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ILLUMINATING PHYSICS:

part 2

Учебное пособие

Саратов

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PREFACE

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

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

Пособие состоит из 5 разделов, рассматривающих проблемы и достижения в сфере информационных технологий в современном мире. Каждый из них содержит аутентичные материалы (источники: *Aeon, Quanta Magazine, The Wired, The Atlantic*) 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. How cosmic is the cosmos?

Exercise I.

Say what Russian words help to guess the meaning of the following words: cosmos, philosophy, romance, addressing, series, leader, tandem, theories, practice, tradition

Exercise II.

Make sure you know the following words and word combinations.
to pervade, to riff, compelling, pesky, to pervade, to weave, to demarcate, squash, cleansing, to ponder

How cosmic is the cosmos?

Ever since Heisenberg and Tagore, physicists have flirted with Eastern philosophy. Is there anything in the romance?

There is a story that the Buddha was once addressing the monastic community who had gathered around to listen to him preach, when one of his bright young followers posed a series of questions. What, he asked his spiritual leader, is the origin of the Universe? Is the cosmos infinite? Is it eternal, or did it have a beginning? After the student had finished, he looked up to the Buddha to hear his pearls of wisdom, but the older man was silent. Eventually, the young monk left, disappointed, only to come back the next day with the same queries. Once again, however, the Buddha remained quiet. On the third day, the young man returned and said in frustration: 'I have asked you these questions twice. If you don't know the answer, then admit that you don't know. If you do know but you think I won't understand, then just say that, but I urge you to try to explain. If, however, you stay silent, then I'm going to leave and not return.' Finally the Buddha replied, saying gently but firmly that these are simply not issues to which the Buddha speaks. 'What I address is human suffering and liberation from this suffering,' he said. 'Nobody asked you to come here, and you are always free to leave.' This tale was recounted to me by Abhay Ashtekar, a physicist at Pennsylvania State University who, over the past two decades, has delved deeply into Buddhist philosophy. In tandem, however, he has investigated precisely those puzzles about the origins of the Universe and the nature of time that the Buddha deemed irrelevant. Unlike the Buddha, Ashtekar sees profound resonances between his spiritual quest and his scientific one. Though his theories of the early Universe are not directly based on Buddhist concepts, Ashtekar has uncovered some surprising similarities, both in the methods of his scientific and spiritual practice and in some of the answers that they can offer about the nature of physical reality. Ashtekar is not alone in connecting modern cosmology with ancient non-Western thinking. There is a long tradition devoted to uncovering parallels between the two. Werner Heisenberg, one of the founding fathers of quantum mechanics, had a meeting on the issue with Rabindranath Tagore, the Indian poet and philosopher, in 1929. Later, the Austrian physicist Fritjof Capra popularised the connection between modern physics and mysticism through his groundbreaking book, The Tao of Physics (1975).

The discussion has gone on ever since. I partook in 2014, while researching my book, A Big Bang in a Little Room (2017), about experiments on recreating the origins of the Universe in the lab. Not only did I meet with Ashtekar at Penn State but also with his kindred spirit, the cosmologist Andrei Linde, at Stanford University in California. Linde had just returned from giving a series of guest lectures at the University of Hamburg in Germany on the philosophical implications of 'quantum cosmology', the discipline that applies the rules governing the micro realm – quantum theory – to the study of how the Universe evolved in its infancy, when it was still growing from a tiny seed.

