first decade has a poor showing. In that decade, the Nobel Committee was still figuring out exactly what the prize was for. There was, for instance, a prize for a better way of illuminating lighthouses. That’s good news if you’re on a ship, but scored poorly with modern physicists. But by the 1910s the prizes were mostly awarded for things that accord with the modern conception of physics. A golden age of physics followed, from the 1910s through the 1930s. This was the time of the invention of quantum mechanics, one of the greatest scientific discoveries of all time, a discovery that radically changed our understanding of reality. It also saw several other revolutions: the invention of X-ray crystallography, which let us probe the atomic world; the discovery of the neutron and of antimatter; and the discovery of many fundamental facts about radioactivity and the nuclear forces. It was one of the great periods in the history of science.

Following that period, there was a substantial decline, with a partial revival in the 1960s. That was due to two discoveries: the cosmic microwave background radiation, and the standard model of particle physics, our best theory of the fundamental particles and forces making up the universe. Even with those discoveries, physicists judged every decade from the 1940s through the 1980s as worse than the worst decade from the 1910s through 1930s. The very best discoveries in physics, as judged by physicists themselves, became less important. Our graph stops at the end of the 1980s. The reason is that, in recent years, the Nobel Committee has preferred to award prizes for work done in the 1980s and 1970s. In fact, just three discoveries made since 1990 have yet been awarded Nobel Prizes. This is too few to get a good quality estimate for the 1990s, and so we didn't survey those prizes. However, the paucity of prizes since 1990 is itself suggestive. The 1990s and 2000s have the dubious distinction of being the decades over which the Nobel Committee has most strongly preferred to skip back and award prizes for earlier work. Given that the 1980s and 1970s themselves don't look so good, that's bad news for physics. Many reasonable objections can be leveled at our survey. Maybe the surveyed physicists are somehow biased, or working with an incomplete understanding of the prizewinning discoveries. As discussed earlier, it's hard to pin down what it means for one discovery to be more important than another. And yet, scientists' judgments are still the best way we have to compare discoveries. Even if physics isn't doing so well, perhaps other fields are doing better? We carried out similar surveys for the Nobel Prize for chemistry, and the Nobel Prize for physiology or medicine. The results are slightly more encouraging than physics, with perhaps a small improvement in the second half of the 20th century. But it is small. As in physics, the 1990s and 2000s are omitted, because the Nobel Committee has strongly preferred earlier work: Fewer prizes were awarded for work done in the 1990s and 2000s than over any similar window in earlier decades.

The picture this survey paints is bleak: Over the past century we've vastly increased the time and money invested in science. On a per-dollar or per-person basis, this suggests that science is becoming far less efficient. Now, a critic might respond that the quality of Nobel Prize discoveries isn't the same as the overall rate of progress in science. There are certainly many limitations of this measure. Parts of science are not covered by the Nobel Prizes, especially newer areas like computer science. The Nobel Committee occasionally misses important work. Perhaps some bias means scientists are more likely to venerate older prizes. And perhaps what matters more is the bulk of scientific work, the ordinary discoveries that make up most of science. We recognize these limitations: The survey results are striking, but provide only a partial picture. However, we'll soon see supporting evidence suggesting that it's getting much harder to make important discoveries across the board. It's requiring larger teams, far more extensive scientific training, and the overall economic impact is getting smaller. Taken together, these results suggest diminishing returns to our scientific efforts. When we report these diminishing returns to colleagues, they sometimes tell us that this is nonsense, and insist that science is going through a golden age. They point to amazing recent discoveries, such as the Higgs particle and gravitational waves, as evidence that science is in better shape than ever. These are, indeed, astonishing discoveries. But previous generations also made discoveries that were equally, if not more, remarkable. Compare, for example, the discovery of gravitational waves to Einstein's 1915 discovery of his general theory of relativity. Not only did general relativity predict gravitational waves, it also radically changed our understanding of space, time, mass, energy, and gravity. The discovery of gravitational waves, while enormously technically impressive, did much less to change our understanding of the universe. And while the discovery of the Higgs particle is remarkable, it pales beside the pantheon of particles discovered in the 1930s, including the neutron, one of the main constituents of our everyday world, and the positron, also known as the antielectron, which first revealed the shadowy world of antimatter. In a sense, the discovery of the Higgs particle is remarkable because it's a return to a state of affairs common in the first half of the 20th century, but rare in recent decades.

Another common response is from people who say science is in better shape than ever because their own field is making great progress. We hear this most often about artificial intelligence (AI) and the CRISPR gene-editing technology in biology. But while AI, CRISPR, and similar fields are certainly moving fast, there have always been fields just as hot or hotter through the entire history of modern science. Consider the progress of physics between 1924 and 1928. Over that time, physicists learned that the fundamental constituents of matter have both a particle and a wave nature; they formulated the laws of quantum mechanics, leading to

Heisenberg's uncertainty principle; they predicted the existence of antimatter; and many other things besides. As one of the leading protagonists, Paul Dirac, said, it was a time when "even second-rate physicists could make first-rate discoveries." For comparison, major discoveries in AI over the past few years include an improved ability to recognize images and human speech, and the ability to play games such as Go better than any human. These are important results, and we're optimistic work in AI will have huge impact in the decades ahead. But it has taken far more time, money, and effort to generate these results, and it's not clear they're more significant breakthroughs than the re-ordering of reality uncovered in the 1920s. Similarly, CRISPR has seen many breakthroughs over the past few years, including the modification of human embryos to correct a genetic heart disorder, and the creation of mosquitoes which can spread genes for malaria resistance through entire mosquito populations. But while such laboratory proofs-of-principle are remarkable, and the long-run potential of CRISPR is immense, such recent results are no more impressive than those of past periods of rapid progress in biology.

Why has science gotten so much more expensive, without producing commensurate gains in our understanding? A partial answer to this question is suggested by work done by the economists Benjamin Jones and Bruce Weinberg. They've studied how old scientists are when they make their great discoveries. They found that in the early days of the Nobel Prize, future Nobel scientists were 37 years old, on average, when they made their prizewinning discovery. But in recent times that has risen to an average of 47 years, an increase of about a quarter of a scientist's working career. Perhaps scientists today need to know far more to make important discoveries. As a result, they need to study longer, and so are older, before they can do their most important work. That is, great discoveries are simply getting harder to make. And if they're harder to make, that suggests there will be fewer of them, or they will require much more effort. In a similar vein, scientific collaborations now often involve far more people than a century ago. When Ernest Rutherford discovered the nucleus of the atom in 1911, he published it in a paper with just a single author: himself. By contrast, the two 2012 papers announcing the discovery of the Higgs particle had roughly a thousand authors each. On average, research teams nearly quadrupled in size over the 20th century, and that increase continues today. For many research questions, it requires far more skills, expensive equipment, and a large team to make progress today.

If it's true that science is becoming harder, why is that the case? Suppose we think of science—the exploration of nature—as similar to the exploration of a new continent. In the early days, little is known. Explorers set out and discover major new features with ease. But gradually they fill in knowledge of the new continent. To make significant discoveries explorers must go to ever-more-remote areas, under ever-more-difficult conditions. Exploration gets harder. In this view, science is a limited frontier, requiring ever more effort to "fill in the map." One day the map will be near-complete, and science will largely be exhausted. In this view, any increase in the difficulty of discovery is intrinsic to the structure of scientific knowledge itself.An archetype for this point of view comes from fundamental physics, where many people have been entranced by the search for a "theory of everything," a theory explaining all the fundamental particles and forces we see in the world. We can only discover such a theory once. And if you think that’s the primary goal of science, then it is indeed a limited frontier. But there’s a different point of view, a point of view in which science is an endless frontier, where there are always new phenomena to be discovered, and major new questions to be answered. The possibility of an endless frontier is a consequence of an idea known as emergence. Consider, for example, water. It’s one thing to have equations describing the way a single molecule of water behaves. It’s quite another to understand why rainbows form in the sky, or the crashing of ocean waves, or the origins of the dirty snowballs in space that we call comets. All these are “water,” but at different levels of complexity. Each emerges out of the basic equations describing water, but who would ever have suspected from those equations something so intricate as a rainbow or the crashing of waves? The mere fact of emergent levels of behavior doesn’t necessarily imply there will be a never-ending supply of new phenomena to be discovered, and new questions to be answered. But in some domains it seems likely. Consider, for example, that computer science began in 1936 when Alan Turing developed the mathematical model of computation we now call the Turing machine. That model was extremely rudimentary, almost like a child’s toy. And yet the model is mathematically equivalent to today’s computer: Computer science actually began with its “theory of everything.” Despite that, it has seen many extraordinary discoveries since, ideas such as the cryptographic protocols that underlie internet commerce and cryptocurrencies; the never-ending layers of beautiful ideas that go into programming language design; even, more whimsically, some of the imaginative ideas seen in the very best video games. These are the rainbows and ocean waves and comets of computer science. What's more, our experience of computing so far suggests that it really is inexhaustible, that it's always possible to discover beautiful new phenomena, new layers of behavior which pose fundamental new questions, and give rise to new fields of inquiry. Computer science appears to be open-ended. In a similar way, it's possible new frontiers will continue to open up in biology, as we gain the ability to edit genomes, to synthesize new organisms, and better understand the relationship between an organism's genome and its form and behavior. Something similar may happen in physics and chemistry too, with ideas such as new designer phases of matter. In each case new phenomena pose new questions, in what may be an open-ended way. So the optimistic view is that science is an endless frontier, and we will continue to discover and even create entirely new fields, with their own fundamental questions. If we see a slowing today, it is because science has remained too focused on established fields, where it's becoming ever harder to make progress. We hope the future will see a more rapid proliferation of new fields, giving rise to major new questions. This is an opportunity for science to accelerate.