In those talks, Linde had pointed to a harmony between cosmology and the ancient Hindu philosophical school Advaita Vedanta, which posits a unity between the eternal cosmos and the self. Specifically, he found resonance between Advaita Vedanta and theories developed by modern physicists to explain why time's arrow points in one direction, inexorably marching us from cradle to grave. Ashtekar, independently, was challenging the conventional view that our cosmos was born at the Big Bang, replacing it with a model of an eternal universe that once contracted and is now expanding again. He even began to ponder whether it might be possible to construct a scientific model aligned with non-Western philosophies, in which individual human consciousnesses are embedded in a larger communal consciousness that pervades the Universe. Mentioning spiritual texts in the same breath as physics is not fashionable; the danger is you will come over as both a wannabe guru and a flaky physicist. Linde recalls his reticence before the Hamburg meeting: 'I was so scared about that, about talking to them about reality, because this is the least understood thing about quantum mechanics and quantum cosmology.' Born in Moscow when Russia was still in the Soviet Union and religiosity was taboo, Linde had no formal religious upbringing. Today he identifies as an atheist, albeit one who grew up with a taste for big theological questions, voraciously reading both philosophy texts and science fiction for thoughts about the nature of the self and consciousness. ‘The climate was to ignore religion, so I was, with my strange philosophy, the most religious person around,’ Linde says, laughing.Linde is now most famed as one of the co-founders of inflation theory, which he developed while in Russia in the 1980s, and which posits that the early Universe went through a rapid period of expansion, racing outwards faster than the speed of light, for a fraction of a second after the Big Bang, before slowing to a more sedate pace of growth. That idea, though not yet fully confirmed, has passed pretty much into mainstream cosmology. But while cosmologists largely agree about what happened just after the Universe’s birth, they are still perplexed about the physics that occurred before inflation, at the Big Bang itself, when – according to the conventional view – the cosmos came into being. It was an early attempt to unpack this birthing moment that raised paradoxical puzzles about the nature of time, calling its very existence into question – and echoing non-Western philosophy long before cosmologists entered the fray. The so-called ‘problem of time’ in physics arose back in the 1960s, as physicists grappled with deriving a mathematical description of the Universe’s birth. The standard story is that the cosmos exploded out of an infinitely small, infinitely dense point, or ‘singularity’ at the Big Bang, creating both space and time. Before the Big Bang, there was nothing, no time and no space. The trouble is that our current understanding of physics does not allow us to say much about what singularities are, or what happens within them. On the one hand, physicists feel that since singularities are tiny, they should be beholden to the laws of quantum physics, which governs the behaviour of small objects. Quantum theory provides a well-developed mathematical framework for describing what happens to small things such as atoms, electrons or photons in lab experiments. This includes a number of oddball characteristics they display that we do not usually see in everyday life; for instance, two quantum objects can become inextricably linked, or 'entangled' with each other, influencing each other over great distances.

Another weird, but central tenet of standard quantum physics is that a modicum of unpredictability is woven into reality, so the fate of an individual particle cannot be calculated with absolute certainty in advance. By using an equation developed by the Austrian physicist Erwin Schrödinger in the 1920s, physicists can work out the probability of a particle behaving in one way or another when it is monitored in the lab – whether it will travel in this direction or that, or be found here or there. And when multiple experiments are carried out on many thousands of similar particles, the equation's predictions for the proportion that will behave a certain way are stunningly accurate. At the heart of the equation is a 'wavefunction' – the mathematical description of the tiny object in question, which encompasses the myriad of many possible outcomes that could manifest when the object's properties are measured in an experiment.

Linde and many others think that the ultimate description of the Universe can be found by applying quantum rules to the newborn Universe. The catch is, however, that unlike small lab particles, our infant Universe was cosmically heavy, containing within it the seeds of all the stars, galaxies and planets we see today. Massive cosmic objects such as stars and planets are not usually subject to quantum laws; instead, their motion is calculated using Albert Einstein's general theory of relativity, also developed in the early 20th century. In Einstein's framework, the Universe is pervaded by a four-dimensional fabric that bends around masses, knitting together space and time. This warping creates dips and contours in spacetime around more massive bodies, such as stars, channelling planets to orbit around them. In a now famous adage, the physicist John Wheeler at Princeton University succinctly explained: 'Spacetime tells matter how to move; matter tells spacetime how to curve.' The trouble for time came when physicists attempted to put these two cornerstones of modern physics – quantum theory and general relativity – together. In the 1960s, the US physicist Bryce DeWitt, inspired by Wheeler, defined a quantum wavefunction for the infant Universe, and set out an equation that combined Schrödinger's and Einstein's mathematics in an attempt to explain how the early cosmos evolved through time, governed by both quantum physics and relativity. It is now known as the Wheeler-DeWitt equation, even if, as Linde says: 'Wheeler did not derive it and DeWitt did not like it. It is a really strange equation.' The weirdness Linde refers to that discomfited DeWitt was that, while quantum and relativistic equations each individually contain a variable that marks the passage of time – an essential component if you want to use your equation to calculate how systems evolve – when DeWitt brought the equations together, the time variable cancelled out the Wheeler-DeWitt equation entirely: his equation for the wavefunction of the Universe was telling him that the cosmos does not evolve, or change in time, at all. It should not expand out from a small singularity, seed stars, galaxies, planets or people. It should just be frozen. ‘That’s a theorem,’ Linde says emphatically: the problem of time is that it is an illusion, and there is no such thing as time, at the fundamental level. And yet, time passes… Things happen – even though the Wheeler-DeWitt equation seemed to say that they could not. ‘Now, you may think that this is a kind of a joke, and that wise people would find a solution to that,’ says Linde. But when ‘wise people’ first tried, matters got only more confusing. Linde recalls his friend and colleague the British physicist Stephen Hawking visiting him in Russia in the mid-1980s, and telling him of his attempt to make sense of the prediction from the Wheeler-DeWitt equation that nothing could happen in the Universe overall. Hawking argued that since the evolution of the wavefunction of the Universe apparently did not depend on time, it must depend instead on how big the Universe is.