If science is suffering diminishing returns, what does that mean for our long-term future? Will there be fewer new scientific insights to inspire new technologies of the kind which have so reshaped our world over the past century? In fact, economists see evidence this is happening, in what they call the productivity slowdown. Roughly speaking, a worker's productivity is the ingenuity with which things are made. So productivity grows when we develop technologies and make discoveries that make it easier to make things. Productivity growth is a sign of an economically healthy society, one continually producing ideas that improve its ability to generate wealth. The bad news is that U.S. productivity growth is way down. It’s been dropping since the 1950s, when it was roughly 6 times higher than today. That means we see about as much change over a decade today as we saw in 18 months in the 1950s. That may sound surprising. Haven’t we seen many inventions over the past decades? Isn’t today a golden age of accelerating technological change? Not so, argue economists Tyler Cowen and Robert Gordon. In their books *The Great Stagnation* and *The Rise and Fall of American Growth*, they point out that the early part of the 20th century saw the large-scale deployment of many powerful general-purpose technologies: electricity, radio, telephones, air travel and many more. By contrast, they marshal economic data suggesting that things haven’t changed nearly as much since the 1970s. Yes, we’ve had advances associated to two powerful general-purpose technologies: the computer and the internet. But many other technologies have improved only incrementally. Think, for example, about the way automobiles, air travel, and the space program transformed our society between 1910 and 1970, expanding people’s experience of the world. By 1970 these forms of travel had reached something close to their modern form, and ambitious projects such as the Concorde and the Apollo Program largely failed to expand transportation further. Perhaps technologies like self-driving cars will lead to dramatic changes in transport in the future. But recent progress in transport has been incremental when compared to the progress of the past.

What's causing the productivity slowdown? The subject is controversial among economists, and many different answers have been proposed. Some have argued that it's merely that existing productivity measures don't do a good job measuring the impact of new technologies. Our argument here suggests a different explanation, that diminishing returns to spending on science are contributing to the productivity slowdown. We aren't the first to suggest scientific discovery is showing diminishing returns. In 1971 the distinguished biologist Bentley Glass wrote an article in Science arguing that the glory days of science were over, and the most important discoveries had already been made: "It's hard to believe, for me, anyway, that anything as comprehensive and earthshaking as Darwin's view of the evolution of life or Mendel's understanding of the nature of heredity will be easy to come by again." In the book The End of Science, the science writer John Horgan interviewed many leading scientists, and asked them about prospects for progress in their own fields. What he found was not encouraging. Here, for instance, is Leo Kadanoff, a leading theoretical physicist, on recent progress in science: "The truth is, there is nothing—there is nothing—of the same order of magnitude as the accomplishments of the invention of quantum mechanics or of relativity. Just nothing like that has happened in the last few decades." But while many individuals have raised concerns about diminishing returns to science, there has been little institutional response. The problem of diminishing returns is mentioned nowhere in the 2018 report of the National Science Foundation, which instead talks optimistically of “potentially transformative research that will generate pioneering discoveries and advance exciting new frontiers in science.” Of course, many scientific institutions—particularly new institutions—do aim to find improved ways of operating in their own fields. But that’s not the same as an organized institutional response to diminishing returns.

Perhaps this lack of response is in part because some scientists see acknowledging diminishing returns as betraying scientists’ collective self-interest. Most scientists strongly favor more research funding. They like to portray science in a positive light, emphasizing benefits and minimizing negatives. While understandable, the evidence is that science has slowed enormously per dollar or hour spent. That evidence demands a large-scale institutional response. It should be a major subject in public policy, and at grant agencies and universities. Better understanding the cause of this phenomenon is important, and identifying ways to reverse it is one of the greatest opportunities to improve our future.

Adapted from The Atlantic

Exercise III.

Fill in the gaps.

1) Lead levels can also build up as water sits ____________ over weekends and holidays.

2) Reforms to ________________ this new model are slow and hampered with vested interests.

3) Despite the setback, the results of research into exon skipping are ________________.

4) ______________aside, it was the most difficult thing anyone has ever asked me to do.

5) They ______________ great individuals without understanding that not everyone is great.

6) I am not convinced that a raised retirement age _________________is a good idea.

7) The Kingdom of Bhutan is in the midst of an ___________________ cultural transformation.

8) The quake drew a _________________ emergency response from the international community.

9) If cold fusion worked, it could provide an ______________ supply of clean energy.

10) Nuclear _________________ has not gone as far or as fast as was feared in the 1960s.

Exercise IV.

Make up sentences of your own with the following word combinations: to skip back, to level at, across the board, to keep pace with the past, to be dominated by, to underpin much of the advance of human welfare, long-term progress, to be reflected in, to get a proportional increase in scientific understanding, in meaningful ways

Exercise V.

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

stagnant	extremely surprising or impressive; amazing
to underpin	understanding of a situation or event only after it has happened or developed
remarkable	forming or characterizing an epoch; epoch-making

to twitch	tending to suggest an idea
hindsight	complete; including all or nearly all elements or aspects of something
epochal	give or cause to give a short, sudden jerking or convulsive movement
suggestive	support (a building or other structure) from below by laying a solid foundation below ground level or by substituting stronger for weaker materials
comprehensive	having no current or flow and often having an unpleasant smell as a consequence
astonishing	worthy of attention; striking

Exercise VI.

Identify the part of speech the words belong to: writer, technology , civilization, investment, scientists, scientific, proportional, difficult, meaningful, accurately

Exercise VII.

Match the words to make word combinations:

Nobel	reason
background	leg
survey	increase

standard	papers
metal	progress
frog’s	prizewinning
proportional	radiation
scientific	question
long-term	approach
apparent	scalpel

Exercise VIII .

Summarize the article “Science Is Getting Less Bang for Its Buck.”

SUPPLEMENTARY READING

Thus spake Albert

You probably know a quote from him. He probably never said it. How did Einstein become a touchstone of all that is wise?

In late 2017, a sheet of paper bearing a 13-word sentence in German in the original handwriting of Albert Einstein went on sale at an auction house in Jerusalem. The city is home to the archives of Einstein, which he willed before his death in 1955 to the Hebrew University, the institution that he helped to found in the 1920s. The Albert Einstein Archives now contain some 30,000 documents. Several times the size of Galileo Galilei's and Isaac Newton's archives, they rival the archives of Napoleon Bonaparte. However, the provenance of this particular paper had nothing to do with the Archives, despite a copy of it being held in the collection. It was decidedly more intriguing.

The paper was inscribed and autographed in Japan on the stationery of the Imperial Hotel in Tokyo and dated November 1922, the month in which Einstein was awarded the Nobel Prize in Physics. He stayed at this hotel during his massively popular lecture tour of Japan, when he attracted even more attention than the Japanese imperial family. Apparently somewhat embarrassed by such frenetic publicity, Einstein decided to record some of his thoughts and feelings about life in writing. He gave this particular sentence (and another shorter one) to a Japanese delivery courier, either because the courier refused to accept a tip, in keeping with local practice, or because Einstein had no small change. 'Maybe if you're lucky those notes will become much more valuable than just a regular tip,' Einstein apparently told the unnamed Japanese courier, according to the document's seller, reported by the BBC to be the courier's nephew.

The Jerusalem auction house estimated that the note would sell for between $5,000 and $8,000. Bidding started at $2,000. For about 20 minutes, a flurry of offers pushed up the price rapidly, until the final two bidders vied for the trophy by telephone. By the end, the price had risen to a scarcely believable $1.56 million.

Translated into English, Einstein's sentence reads: 'A calm and modest life brings more happiness than the pursuit of success combined with constant restlessness.' The absurdity of this auction would not have been lost on Einstein, were he still with us. During the second half of his life, following the British-led astronomical confirmation of his theory of general relativity in 1919, he was unfailingly puzzled by his celebrity and uninterested in amassing money for its own sake. He was happiest when left alone with his mathematical calculations or with a select handful of fellow physicists and mathematicians – in Zurich, Berlin, Oxford, Pasadena and Princeton. On the long sea journey from Europe to Japan and back, he loved to retreat into his cabin and scribble mathematical equations.

As Einstein wrote of his celebrity in a preface intended for a biography of himself, written by the physicist Philipp Frank: I never understood why the theory of relativity with its concepts and problems so far removed from practical life should for so long have met with a lively, or indeed passionate, resonance among broad circles of the public … I have never yet heard a truly convincing answer to this question.

And, as he mused on the meaning of life to Life magazine just before his death in 1955: Try not to become a man of success but rather try to become a man of value. He is considered successful in our day who gets more out of life than he puts in. But a man of value will give more than he receives.

Einstein's death was universally covered. The New York Times carried tributes from the presidents of the United States and West Germany, and the prime ministers of Israel, France and India. Prominent intellectuals who had known Einstein personally chimed with the politicians. 'For all scientists and most men, this is a day of mourning. Einstein was one of the greats of all ages,' stated J Robert Oppenheimer, the US physicist who had directed the building of the atomic bomb in the Second World War. The Danish physicist Niels Bohr, who had disagreed with Einstein over quantum theory, wrote: The gifts of Einstein are in no way confined to the sphere of science. Indeed, his recognition of hitherto unheeded assumptions in even our most elementary and accustomed assumptions means to all people a new encouragement in tracing and combating the deep-rooted prejudices and complacencies in every national culture.

According to the British philosopher Bertrand Russell: Einstein was not only a great scientist, he was a great man. He stood for peace in a world drifting towards war. He remained sane in a mad world, and liberal in a world of fanatics.

Today, Einstein is history's most-quoted scientist: way ahead of Aristotle, Galileo, Newton, Charles Darwin and Stephen Hawking, judging by the number of Einstein quotations in his online entry on Wikiquote – and way ahead of his 20th-century non-scientist contemporaries Winston Churchill, George Orwell and George Bernard Shaw. Let me quote from The Ultimate Quotable Einstein (2010), published by Princeton University Press, the publisher of Einstein's ongoing Collected Papers – an anthology now in its fourth and officially final edition: 'There appears to be a bottomless pit of quotable gems to be mined from Einstein's enormous archives,' remarks the book's editor, Alice Calaprice, in her introduction.

Unsurprisingly, Einstein is quoted as an authority on science. For example: 'The most incomprehensible thing about the Universe is that it is comprehensible.' But he is more frequently quoted on a wide variety of non-scientific subjects, including education, intelligence, politics (he was offered the presidency of Israel in 1952), religion, marriage, money and music-making. On education we get: 'Education is what remains after you have forgotten everything you learned in school.' On intelligence: 'The difference between genius and stupidity is that genius has its limits.' On politics: 'Insanity is doing the same thing over and over again and expecting different results.' On religion: 'God does not play dice.' On marriage: 'Men marry women with the hope they will never change. Women marry men with the hope they will change. Invariably they are both disappointed.' On money: 'Not everything that can be counted counts, and not everything that counts can be counted.' On music: 'Death means that one can no longer listen to Mozart.' And on life in general: ‘Things should be made as simple as possible but not any simpler.’ The last of these quotations recently filled an entire page of an in-house advertisement in Nature, where it was intended to promote the magazine’s news coverage of science as being neither specialised nor sensationalised. All of the quotations have appeared, and reappeared, in the world’s leading newspapers, and are extensively disseminated online.

But here we are making an assumption. Did Einstein definitely say or write the above statements? Judging by the detective work on display in The Ultimate Quotable Einstein, on Wikiquote and on QuoteInvestigator.com, plus my own research as an Einstein biographer, there is ample room for doubt. In fact, not a single one of the above quotations has been definitely attributed to Einstein, with the exception of ‘God does not play dice’! And even this is a pithy rendition of Einstein’s precise comment on quantum theory, in a 1926 letter to the physicist Max Born, where he wrote (in German): ‘The theory says a lot, but does not bring us any closer to the secrets of the “old one”. I, at any rate, am convinced that He is not playing at dice.’

Another statement: ‘If the facts don’t fit the theory, change the facts.’ This has been widely attributed to Einstein, including by Ivanka Trump, who Tweeted it and generated a brouhaha on the internet in 2017 by seeming to weigh in on the controversy over ‘fake news’ stirred by her father, President Donald Trump. Einstein might have been sympathetic to the statement’s underlying idea. In a well-known exchange with a student who, in 1919, following the confirmation of general relativity, asked: what if the astronomical facts had contradicted the theory? Einstein replied: ‘In that case, I’d have felt sorry for God, because the theory is correct’. But there is no record of Einstein’s making such a categorical statement in speech or in writing. Similar comments about facts and theories date from the 19th century; and this particular statement was not attributed to Einstein until 1991, in The Art of Computer Systems Performance Analysis by Raj Jain – and then without any source.

Now consider a statement prominently attributed to Einstein in the concluding section of a current British Museum exhibition on religion, ‘Living with Gods’: ‘The most beautiful and profound experience is the sensation of the mystical. It is the sower of all true science.’ Absent from The Ultimate Quotable Einstein, it seems to have been derived in the decades after Einstein’s death from the following comment, in his handwriting, spoken by him in 1932 for a recording issued by the German League for Human Rights. Translated from Einstein’s original German it reads: ‘The most beautiful and profound experience is the feeling of mystery. It underlies religion as well as all deeper aspirations in art and science.’ Note the most significant modification: ‘mystery’ in 1932 has become ‘mystical’ by 2018.

In other words, quotations from Einstein vary vastly in authenticity. Many can be traced to his writings; some are based on the recollections of those who knew him well; some have mutated over time; some resemble his thinking, or seem consistent with his personal behaviour but are not really his. And a number are simply bogus, invented to take advantage of his reputation as a genius and iconoclast – one being a notorious Einstein quotation apparently embracing astrology as ‘science’. As Calaprice observes: ‘Some sound genuine, some are apocryphal, and others are no doubt fakes, created by those who wanted to use Einstein’s name to lend credibility to a cause or an idea.’

So why are we still fascinated enough by Einstein to embroider, and even manufacture, extensive quotations from him? The answer must be as diverse, complex and unique as the man and his life, but is surely rooted in Einstein’s scientific genius. Consider this irresistible anecdote about Einstein, caught in the late 1930s in the very act of thinking, and recalled by one of his physicist assistants, Banesh Hoffmann: When it became clear, as it often did, that even resorting to German did not solve the problem, we would all pause, and then Einstein would stand up quietly and say, in his quaint English: ‘I vill a little t’ink.’ So saying, he would pace up and down or walk around in circles, all the time twirling a lock of his long, greying hair around his forefinger … A minute would pass in this way and another, and Infeld [another assistant] and I would eye each other silently while Einstein continued pacing and all the time twirling his hair. There was a dreamy, far-away, and yet sort of inward look on his face. There was no appearance at all of intense concentration. Another minute would pass and another, and then all of a sudden Einstein would visibly relax and a smile would light up his face. No longer did he pace and twirl his hair. He seemed to come back to his surroundings and to notice us once more, and then he would tell us the solution to the problem and almost always the solution worked.

It is easy to understand Einstein’s profound appeal to scientists. In its special issue on Einstein for the centenary of special relativity, Scientific American estimated that two-thirds of the ‘crackpot missives’ sent to scientists and science magazines relate to Einstein’s theories. Either the writer claims to have found a unified theory of gravity and electromagnetism, where Einstein failed, or the claim is to have proved Einstein’s ideas, especially relativity, wrong. (The other third of the missives concern perpetual-motion machines and infinite-energy sources.)

But there must be much more to Einstein’s appeal, which goes far beyond the world of science, than his great thinking power. In 2005, Arthur C Clarke – whose own writings and personality reached well beyond readers and cinemagoers who like science fiction – put Einstein’s enduring global fame down to ‘the unique combination of genius, humanist, pacifist and eccentric’. While Newton, for example, is a household name, how many advertisers would think to use his image – as they frequently do Einstein’s – to promote a product for the general public, except perhaps apples? No politician is likely to drop Newton’s name in a speech, and Newton is seldom quoted outside a scientific context. Of course, Newton biographies continue to be written, but Newton does not pop up in newspaper headlines, cartoons and ordinary conversation. There are only a handful of well-known anecdotes about Newton, and no Newton jokes. One cannot imagine a popular book entitled ‘The Quotable Newton’.

Newton is celebrated for his scientific achievements, for which all subsequent physicists, especially Einstein, have continued to revere him. But after Newton departed Cambridge and moved to London, in 1696, he left behind not a single friend in the place where he had spent 35 years and done his revolutionary work; there is not one surviving letter written by him to any of his Cambridge acquaintances between 1696 and his death in 1727. His successor as Lucasian professor of mathematics, William Whiston, wrote of Newton in his memoirs (long after his patron's death): 'He was of the most fearful, cautious and suspicious temper that I ever knew.' As Jacob Bronowski rightly said in his book The Ascent of Man (1973): 'Newton is the Old Testament god; it is Einstein who is the New Testament figure … full of humanity, pity, a sense of enormous sympathy.'

Einstein and Newton shared a great deal in their scientific work, but had very little in common as human beings. For all Einstein's skepticism about personal relationships and institutional life, his two unsuccessful marriages and family tragedies (his second son, Eduard, spent his last three decades in a Swiss mental hospital), he was frequently highly sociable. He was a regular public speaker, kept up a vast correspondence with friends, colleagues and strangers, and made constant efforts to help scientific 'rivals' and newcomers – for example, the then-unknown Indian mathematician Satyendra Nath Bose, with whom he created Bose-Einstein statistics.

Unlike Newton, Einstein's disagreements over science and all other matters – except anti-Semitism and Nazism – were conducted without polemic, and usually without rancour. There is no malice even in his long and inconclusive battle with Bohr over quantum theory. Einstein hit hard but not in order to wound. Arguing with his close friend Born on the same subject in the 1940s and '50s, the closest Einstein came to an ad hominem attack was the sardonic comment: 'Blush, Born, blush!'

In addition, almost all the public causes that Einstein supported were admirable and far-sighted. Many required moral courage. He stood up to be counted – and attacked – against anti-Semitism, segregation and the lynching of black people in the US; against the witch-hunts of McCarthyism, the build-up of the military-industrial complex, and against the drift towards nuclear war, at a time when few of these causes was either fashionable or 'respectable'. Instead of basking in his fame and enjoying himself with physics, music and sailing, Einstein fought oppression wherever he thought his name and reputation might have a desirable impact. One cannot say that his various interventions were decisive, but there is ample testimony that he gave hope to the persecuted and influenced public debate. The very fact that J Edgar Hoover, director of the FBI, was determined to 'get' Einstein as a Communist sympathiser in 1950-55 shows just how seriously Einstein's activism was taken by reactionary forces.

It's worth noting that Einstein was himself inspired by Mahatma Gandhi, and he shared Gandhi's indifference to material success – though he rejected Gandhi's view that civil disobedience could be weaponised against the Nazis. In 1952, Einstein called Gandhi 'the greatest political genius of our time'. Gandhi proved 'of what sacrifice man is capable once he has discovered the right path. His work on behalf of India's liberation is living testimony to the fact that man's will, sustained by an indomitable conviction, is more powerful than material forces that seem insurmountable.' Einstein's answer to religion, which was tantamount to sacralising the scientific endeavour, has been taken seriously across the religious spectrum. In 2004, the biologist and militant atheist Richard Dawkins wrote that: Einstein was profoundly spiritual, but he disowned supernaturalism and denied all personal gods … I gladly share his magnificently godless spirituality. No theist should presume to give Einstein lessons in spirituality.