Astronomical observations made in the 1930s told us that neighbouring galaxies are receding away from us, and our Universe is currently expanding. Hawking speculated that this growth might come to an end; at some point, he said, the Universe could reach a maximum size and then begin contracting. Since, in his proposal, the Universe’s evolution depends only on its size, as the cosmos shrinks back down, all the cosmic changes that had happened when the Universe was growing would rewind and be unmade. This way, Hawking posited, the overall wavefunction would ultimately be unchanged. Linde baulked at Hawking’s suggestion: instead of humans experiencing first birth, life and then finally death, time would turn back as the Universe contracted, and ‘the dead would stand up from the graves', he scoffs. 'People would get younger and younger, broken glass would suddenly jump from the floor and become glued together again, and dinosaurs will reappear on the Earth.' Though physicists wouldn't admit that this was explicitly the consequence of such a theory, 'because it is too obviously ridiculous', that, Linde insists, was the physical upshot. 'You could call this the greatest blunder of Hawking's life.' Anyone who has met Linde will know that he is a man with great a passion for his physics; in fact, he feels such 'blunders' and missteps in the development of his corner of cosmology viscerally. As a young researcher in Russia, he hit a temporary intellectual roadblock with the development of inflation theory (he, and others, had been unable initially to work out a mechanism that would explain how the Universe would stop inflating at a breakneck, faster-than-light speed – as ours has, today expanding at a much more modest rate). While struggling with the mathematics, before eventually solving the conundrum, he fell into a funk. It was during this year of emotional frustration that he turned to the Advaita Vedanta, the philosophy that emphasises oneness between the self and the Universe. 'I should not jump into Indian philosophy, which I am not exactly an expert in,' says Linde, cautiously. Rather than making stark pronouncements about physics based on the readings of his youth, he simply wants to point out the similarities that struck him between the problem of vanishing time arising from the Wheeler-DeWitt equation and the Indian conception of time. In contrast to Judeo-Christian-Islamic notions of a God as a superior being, notes Linde, or perhaps thought of as a powerful, but external, force of nature – there is the more Eastern abstraction of God as absolute perfection encompassing everything. This perfection cannot change in time because if it did, then it would either have to have been less perfect in the past, or become less perfect in the future. ‘And then you think about the wavefunction of the Universe, which is absolute perfection, which does not depend on time, which embeds everything – everything including observers,’ says Linde. Indian philosophers two millennia ago were faced with the same paradox as modern physicists: how can an unchanging reality hold within it observers that undergo change? The ancient philosophers’ solution, Linde notes, is that time ticks for humans because we have ‘cut ourselves out from God’. Once we do so, then from our individual perspective, experiencing reality as a separate being, the rest of the Universe starts to tick, evolving in time relative to each human being as an observer.