The physicist Hawking revealed a similar outlook to Einstein's when he wrote in 1984: It would be perfectly consistent with all we know to say that there was a Being who was responsible for the laws of physics. However, I think it could be misleading to call such a Being 'God', because this term is normally understood to have personal connotations which are not present in the laws of physics.

And Pope John Paul II, speaking in 1979 on the centenary of Einstein's birth to a meeting of the Pontifical Academy of Sciences, said he was: Filled with admiration for the genius of the great scientist, in whom is revealed the imprint of the creative spirit, without intervening in any way with a judgment on the doctrines concerning the great systems of the Universe, which is not in her power to make, the Church nevertheless recommends these doctrines for consideration by theologians in order to discover the harmony that exists between scientific truth and revealed truth.

How much do artists revere him? During Einstein's lifetime, Max Brod – Franz Kafka's literary executor – wrote a novel, his most famous work,Tycho Brahe's Path to God (1915), in which the character of Kepler was closely based on Einstein, whom Brod came to know in Prague in 1911-12. Brod commented that Einstein 'time and again filled me with amazement, and indeed enthusiasm, as I watched the ease with which he would, in discussion, experimentally change his point of view, at times tentatively adopting the opposite view, and viewing the whole problem from a new and totally changed angle'. William Carlos Williams, E E Cummings and the Czech writer Karel Čapek, have all mentioned Einstein in their works. In Bertolt Brecht's play Life of Galileo (1943), Brecht called himself the 'Einstein of the new theatrical form'. Since Einstein's death, he has made notable appearances in Friedrich Dürrenmatt's play The Physicists (1962), Philip Glass's opera Einstein on the Beach (1976), and in the physicist Alan Lightman's novel Einstein's Dreams (1992).

As for the more subtle influences of Einstein's ideas on artists, attempts have been made to link him with the works of, among other modernist writers who use multiple viewpoints, T S Eliot, Virginia Woolf and Lawrence Durrell. But as the authors of the study Einstein as Myth and Muse (1985) admit, there is no clinching evidence. Referring to Durrell's Alexandria Quartet (1957-60), Alan Friedman and Carol Donley comment honestly: 'Simply because writers say they are using relativity … does not mean either that they understand it or that their adaptations of relativity principles succeed artistically.' By the same token, the historian of science Arthur Miller's book-length study Einstein, Picasso: Space, Time, and the Beauty that Causes Havoc (2001) tries to link relativity with cubism, arguing that Einstein, like Pablo Picasso, was motivated to undermine the understanding of reality that constituted classicism. This, in spite of there being ample evidence that Einstein's tastes in the arts were largely classical.

It is tempting to recall here Einstein's comment on the philosophers of relativity: 'the less they know about physics, the more they philosophise'. And perhaps also the physicist Paul Dirac's unintentionally amusing warning about trying to link science and art: 'In science, one tries to tell people, in such a way as to be understood by everyone, something that no one ever knew before. But in poetry, it's the exact opposite.'

The phenomenon of Einstein misquotation is largely driven by an all-too-human desire for mystification and for authority figures, epitomised by the two words 'iconic' and 'genius'. When relativity first became popular in the 1920s, many people assumed that Einstein could be cited to the effect that everything is relative, including truth; that all observations are subjective; and that anything is possible. 'I like quoting Einstein,' as the Jewish-American author, historian and broadcaster Studs Terkel declared with a grin in an interview with The Guardian on his 90th birthday in 2002. 'Know why? Because nobody dares contradict you.' Terkel's quip is especially ironic, given Einstein's lifelong distrust of authority – particularly in physics, education or politics. But even here, Einstein commands the last word. In an authentic aphorism for an unnamed friend, he wrote in 1930: 'To punish me for my contempt of authority, Fate has made me an authority myself.'

Adapted from Aeon

Curving the Universe

A century ago, a team of scientists chased the arc of starlight across a total eclipse to prove Einstein right on relativity

Usually, when scientists test a theory, they get everything nicely under control. But in 1919, as the First World War was drawing down, the British astronomer and physicist Sir Arthur Stanley Eddington did not have that luxury. He was going to test Albert Einstein's theory of relativity at a solar eclipse thousands of miles from the nearest precision laboratory. This was not easy. 'In journeying to observe a total eclipse of the Sun, the astronomer quits the usually staid course of his work and indulges in a heavy gamble with fortune,' wrote the young Eddington. For him, treacherous weather and war made true control even more difficult to attain.

Einstein's situation was unstable as well. Berlin, his scientific space, was increasingly messy. His lectures on relativity were postponed because the university lacked coal to heat the lecture hall. Temporarily in Zurich to deliver lectures, Einstein found a lack of interest there too; only 15 students registered to hear him speak about relativity – and the university cancelled the event.

Back in Berlin, it was hard to know that the war was over, and there would be no true peace until the warring countries could agree upon a binding treaty. The negotiations involved setting up the League of Nations, as well as dividing Africa and the Middle East into new colonial possessions. As the scientists pursued their work, victorious empires gobbled up ever more of the world.

Those new imperial boundaries were of huge importance to astronomers planning solar-eclipse expeditions for May 1919. The first step for Eddington and his fellow physicist, the Astronomer Royal Frank Watson Dyson, was simply to figure out where and when the eclipse would be visible. The zone of totality – the place from which the Moon completely blocks the Sun – is typically some miles wide, but the eclipse is visible only for minutes (if one is lucky). The shadow of the Moon hurtles across the surface of the Earth at more than 1,000 miles per hour, and astronomers need to be in the right place at the right time with their telescopes and cameras. The path of totality was an arc across the Southern Hemisphere from Africa to South America. Many factors entered into the choice of where to make the observations: did the location have a reputation for good weather? How low in the sky would the eclipse be? Were there nearby steamship and railway networks to carry the astronomers and their heavy equipment? Was a telegraph station close by?

Dyson and Eddington ultimately decided that there were two locales – each would have about five minutes of totality – that best met all these conditions, one on each side of the Atlantic. Sobral, a city 80 miles inland in Brazil, was on the rail lines. It was not quite in the centre of the path, so totality would be a few seconds shorter. But the logistical advantages more than made up for that. Word was that the rainy season would be over by May, though no one was sure.

The other observation site was Príncipe, an island 110 miles off the west coast of Africa just north of the equator. It was under Portuguese imperial possession and known for its cocoa exports. The chocolate industry meant both that it was served by a fortnightly steamer from Lisbon, and that there was likely European-style infrastructure there. Its isolation in the ocean was a positive feature – being surrounded by water meant more stable temperatures throughout the day and easy sight-lines to the horizon.

Dyson had been given £1,000 for travel costs in 1918 (about $75,000 today). During wartime, that was an enormous grant – he decided he could stretch that money to cover expeditions to both sites, important insurance against bad weather or other mishap, dramatically increasing the chance of success.

Eddington would go to Príncipe, accompanied by Edwin T Cottingham, a clockmaker who had worked for years with both Dyson and Eddington maintaining the timepieces at their observatories. Meanwhile, the observations in Sobral were conducted by Charles Davidson, who had a reputation as an absolute wizard with mechanical devices and scientific instruments. Dyson trusted him implicitly to make any mechanism work properly.

The equipment that Davidson had been preparing included three carefully chosen telescopes. Eddington needed crisp images of stars, not something that eclipse-observers usually look for. So the teams decided to use astrographic telescopes – specially designed to capture precise, faint images. Dyson tried to secure two telescopes of this sort that had been used at previous eclipses. One mounted in

Greenwich was easily acquired. The other was at the Oxford observatory overseen by H H Turner, the most vocal anti-German astronomer in the country. We do not know how Dyson persuaded Turner to contribute this valuable instrument to Einstein-centric expeditions, but somehow he succeeded.

Even with the right equipment, in 1919 these measurements were outrageously complicated. Because the Earth rotates, the eclipsed Sun and the stars appear to move across the sky. Even over the course of just a few seconds, this apparent motion will blur the images on the photograph. One solution to this problem is to mount the telescope on a pivot and slowly turn it to match the Earth's movement. But this is not a very good solution for an expedition – telescopes are heavy and large, and very difficult to move without shaking or bending, which would ruin the image. The traditional answer was to use a coelostat, a kind of 'clockwork mirror' that Eddington had used in the past.

The telescope would be laid horizontally, nicely stable. The lens of the telescope would be pointed at the coelostat mirror, which would then be adjusted so that the image of the Sun would fall in the middle of the camera. Then the mirror could be turned smoothly during the eclipse to keep the image centred without blurring.

Greenwich had a set of these coelostats that had been used for many previous expeditions. Unfortunately, they were old and unreliable. Normally, overhauling them would be a straightforward, if tedious, process, but the early preparations for the expeditions were happening during wartime, and a 'priority certificate' from the Ministry of Munitions was required to get any precision work done. So, as a backup, the researchers brought along some small, four-inch telescopes – just in case.

The expeditions were not passive attempts to look for something interesting during the eclipse. Their goal was to test a specific prediction of Einstein's theory of relativity. Einstein had said, let's look at a star that appears to be just at the edge of the Sun's disk (the star was actually trillions of miles away, it just happened to line up with the edge). The image of that star is being carried to us by a ray of light. As that light passes by the Sun, the curvature of space-time there (created by the Sun's gravity) will bend that ray of light. To an observer on Earth looking at the star's image, the bending means that the image will be shifted slightly from its original location. General relativity predicted the exact angle between where the star should be when the Sun's gravity was not in the way, and where it appeared to be when the Sun's gravity was. That angle was measured in arc-seconds (one-60th of one-60th of a degree). Einstein said the change should be 1.75 arc-seconds. On the photographic plates Eddington would be using, that would translate to about one-60th of a millimetre.

Astronomers were able to make these precise measurements because they took everything into account. Photographs taken during the eclipse needed to be compared with photographs of the same field of stars when the eclipsed Sun is not in front of them. It is the change of position of the star that matters – they had to have an exact reference for that change. It can take months for the Sun to move far enough across the sky that the images would be undistorted by its gravity.