So far, so mystical. But, perhaps surprisingly, a similar solution to the problem of time in physics was proposed in 1983 by one of Hawking’s students and later collaborator, Don Page, in Canada without any consideration of Hindu teachings. Page and his colleague Bill Wootters turned instead to a well-established quantum phenomenon known as ‘entanglement’, which has been demonstrated many times in the lab. Here, the very laws of quantum physics hold that some particles are connected together no matter how far they are pulled apart; indeed, in experiment after experiment, measurements carried out on one always instantaneously influences the properties of its entangled mate. Page and Wootters pondered what would happen if you took the whole unchanging Universe and chopped it into two entangled pieces. They calculated that an observer, a human consciousness, say, or maybe even an inanimate recording device, sitting in one entangled part would monitor the other part of the Universe evolving relative to its own. The crucial insight was that the presence of an observer on one side starts the clock running on the other side. 'How do you know that people are dying and being born? You first look at them,' says Linde, slapping his hand to his knee, for emphasis. 'That is the key: there must be somebody who looks.' Importantly, Page and Wootters calculated that when both divided parts of the Universe are monitored in conjunction by some imagined superobserver, the evolution within the individual parts should counterbalance, so that from an external god's-eye view there would be no evolution in the cosmos as a whole. The wavefunction of the entire Universe would remain timeless, just as DeWitt had predicted, solving the problem of how an unchanging Universe can house time. Though this was just a mathematical speculation, it has since been tested in the lab, in an extremely pared-down version of the Universe, containing a meagre two particles – not a complex enough model system for anything too exciting to happen, perhaps, but with just enough pieces to test the theoretical claim. The quantum physicist Marco Genovese and colleagues used two photons to represent the two sides of a divided microcosmos. The photons were both polarised, meaning that each one vibrated along its length. The team entangled the pair of photons in such a way that, if the polarisation of the first photon was measured to be vibrating up and down, its entangled partner would instantaneously be forced to vibrate from side to side. The photons also served as mini clocks because, in addition to being polarised, they also each literally rotated at a constant rate, like the hands on a watch. The team could thus, in principle, measure how time passed within each half – if time did indeed pass – by monitoring how far the photon in that half had rotated. Technically, the act of measuring one photon's rotation causes the experimenters to become entangled with it themselves, so in essence the physicists then became part of the first photon's side of the micro-Universe. From this vantage point, they could then monitor how the second photon – the second half of the Universe – evolved, by measuring how far it had rotated, relative to the first photon. By doing this, the team was able to confirm one part of Page and Wootters's proposition, that if you are housed within one part of the Universe, you will be able to view changes in the other half. The trick was then to repeat the experiment, but this time from the god's-eye viewpoint that remained external to both halves of the microcosmos, or both photons. In that case, the team could not allow themselves to become entangled with either photon; they were allowed only to measure the joint state of both photons, taken together as a pair. That meant that they could no longer see any relative rotation between the two photons, or the passage of time. All they could do was confirm that the two photons were permanently polarised in opposing directions – up-and-down and side-to-side – with this eternal embrace never changing. Research confirmed that when viewed from outside, their two-photon Universe, as a whole, was frozen in time.

'So as long as you do not have an observer, the arrow of time doesn't exist, and the paradox doesn't exist,' Linde explains. 'But as soon as you have an observer, the Universe becomes alive. This duality between you and the Universe is part of the whole package.' Though not a religious man, this has inspired him to riff about the fate of people after death;

perhaps, as some non-Western philosophies suggest, their individual consciousnesses become unified with the wholeness of the Universe, once more. Nobody is suggesting that progress in physics will be found by mining ancient Hindu scriptures directly for inspiration. Nor, indeed, that scholars of the Advaita Vedanta had some privileged insight into scientific truths. Yet, curious resonances between the philosophical ideas read in one's youth, and theoretical speculations that arise from the physics of today can sometimes make the latter seem more compelling. Perhaps that is why Linde was more intuitively drawn to Page and Wootters's solution to the problem of time than to Hawking's. More so than Linde, Ashtekar has spent many years practising meditation, and he is unabashed about the interplay between his scientific thinking and his spirituality – the parallels between his two worlds are poetic and profound. With colleagues, he has proposed an alternative to the conventional picture, in which time is created in the explosion of the Big Bang, arguing instead that the cosmos is eternal, and removing the need for those pesky infinitely small and dense singularities that physicists have spent decades struggling to explain. But he has also thought about ways to bring the two modes of thought – spiritual and scientific – together more explicitly, when considering the nature of consciousness.