That means a second set of photographs would have to be taken either months before or after the eclipse itself. Further, they had to be taken with exactly the same lens and photographic setup – every lens is a little bit different, and it was essential to make sure that an apparent change in the star's location was not due to an imperfection introduced by a different lens. So photographs of the stars they would measure were taken from England with the lenses they planned to use in the field.

Hoping to get those preliminary results home as soon as possible, Eddington and Dyson even arranged a special telegraphic code. Before his departure, Eddington wrote an article presenting all this information to his colleagues so they would know how to interpret the results as they came back. Eddington declared that there were three possibilities: no deflection; 1.75 arc-seconds, the Einstein prediction; or 0.87 arc-seconds, which would support Newtonian gravity and challenge the ideas of Einstein. Eddington made a shrewd choice in framing the possible results this way. The test suddenly became a direct struggle between Einstein and Newton – a single moment in which this upstart German could dethrone the greatest thinker in history. Eddington had created a narrative and a thrilling background against which to present the expeditions' results.

Eddington was in a hurry to get his show on the road. At the beginning of March, he embarked upon a 5,000-mile ocean journey, arriving off the coast of Africa with Cottingham on 26 April. The two men stayed in the port of Santo António on Príncipe for about a week as they scouted the island for the best observation sites. They finally decided on the Roça Sundy Plantation on the northwest corner of the island, away from the cloud-gathering mountains, on a plateau overlooking a bay 500 feet below.

The locale and date of 29 May were propitious indeed. This particular eclipse, it turned out, would take place right in front of the Hyades, a handful of bright stars perfect for measuring the Einstein deflection. Eddington wanted bright stars so they could be easily seen on the photograph. And he wanted more than one so he could see how the deflection changed the farther away from the Sun they were: a star right at the edge of the Sun should show the 1.75 arc-second deflection; a star slightly farther away would show less; a star well away would show almost none. Einstein predicted not only a deflection but also a specific way that the deflection would change with distance from the Sun's edge. Multiple stars meant that this aspect of the prediction could be tested as well.

A past or future astronomer might have to wait centuries or millennia for a background as auspicious as the Hyades. They are found in the constellation Taurus. The Hyades are the bull's head, right by the blazing-red star Aldebaran. They were named after five nymphs, the daughters of Atlas. Weeping over the death of their brother, they were placed in the heavens just out of Orion's lustful reach. As one of the brightest clusters in the sky, they are visible to the naked eye and have been watched since antiquity. The Hyades are among the constellations placed on the shield of Achilles, along with Orion and Ursa Major. They were part of the ancient links between the heavens and the Earth, carrying meaning from the celestial realm to the terrestrial.

Eddington had no shield on which to catch these stars, only a telescope with which to look for their message. To see if the light from those stars was bent, he had to point that telescope into the darkness of a total eclipse, when the temperature drops, birds stop singing, and (crucially for Einstein) the stars become visible.

Thursday 29 May 1919 was cloudy in Sobral. The local community had been preparing to make the eclipse a public event, and festivities were ready to go. A small observatory near the edge of the eclipse path sold tickets to look through a telescope. The clouds were still thick at the beginning of the eclipse. When the leading edge of the Moon touched the solar disk (a moment called 'first contact'), the astronomer Andrew Crommelin, who had accompanied Dyson, estimated that 90 per cent of the sky was clouds. But they rapidly diminished, and the Sun sat in a large, clear patch as totality began.

The landscape was plunged into surreal darkness and the astronomers began their work. One of the Brazilians watched a clock and called out the passage of seconds for timing the photographs. Nineteen photos were exposed with the large telescope, and eight with a small four-inch lens. The clear sky held for the entire eclipse; everything had gone smoothly. They cabled home immediately: 'Eclipse splendid.'

On the other side of the Atlantic, the Príncipe dignitaries came to visit Roça Sundy on the morning of the eclipse. They were immediately greeted by a tremendous rainstorm, the heaviest the British visitors had seen, and quite unusual for that time of year. It ended around noon, with a couple hours to go before the eclipse. The clouds, Eddington said, 'almost took away all hope'.

At first contact, the Sun was invisible behind the clouds. It was not until 1:55pm that the astronomers began to get glimpses of the Sun, shaped into a crescent by the Moon's inexorable creep. It slipped in and out of cloud from moment to moment. Even in good conditions, the last few seconds before totality have been described as 'almost painful'. We can only imagine what this kind of knife-edge waiting would have felt like. Totality was calculated to begin five seconds after 2:13pm. At that moment, the astronomers became machines, carrying out the planned procedures regardless of what they could see with the naked eye – machines, though driven by hope and anticipation. As Eddington described it: 'We had to carry out our programme of photographs in faith.' The telescope took all of their attention. Cottingham kept the coelostat mechanism running and handed Eddington fresh plates; Eddington removed the exposed plates and slid in the new ones. He had to pause for a delicate second after each swap, lest the motion caused some tiny tremor that would ruin the image.

When totality ended, the world returned to normal, with no lasting marker of the disruption of the natural order that had just taken place. Eddington could take a moment to breathe. His telegram to Dyson was succinct: 'Through cloud. Hopeful.'

The decision had been made to develop the photographs onsite in Brazil and on Príncipe, and for reasons ‘not entirely from impatience’. The glass plates were delicate and could easily be damaged on the long journey home. Developing them in place and making preliminary measurements would at least guarantee some results, even if they were gathered in imperfect conditions. In Sobral, Davidson and Crommelin developed four of the astrographic photographs the next night. They were shocked to see that the star images were ever so slightly distorted, as though the focus on the telescope had been changed.

This change of focus can be attributed only to the unequal expansion of the mirror through the Sun’s heat. The readings of the focusing scale were checked the next day, but were found unaltered at 11mm. It seems doubtful that much could be revealed from these plates. For normal eclipse observations, this effect would be negligible. But the Einstein deflection was such a small effect that it could easily be swamped by such a phenomenon.

The images from the four-inch telescope, brought along as an afterthought, looked much better. So not all hope was lost. In any case, the pair of astronomers had a long wait ahead of them. They needed to stay in Brazil until July to take check photographs of the Hyades once the Sun had moved out of the way. Eddington was not in a mood to wait. While there were good technical reasons to examine the photographs right away, it seems his incentive might have been more personal. For the six nights after the eclipse, he and Cottingham developed two plates each night. They were not quite what he wanted: ‘The first 10 photographs show practically no stars. The last six show a few images which I hope will give us what we need; but it is very disappointing.’

Eddington then spent each day hunched over the photos with a complicated device called a micrometer making fine measurements. Even with Eddington’s legendary mathematical speed, it still took him three days of feverish work. It was more complicated than he expected because the cloudy images forced him to use different methods from those planned. But at some point in the first week of June 1919, Eddington put down the pen he had been using for his calculations. He had his answer: ‘I knew that Einstein’s theory had stood the test and the new outlook of scientific thought must prevail.’

However, this moment was just a matter of Eddington persuading himself. His preliminary calculations were not nearly enough to convince everyone back home. For that, a great deal of work remained. Eddington had hoped to stay on Príncipe to complete some of that work but his plan was disrupted by labour issues with the local steamship line. If he did not depart immediately, he might be stranded for an unknown length of time. The governor of Príncipe commandeered space for him and Cottingham on the last ship leaving that summer (the SS Zaire). Eddington came home to a new world of ‘international’ science, officially defined as ‘everyone except Germany and Austria’. But he had a trunk full of photographs intimately tied to a theory substantially developed in Berlin.

Scientific observations do not speak for themselves; they do not give up their secrets easily. Bringing the world around to his conclusion that Einstein was right would take Eddington months of tedious measurement and calculation.

Dyson and Eddington kept the expeditions separate even during the process of analysing the data. Perhaps it was thought that independent measurements would be seen as more reliable. The Príncipe photographs would be analysed in Cambridge, the Sobral ones in Greenwich. Eddington probably did the measurements and calculations for the former himself, while Davidson worked with Royal Observatory staff on theirs; the Sobral team had the slightly easier task. Because they were able to take check plates onsite, they could directly compare them with the eclipse photographs. Since both were taken in the same place with the same telescope, they could just measure how far the image of a certain star appeared to move when the Sun's gravity was present.

However, this was not a matter of slapping down a ruler and lining up by eye. Small measurements were made with a micrometer that could assess much tinier distances than the human hand. These measurements required a great deal of training and patience, but were a standard part of an astronomer's toolkit.

Eddington needed an extra step. He had been unable to take check plates from Príncipe, so he could not make a direct measurement. He had to compare the image of the Hyades he took during the eclipse with the image of the Hyades taken with the same telescope in Oxford. But he had to account for the possibility that there was some subtle difference between Oxford and Príncipe that changed the image. So he had taken an image of a different star field in both locations and, by comparing those two photographs, he could see what differences there were.

Armed with that information, he could then account for that in his final measurements. It is very rare that a measurement in science has no interference or error. Rather, the trick is to understand those problems and correct for them. The Príncipe observations produced 16 photographs, though thanks to the cloud only seven had useful images of stars. Fortunately, all seven had the two stars with the highest predicted deflection. However, a reliable measurement required five stars for cross-reference, and only two of the plates had that many. Those two were consistent, at least, and gave an average deflection of 1.61 arc-seconds, ± 0.30. That uncertainty was not superb, but it was adequate. Einstein's predicted deflection was 1.75. For the first measurement of a completely unknown physical phenomenon, Eddington thought it was pretty good.

As for the work from Sobral, the four-inch backup telescope brought along at the last moment saved the day. Seven of the eight plates taken with it had excellent images of all seven hoped-for stars. Measuring those provided much better results than from Príncipe: 1.98 arc-seconds, ±0.12.