Ashtekar was raised in an Indian religion that eschews the idea of a deity, and places emphasis on avoiding cruelty to humans and animals, as the soul moves through cycles of reincarnation. For Ashtekar, it was not enough to just accept that the Universe is pervaded by a four-dimensional spacetime fabric. He wanted to know how that fabric was stitched together, believing that the answer held the key to explaining how general relativity and quantum theory can come together on the tiniest scales. Ashtekar's speculative theory is known as 'loop quantum gravity' and sounds almost too trivial to be true. Ashtekar was wearing a grey shirt and started to pull at its threads to illustrate his thinking. He remarked that when it is viewed from afar, the shirt appears to be cut from one continuous smooth material; viewed up close, however, you can see the threads from which it is woven. Similarly, he argues that if we had powerful enough microscopes to zoom in on Einstein's fabric, we would see that it is knitted together from 'loops' – hypothetical threads of energy that manifest through quantum processes. There's precedent for the idea that such threads could pop from seemingly nowhere in conventional physics. For instance, physicists have a quantum description for light, which states that light particles, or photons, are actually excited bundles of energy that rise up from a background electromagnetic field – like water waves swelling up from an otherwise still ocean. What's more, the unpredictability of quantum theory also extends to the seemingly empty vacuum, so you can never say with certainty that is it truly empty. That enables pairs of 'virtual photons' to be created fleetingly from apparently empty space, before they recombine and disappear. Ashtekar's proposed loops take these established quantum concepts a step further, spontaneously manifesting as agitations of a hypothetical field of 'quantum geometry', which he posits exists everywhere, eternally. These loops then link together to create a web that weaves together spacetime. At first, it might seem as if he has just replaced one mysterious fabric that pervades the Universe – Einstein's spacetime – with an equally enigmatic web of quantum geometry and loops. But Ashtekar's theory has another nifty feature: it demarcates a minimum loop size below which the loops cannot knit together. That, in turn, sets a minimum size below which spacetime, itself woven from loops, cannot be squeezed. This means that, according to the loop quantum gravity picture, the Universe could never have been squashed into a tiny singularity, even at its birth.

To find out what might have happened at the Big Bang, according to his loopy framework, Ashtekar and colleagues created a computer simulation of the Universe and then wound the clock back roughly 13 billion years, to the time when the Big Bang is thought to have occurred. At first, things proceeded in the conventional way: as time reversed, the cosmos became smaller and smaller. But just before reaching the point where conventional physics puts the Big Bang's infinitely small singularity, the cosmos shrunk down to a certain minuscule but finite size, and then began to expand outwards again. Ashtekar argues that this indicates that our cosmos had no beginning – no birth at a Big Bang singularity – but instead has always existed. At some point, in the past, he says, the cosmos contracted, and then bounced outwards again, and we now live in that expanding phase. Ashtekar says that the parallels between his theory of loops and the ancient scriptures – both describing a universe cycled through phases of creation and destruction – are merely coincidental. But there are other areas where he makes more explicit links between his physics and spirituality.

Over the past decade or so, Ashtekar has become a more committed adherent of Buddhism. Isolated from the world, he strives to reach a state of consciousness 'beyond thought', challenging the intellectual focus and diligence of the physicist. ‘From my intellectual life I had the inner pride of being able to concentrate for hours,’ he says. ‘When I am working on something, I completely lose track, sometimes to my detriment.’ But this paled against the strength of mind needed to sustain deep meditation. Ashtekar felt like a helpless child. ‘They do say that the first time you do it, it is like “surgery for the mind”, and it does have very, very deep cleansing effect on your consciousness,’ he says. Inspired by his meditative practice, Ashtekar is training a scientific eye on other aspects of Buddhist philosophy. The practice teaches of a cycle of personal reincarnation broken by reaching enlightenment. Ashtekar has been pondering whether it might be possible to develop a physical model of consciousness that chimes with this. His viewpoint is that there is a universal field of consciousness, embedding our individual selves. Harking back again to quantum physical description of photons as excitations of an electromagnetic field, and his own proposal that loops are lumps of energy thrown up from a background sea of quantum geometry, Ashtekar describes our individual consciousnesses as agitations in this ocean. As we experience the daily trials of life as well as profound suffering, we are pulled from this calm background like angry turbulent waves. Meditation, Ashtekar posits, quiets our minds, enabling us to sink back into a still sea. ‘Perhaps nirvana is just the ground energy state’ – the lowest energy state – ‘of this consciousness field,’ Ashtekar speculates. This is not simply a metaphor for Ashtekar, but a scientific proposal, though one that he has yet to rigorously develop and for which there is, for now at least, no means to test. This does not dismay Ashtekar, who points out that way back in 1916