While Eddington and Dyson were furiously measuring and calculating, they somehow still made time to set the stage for the eventual presentation of the results. Dyson asked the Royal Society Council to schedule a special meeting on 6 November, at which the results would be formally presented. There was no turning back. Nonetheless, it was still impossible to send a message directly to Berlin, so they did the next best thing. The Dutch physicist Hendrik Lorentz sent a telegram to Einstein, urgent and brief: ‘Eddington found stellar shift at solar limb, tentative value between nine-tenths of a second [of a degree] and twice that.’

Unfortunately, we have no eyewitness account of Einstein first receiving the news. Fortunately, he then showed the telegram to anyone who came into his apartment, so we can see it through other eyes. Ilse Rosenthal-Schneider, a young physics student, was sitting with Einstein at his desk going through a book full of objections to relativity. Einstein suddenly interrupted their reading to reach for a document on the windowsill. He coolly remarked: ‘This may interest you,’ and handed her Lorentz’s telegram. Einstein could think of little else and was in no mood to be shy about spreading the word.

That was the attitude Eddington was hoping to instil in his British colleagues at the Royal Society’s rooms at Burlington House in Piccadilly. The audience on 6 November was seated in pews, with an overflow crowd standing among the columns lining the sides. One of the attendees was Alfred North Whitehead, the distinguished philosopher-mathematician. He reported on the excitement in the air, writing: ‘The whole atmosphere of tense interest was exactly like that of the Greek drama.’

The next day, The Times newspaper in London presented the greatest scientific headline in history: ‘Revolution In Science’. The discovery was attributed to ‘the famous physician Einstein’ (he was neither). On Saturday there was a follow-up article with the same title, with the addition ‘Einstein V Newton’. This was the general public’s first introduction to Einstein, and he appeared exactly as Eddington wanted to present him: a peaceful genius who repudiated all the wartime stereotypes of the militaristic German.

The excitement jumped the Atlantic and, on 10 November 1919, The New York Times blared: ‘Men Of Science More Or Less Agog Over Results Of Eclipse Observations’. It is important to look back and remember that this was virtually the Times’ first mention of Einstein.

The explosion of interest finally made it possible for Eddington and Einstein to write directly to each other. ‘All England has been talking about your theory … it is the best possible thing that could have happened for scientific relations between England and Germany,’ Eddington wrote to Einstein later that year. The eclipse expedition became a symbol of German-British solidarity because Eddington chose to craft it that way. Einstein chose to fight against militarism in German science, raising the stakes. This was a great moment for science across the gulf of war because certain scientists turned it into one.

Adapted from Aeon

Monsters in the dark

The Universe's biggest galaxies could hold the key to the birth of the cosmos. Why are these behemoths so hard to find?

I was about 10 years old when I saw the Milky Way for the first time. On holiday in the countryside, blissfully far away from the polluting airglow of city lights, the night sky was like nothing I'd ever seen before. There were more stars, of course, but there was also something wholly new: a vast silvery band of light, arcing across the sky.

For most of human history, the Milky Way was something of an enigma. Different cultures offered up a dizzying variety of folk tales and explanations. There's the Roman story of a goddess spilling milk across the sky (from which we get our term 'Milky Way'), and many tales of heavenly rivers in the firmament. My personal favourite is the Cherokee legend, in which a dog stole a basket of cornmeal, leaving a trail behind. The Cherokee call the Milky Way gi li' ut sun stan un' yi – 'the way the dog ran away'.

It was the astronomer Thomas Wright who, in 1750, first described our galaxy as science now understands it: a vast disk of stars, held together by the same gravitational forces that define the Solar System, though operating on incomparably larger scales. Our Milky Way is a large-ish spiral galaxy, made up of around 200 billion stars and stretching 100,000 light years across. If these numbers seem huge to you, you're not alone: up until the turn of the 20th century, astronomers assumed something so absurdly big must constitute the entire material Universe. So it was a considerable surprise in 1924 when Edwin Hubble demonstrated that our Milky Way is just one tiny corner of a Universe, containing hundreds of billions of galaxies of all shapes and sizes.

Why do galaxies exist at all? Why do the basic laws of nature come together to produce a Universe filled with these ridiculously vast – and incomparably beautiful – structures? Over the past century, astronomers have pieced together much of the picture. In the smooth, uniform, early Universe, tiny quantum fluctuations acted like seeds, growing under the influence of gravity and eventually forming what we know as modern galaxies, those massive, complex and ordered systems of gas, dust and stars. But parts of the puzzle are still missing – and to find the answers, we need to look further afield.

If we 'zoom out' from our Milky Way and look at our local cosmic neighbourhood, we start to get a sense of the diverse range of galaxy types. Our 'Local Group' of galaxies consists of a veritable galactic zoo, from the large twin spirals of the Milky Way and Andromeda, to the small fluffy-looking Triangulum Galaxy, and more than 50 smaller dwarf and irregular galaxies. Given the galactic diversity on display, you'd be forgiven for assuming that the Local Group provides a pretty good census of galaxy types. But a type of galaxy is missing.

The largest galaxies in our Universe are so rare that they don't show up in our small Local Group. These are the 'giant elliptical' galaxies, the biggest of which are behemoths that would dwarf even our Milky Way. The galaxy IC 1101, for example, is millions of light years across – big enough to swallow the Milky Way, Andromeda and all the space between. These giant elliptical galaxies have another unusual property, aside from being so massive: they are all dead.

It might sound strange to refer to a galaxy as being ‘dead’. But this is meant to contrast with galaxies such as those in our Local Group, which are actively forming new stars. Galaxies that create stars (such as our own Milky Way) are full of giant interstellar gas clouds, light-years across, floating through space. These gas clouds are unstable though, and if disturbed – say, by a nearby supernova – they fragment and collapse under their own gravity, turning into stars. Making stars is a perfectly normal process for many galaxies: our own Milky Way makes one or two new stars every year, in places such as the Orion Nebula. But massive elliptical galaxies do not form new stars, and haven’t done so for billions of years. They’re ‘dead’. And, just as a palaeontologist who discovers a fossilised dinosaur can infer that there must have been an extraordinarily massive creature to leave behind such remains, an astronomer who comes across a gigantic dead galaxy can conclude it’s the wreckage of a truly titanic system that lived in the deep past of the Universe. Astronomers have an advantage over palaeontologists, though: we can actually go looking for our dinosaurs. And to do that, we have to look back in time.

Fortunately that’s easier than it sounds – a fact related to the speed of light, which is, as you’d expect, rather fast. A wave of light, after being emitted by a star, will zip through the Universe at a blistering 300,000 kilometres every second. But as absurdly fast as this is, it still does take time for light to move around. Light from the Moon takes around a second to get to Earth, and light from the Sun – about 100 million miles away – travels for eight minutes before reaching us. And just like a letter might take a while in the post (and be ‘old news’ by the time it arrives), light also brings us messages from the past. This is just as true on Earth as it is in space, by the way – when you sit across a table from someone, you are actually seeing them as they were a fraction of a second ago. But over astronomical distances, the time difference can really stack up. Nearby stars might allow us to look back decades, and we see nearby galaxies, such as our nearest neighbour Andromeda, as they were millions of years ago.

But even millions of years is small-time stuff, compared with the Universe as a whole. If we want to go looking for our cosmic monsters, living in the deep past, we need to go back billions of years. This means looking very far away indeed.

One of the best images of our distant Universe was taken by the Hubble Space Telescope over 10 consecutive days in 1995. Known as the ‘Hubble Deep Field’, the photo is an exposure hundreds of hours-long of a tiny patch of sky, around one-10th the width of the full Moon. Go and look up the image now – it has to be one of the most awe-inspiring photographs ever taken. At first glance it looks like a starry night sky, but a closer look causes a dizzying perspective shift: everything in the image is a galaxy. Even the faintest red dots, barely visible, are entire galaxies, rendered in miniature by the billions of light-years of intervening space. The most distant galaxies you can see (which are therefore the most ancient galaxies, remember) lived nearly 13 billion years in the past.

At this point, though, our monster-hunting expedition hits a snag. Even an image such as the Hubble Deep Field and its successors, showing thousands of galaxies spanning a vast gulf of cosmic time, doesn't contain anything remotely extreme enough to be an ancestor of the giant dead galaxies we see in our modern Universe. These 'red-and-dead' giant galaxies need to grow somehow, and all those billions of stars being formed should stand out like a cosmic firework show. But there's nothing in the Hubble Deep Field that even approaches the titanic building project that would be needed to produce a giant galaxy.

So far, so mysterious. The answer to this problem lies in the fact that the Hubble Deep Field, as impressive as it is, is only a small part of the picture. While it showcases galaxies across most of cosmic history, it does so using only 'optical' light – wavelengths that we can see with our eyes. But the light we see makes up just a small fraction of the total spectrum. The rest of the spectrum – all the light we cannot see, in other words, from radio waves to high-energy X-rays – tells us about the Universe too. And these other wavelengths can paint a radically different picture of our cosmos.

In 1880, the American astronomer Samuel Pierpont Langley achieved something rather remarkable: he built a piece of equipment capable of spotting a cow at a distance of around a quarter of a mile. This might not sound like a feat destined for the history books, but what made this special was the wavelength of light that he used. Langley had built the first ever 'bolometer', a telescope-like heat-detector capable of seeing very long wavelengths of infrared light.

Bolometers were used to study outer space from the very beginning, with Langley himself using his new invention to study the thermal radiation from our Sun. But throughout most of the 20th century, bolometers were limited to single-pixel devices, making it horrendously time-consuming and fiddly to make actual images of anything (imagine having to use a one-pixel phone camera). The big breakthrough came in the 1990s, when scientists discovered how to link multiple bolometers together to make a multi-pixel camera. And these new 'bolometer cameras' could then be used to take pictures of the Universe using very long-wavelength infrared light.

It's no exaggeration to say that this was a revolution in astronomy. These new wavelengths, thousands of times longer than what we see with our eyes, represented an entirely new window through which to view our Universe. One of the first bolometer cameras, an instrument called SCUBA, attached to a telescope in Hawai'i, is second only to the Hubble Space Telescope in the amount of important astronomical research it has produced.

So how does this tie in to the hunt for missing monster galaxies, lurking in the prehistory of the Universe? The answer lies in the fact that long wavelengths of light are good at finding hidden things. Firefighters entering burning buildings now use infrared cameras that 'see' in long-wavelength light. These long wavelengths travel easily through dust and smoke, revealing obscured things that would be hidden from our human eyesight. And the same trick works for astronomy, too: observing the Universe at long wavelengths, using a bolometer camera, has the power to make the invisible visible.

And what did astronomers see, when they turned these new cameras skywards? Well, it turned out that the long-wavelength Universe looked like a very alien place, compared with the Universe we know. If you look at a side-by-side comparison of the same patch of sky, one picture taken in optical light and one taken with a bolometer camera, you would never guess that the two pictures have the same subject. What looks bright to our eyes might seem dull and uninteresting in the far-infrared. But the reverse can be true too. The first long-wavelength pictures of the sky revealed a previously invisible Universe: a scattering of blazingly bright galaxies, hidden from normal telescopes, shining out of the dark like great cosmic lighthouses. New galaxies! It was like a magic trick.

The most exciting thing about these new galaxies, though, wasn't just that they were previously invisible. It was that they appeared to be an entirely new type of galaxy – a new galactic species. Astronomers have been cataloguing galaxies for hundreds of years, separating them into 'spirals', 'ellipticals', and so on. But these new galaxies seemed to be an entirely unknown population. This kind of thing would be the discovery of a lifetime for anyone studying the natural world. Imagine being a biologist, putting on a pair of infrared glasses, and coming face to face with a new species previously invisible to our eyes!

The new galaxies were named Sub-Millimetre Galaxies (or SMGs for short – astronomers love acronyms). The 'sub-millimetre' bit of their name is a bit misleading, since it calls to mind something minuscule – but in fact the label refers to the wavelength of light used to find them. Despite their miniature-sounding name, SMGs are massive and extreme beasts.

So what are our newly discovered galaxies like? And could these be the missing 'dinosaur' galaxies that eventually died and left us with a Universe strewn with 'red and dead' giants? There are a number of things we can learn about galaxies – like how far away they are, how big they are, and what they're made of. It's also good to know how fast galaxies make stars, which is a way of knowing how fast the galaxy is growing. And whichever way you look at it, this new species of galaxy is a record-breaker. They're some of the biggest and most faraway galaxies we've found, and they're making stars at a rate that dwarfs every other galaxy ever discovered.

Of course, all galaxies are 'really far away' – space is a big place. But the distances to these new galaxies boggle the mind. One well-studied galaxy (that goes by the oh-so-catchy name 'SMM J123711.86+622212.6') is around 24 billion light-years away, or 24,000 million light-years. Andromeda, and the rest of our local galaxies, are in our cosmic back-garden by comparison. Being so far away, of course, also means that these galaxies are incredibly ancient; by seeing these galaxies, we are looking back more than 10 billion years into the past. But the real way that these galaxies are exceptional is how efficient they are at making new stars.

As I mentioned before, this is a normal process for most galaxies. A typical nearby 'starburst' galaxy, known for churning out stars unusually rapidly, might make a hundred or so new stars per year. But that's nothing compared with one of these new Sub-Millimetre Galaxies. An SMG can create thousands of new stars per year, making them the most powerful and efficient star factories in the entire Universe. Nothing else comes close. And this is exactly the type of galaxy that would, over the course of billions of years, turn into a red and dead giant. With our new, long-wavelength view into an invisible Universe, it looks like we might have finally found our dinosaurs.

So how did these amazing galaxies remain hidden for so long? If they're really so extreme, why did our telescopes fail to spot them? The answer sounds surprisingly down-to-Earth: they're too dusty. Cosmic dust is a sea of tiny, smoke-like particles, containing heavy elements such as silicates and oxides. All galaxies have some dust, which is very good at blocking out light (dust in our own Galaxy is responsible for the dark stripes that pattern the Milky Way). But SMGs have an abundance of dust, a byproduct of all those millions of stars being formed. They have so much dust, in fact, that almost all their optical light is blocked, leaving them invisible to our eyes. But, like firefighters using infrared goggles to search in smoky rooms, our infrared telescopes can now peer through the haze to reveal the hidden monster galaxies within.

There's still a lot we don't know about these galaxies. At such extreme distances, billions of light years away, SMGs appear as little more than faint, fuzzy blobs in even our most powerful telescopes. As a result, learning even basic things about them – such as their shape and structure – involves some educated guesswork. Due to the titanic forces at work within them, they must exist as chaotic, whirling maelstroms of gas, wind and light. But whether they mostly resemble 'scaled up' versions of galaxies we know well, or whether they are far more alien, we don't yet know.

We've only just passed the 20-year anniversary of knowing that they even exist, so astronomers can be excused for not having the full picture just yet. It's still not totally clear what forces lie behind such extraordinary star formation: are they powered by two massive galaxies crashing together? Or can gas (the fuel for star formation) pour down onto a galaxy like a great cosmic waterfall, setting off a firework show of new stars? Right now we don't know the details.

It's also not fully clear just how these galaxies 'die'. What transforms them from the vibrant cosmic powerhouses in the distant Universe into the 'red and dead' fossils that started our story? The answer might well be hidden in the very cores of these monster galaxies. All massive galaxies, including our Milky Way, have a supermassive black hole in their centre, and SMGs are no exception. It's thought that interactions between the central supermassive black hole and the wider galaxy can end up stripping the galaxy of gas, quenching the fires of star-creation and setting the galaxy on a course to becoming a 'red and dead' relic. But right now, we don't really understand how SMGs and their black holes interact.

Answering all these questions might need to wait until the next generation of powerful telescopes get built – like NASA's James Webb Space Telescope, the successor to Hubble, and the futuristic 'Square Kilometre Array' radio telescope, both due in the 2020s. It's often the way in science that our understanding of the

Universe advances in step with technology. For objects such as these extreme galaxies – which sit just at the edge of observability and span the hinterland between knowledge and mystery – are some of the most tantalising phenomena of all.

I still love looking at the Milky Way. One of the best things about being an astronomer is being able to visit the darkest skies in the world, and see our Galaxy laid out like an intricate tapestry across the sky. What seized my imagination at a young age was the sense of mystery, and an awe of whatever vast and ancient forces created such a sight. It thrills me that humanity has reached a point where we are beginning to understand these forces, and to see the Universe on its own terms.

Adapted from Aeon

Cheers! How the physics of fizz contributes to human happiness

Think of the last time you had something to celebrate. If you toasted the happy occasion, your drink was probably alcoholic – and bubbly. Have you ever wondered why it’s so enjoyable to imbibe a glass of something that sets off a series of microexplosions in your mouth?

A glass of a bubbly drink is full of physics, history and culture. We probably first encountered fizz alongside the discovery of alcohol, since both ethanol and carbon dioxide (CO2) gas are byproducts of fermentation. Drinking carbonated substances for pleasure – rather than simply staying hydrated – appears to be something only humans do.

In 17th-century France, the Benedictine monk Dom Pérignon greatly refined what we now know as Champagne. It took him many years to perfect a bottle and cork design that could withstand the high pressures that the process required. In sparkling wine, part of the fermentation takes place after the liquid has been bottled. Since the CO2 can’t escape the closed container, the pressure builds inside. In turn, this results in large gas quantities being actually dissolved into the liquid, in accordance with Henry’s law – a rule stating that the amount of gas that can be dissolved in a liquid is proportional to the pressure.

Among other things, Henry’s law explains why divers can get decompression sickness if they rush their ascent to the surface: at great depths, the body is exposed to a high pressure and, consequently, gases are dissolved in blood and tissues in high concentrations. Then, when surfacing, the pressure returns to the ambient level, such that the gas ‘exsolves’ and is released to form painful, harmful bubbles in the body. The same happens when we uncork a bottle of Champagne: the pressure suddenly drops back to its atmospheric value, the liquid becomes supersaturated with carbon dioxide – et voilà, bubbles emerge!

Over time, as liquid continues releasing gas, the size of the bubbles grows, and their buoyancy increases. Once the bubbles get sufficiently big, they can’t stay stuck to the microscopic crevices in the glass where they originally formed, and so they rise to the surface. Soon after, a new bubble forms and the process repeats itself. That’s why you’ve probably observed bubble chains forming in Champagne glasses – as well as the sad tendency of fizzy drinks to go flat after a while.

Intriguingly, Gérard Liger-Belair, professor of chemical physics at the University of Reims Champagne-Ardenne in France, discovered that most of the gas lost to the atmosphere in sparkling wine doesn't escape in the form of bubbles, but from the surface of the liquid. However, this process is highly enhanced by the way that bubbles encourage the Champagne to flow in the glass. In fact, if there were no bubbles, it would take weeks for a drink to lose its carbon dioxide.

The attractive bubbly character of Champagne can be found in other drinks, too. When it comes to beer and carbonated water, the bubbles don't come from fermentation but are introduced artificially by bottling the liquid at high pressure with an excess amount of carbon dioxide. Again, when opened, the gas can't stay dissolved, so bubbles emerge. Artificial carbonation was actually discovered by the 18th-century English chemist Joseph Priestley – better known for discovering oxygen – while investigating a method to preserve drinking water on ships. Carbonated water also occurs naturally: in the southern French town of Vergèze – where Perrier, the commercial brand of mineral water, is bottled – an underground water source is exposed to carbon dioxide at high pressure, and comes up naturally fizzy.

When a carbonated beverage is rich in contaminants that stick to the surface, known as surfactants, bubbles might not burst when they reach the top but accumulate there as foam. That's what gives beer its head. In turn, this foam affects the texture, mouthfeel and flavour of the drink. From a more physical perspective, foam also insulates the drink, keeping it colder for a longer time and acting as a barrier to the escape of carbon dioxide. This effect is so important that in the Dodger Stadium in Los Angeles beer is sometimes served with a head of artificial foam. Recently, researchers havediscovered another interesting effect: a foam head prevents the beer from spilling when one walks with an open glass in hand.

Despite our solid understanding of bubble formation in drinks, a question remains: just why do we like drinks with bubbles? The answer remains elusive, but some recent studies can help us understand. The interaction of carbon dioxide with certain enzymes found in saliva causes a chemical reaction that produces carbonic acid. This substance is believed to stimulate some pain receptors, similar to those activated when tasting spicy food. So it seems that the so-called 'carbonation bite' is a kind of spicy reaction – and humans (strangely) seem to like it.

The presence and size of bubbles can even affect our perception of flavour. In a recent study, researchers found that people could experience the bite of carbonic acid without bubbles, but bubbles did change how things tasted. We still don't have a clear picture of the mechanism by which bubbles influence flavour, though soft-drink manufacturers have ways of adjusting the amount of carbonation according to the sweetness and nature of the drink. Bubbles also affect the rate at which alcohol is assimilated into the body – so it's true that a bubbly drink will make you feel inebriated more quickly.

As far as we're concerned, all this offers a great excuse to talk about physics. We enjoy bubbly drinks too, of course – but personally, we celebrate adding a touch of science to a subject so that most people can relate to it. What's more, bubbly liquids have many practical applications. They're essential to some techniques for extracting oil; for explaining deadly underwater explosions known as limnic eruptions; and for understanding many other geological phenomena, such as volcanoes and geysers, whose activity is strongly influenced by the formation and growth of gas bubbles in the erupting liquid. So, the next time you celebrate and knock back a glass of bubbly, be sure to know that physics contributes to the sum of human happiness.

Adapted fron Aeon

Would New Physics Colliders Make Big Discoveries or Wander a Particle Desert?

Around the globe, imminent decisions on proposed next-generation experiments are set to shape particle physics for decades to come

Crisis, what crisis? The future of particle physics has been a major talking point of late, with decisions on next-generation high-energy colliders contrasting with skepticism as to whether such monumental (and monumentally expensive) megamachines should be built in the first place. Many physicists say such critiques are unjustified, yet acknowledge the profound uncertainties surrounding plans for future forays deeper into the subatomic realm.

Late last week Japan announced it would delay its decision on whether or not to build a new facility called the International Linear Collider (ILC). Among other goals, this vast machine spanning 20 kilometers and costing an estimated $7.5 billion would enable unprecedented studies of the Higgs boson—the enigmatic particle that imbues others with mass, discovered in 2012 by the purpose-built Large Hadron Collider (LHC) at CERN in Switzerland. Japan's cautious approach to the ILC is symptomatic of lingering uncertainties over where the field of particle physics itself should go. "It's an interesting time for particle physics at the moment, because the last big missing piece of the puzzle of the Standard Model was found in the discovery of the Higgs boson," says Carsten Welsch, head of the Department of Physics at the University of Liverpool in England. "The question is now, what's coming next?"

Physicists around the world were closely watching Japan's debate about the ILC, because a "yes" or "no" on that project could trigger a domino effect causing similar plans in other countries to be scrapped or approved. Europe and China are each considering new colliders of their own, but their final decisions will be heavily dictated by what occurs elsewhere. "If the Japanese government had said they really wanted to build the ILC, that would have had a huge impact on the European strategy for sure," says Jon Butterworth from University College London (U.C.L.), the U.K.'s delegate for the CERN Council's European Strategy for Particle Physics. "Given they've effectively said 'no' for now, that will also have an impact."

The major debates in particle physics at the moment concern which questions researchers should attempt to answer next. The discovery of the Higgs boson essentially completed the Standard Model of physics, the theory that governs our understanding of the subatomic world and dictates how all but one of the known fundamental forces should collectively behave (the force of gravity is the glaring omission). Nevertheless, scientists are now wondering whether we should explore this area further, creating so called “Higgs machines” to churn out countless Higgs bosons, or whether we should instead seek to dive even deeper into physical frontiers by smashing particles together at ever-greater energies. “We’re right on the cusp of a revolution but we don’t really know where that revolution is going to be coming from,” says James Beacham, a particle physicist on the LHC and postdoc at Duke University. “It’s so exciting and enticing. I would argue there’s never been a better time to be a particle physicist.”

At present, the LHC remains the most powerful particle collider on Earth—and is presently receiving upgrades to maintain its front-runner status into the 2020s. But an even larger circular collider would reach energies higher than those possible at the LHC, allowing physicists to probe new parts of the subatomic realm. Earlier this year CERN unveiled a proposal for such a machine, called the Future Circular Collider (FCC), which would use a 100-kilometer ringed tunnel to surpass the LHC’s power by a factor of 10, reaching energies of 100 tera–electron volts (TeV). Such a machine, however, would likely cost in excess of $20 billion and only begin operations in the 2050s, leading some critics to question whether it is the right route to take.

Further complicating matters is China’s own plan for a similar large collider, called the Circular Electron Positron Collider (CEPC). Most experts agree there would be little need to construct both the CEPC and the FCC, so discussions are taking place in Europe on whether to work with China on such a project, unilaterally build the FCC or let China pursue the CEPC alone. These questions will be formally addressed in the European Strategy for Particle Physics, set to be drafted in January 2020. “I wouldn’t think there would be room for two machines of that scale,” Welsch says.

CERN also has a proposal for a linear collider akin to Japan’s ILC, called the Compact Linear Collider (CLIC). Again, there is little need for both the ILC and the CLIC, so Japan’s final decision on whether to proceed could effectively determine Europe’s decision, too. At the same time two next-generation non-collider experiments are being developed, one in the U.S. called the Deep Underground Neutrino Experiment (DUNE) and another in Japan called Hyper-Kamiokande (HK). Both of these projects intend to perform breakthrough studies of neutrinos, nearly massless particles that exhibit subtle hints of physics beyond the Standard Model.

This cavalcade of detectors and experiments demonstrates that although particle physics is hardly facing a crisis, it is certainly at a crossroads. Additionally, floating above all the proposals is the notion that the wisest approach would be delaying new machines entirely until potential breakthrough techniques become available. One such technique is plasma wakefield acceleration, a cheaper, more efficient method of accelerating particles using plasmas in comparison with the sprawling and expensive electromagnets employed in present-day colliders. “Everyone's keeping a lazy eye on that, and some people are doing full-time research on it,” Beacham says. “But it’s really not going to be possible to use [in] a gigantic collider for probably decades, if not longer."

Some scientists even suggest it is premature to consider expensive, multidecadal projects like the FCC at all, given the current listlessness of particle physics. They argue that in the case of circular colliders, we would be looking for physics that we aren't even sure exists. The nightmare scenario would be a project with energies beyond that achievable by the LHC that would only reveal what some theorists call "the desert," a barren region otherwise devoid of new discoveries. "This next larger collider will be ridiculously expensive and it has no clear discovery potential," says Sabine Hossenfelder, a theoretical physicist from the Frankfurt Institute for Advanced Studies in Germany. "If the LHC does not see anything in the upcoming run and at the high luminosity phase, then I think it's not a good investment to build a larger collider at this point."

Sir David King, the U.K.'s former chief scientific advisor, even goes as far to suggest it might be time to wrap up particle physics as we know it, not only because of what might be diminishing returns in terms of new discoveries but also due to the opportunity cost next-generation machines would bear for dealing with more pressing concerns. "I'm happy to draw a line at the FCC, congratulate all the particle physicists on the amazing work they've done, but suggest they move on to other extraordinarily challenging aspects of fundamental science," he says. "I'm saying this at a time when humanity is faced with the biggest potential crisis it has ever had to face up to, which is climate change. I believe our intellectual resources should be focused on that."

Most leading physicists, understandably, disagree with this viewpoint. "Only people who have no knowledge about science can believe that we are at the end of particle physics," says Gian Giudice, the head of CERN's Department of Theoretical Physics. "There are still lots of open questions that need to be answered." Those questions include searching for weakly interacting massive particles (WIMPs), the leading candidates for dark matter, which could—but not definitely—spring up in machines such as the FCC. Scientists are also keen to test supersymmetry, the idea each particle in the Standard Model has a "partner particle" of sorts. And, of course, there is the troubling matter–antimatter problem—namely, if matter and antimatter were created in equal amounts in the big bang and destroyed each other, how did a tiny amount of matter manage to survive?

It is perhaps unsurprising physicists can offer no guarantees for future multibillion-dollar colliders answering such questions—otherwise, the reasoning goes, what would be the point of asking? But even if those hoped-for future facilities arise and fail to bear that fullest fruit, the knowledge gained along the way and perhaps even the chance of non-discoveries at higher energy levels present enticing prospects of their own. "We're faced with some enormous questions, things that we don't understand about the universe," says Ritchie Patterson, director of the Cornell Laboratory for Accelerator-based Sciences and Education. "If there's a chance of finding the answers, then we need to pursue that."

Discussions over the next year will be crucial in deciding what direction is taken, if one is taken at all. “In an ideal world we’ll have something like the FCC that goes up to 100 TeV, and we’ll also have one of those ‘tweezer’ machines that really understands the Higgs boson,” Beacham says. But whether that will be the case remains to be seen. “It’s more exciting and more uncertain now than I think it’s ever been in my career,” Butterworth says.
Adapted from Scientific American