Einstein predicted that ripples in his spacetime fabric could potentially be observed. It took another century for physicists to detect these ripples, or gravitational waves, which were set off when two black holes collided long ago. The best and most convincing proof, Ashtekar argues, will not come from a lab test, but from people trying deep meditation for themselves. Both Ashtekar and Linde concede that many scientists will raise their eyebrows at attempts to bring together science and spirituality, worrying about the dangers of dragging physics into mysticism. Scholars of non-Western philosophy will be equally wary about the merits of picking and choosing which aspects of their teachings to use as a lens through which to view cosmology. Yet spiritual lessons do sometimes inform the speculative ideas to which physicists might be drawn intuitively. When faced with rival physical theories, instinct can play a role in deciding which sits better with your taste, even for professional scientists. As Linde puts it, the theories that you pursue with a passion are not the ones that seem right based merely on mathematical grounds, but must also 'tell something to your heart'.
Adapted from Aeon

Exercise III.

Fill in the gaps.

1) Champagne is an exquisite drink, made with delicate precision and ________________ care.

2) Nanoscale spin wave localization using ferromagnetic_____________ force microscopy.

3) However, like many other technologies, scanners are becoming _____________ cheaper.

4) As the calendar flips to a new year, we ____________ the past and dream of the future.

5) Beekeeping fascinated him as a youngster, and he read ___________________ on the topic.

6) When the lights came on after the showing, there were a lot of _________________ looks.

7) That's the question that we on the committee will have to _______________ with this week.

8) Like McDonald's, the company grew at a ______________ speed in its first few decades.

9) The chances of those two alignments being purely _______________ are extremely low.

10) Although it's still ______________, most of us expect that the Higgs will be found.

Exercise IV.

Make up sentences of your own with the following word combinations: swelling up, to recount, to delve, to deem, to ponder, to contract, to pervade, to discomfit, to scoff, to ponder

Exercise V.

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

to recede	a bell or a metal bar or tube, typically one of a set tuned to produce a melodious series of ringing sounds when struck

chime	a small wave or series of waves on the surface of water, esp. as caused by an object dropping into it or a slight breeze
conjunction	consternation and distress, typically that caused by something unexpected
conundrum	a god or goddess
perplexed	a proverb or short statement expressing a general truth
modicum	completely baffled; very puzzled
adage	a confusing and difficult problem or question
deity	go or move back or further away from a previous position
dismay	the act of joining or the condition of being joined
ripple	a small quantity of a particular thing, esp. something considered desirable or valuable

Exercise VI.

Identify the part of speech the words belong to: frustration, resonance, inexorably, reticence, voraciously, counterbalance, diligence, speculative, detriment, viscerally, infinite, adherent

Exercise VII.

Match the words to make word combinations:

wannabe	realm
odd	point
pared-down	consciousnesses
vantage	ball
quantum	guru
ground	version
spiritual	book
micro	texts
groundbreaking	state
human	cosmology

Exercise VIII.

Summarize the article "How cosmic is the cosmos?"

2. Anthropic arrogance

Exercise I.

Say what Russian words help to guess the meaning of the following words: design, categorise, religious, argument, combination, phenomena, gravitational, electric, proton, mass

Exercise II.

Make sure you know the following words and word combinations.

dial-twiddler, hard-headed, puddle, crunch, smidgeon, fodder, token, to barren, to debunk, denigration

Anthropic arrogance

Claims that the Universe is designed for humans raise far more troubling questions than they can possibly answer

Welcome to the 'anthropic principle', or 'intelligent design' for the whole Universe. It's easy to describe, but difficult to categorise: it might be a scientific question, a philosophical concept, a religious argument – or some combination. The anthropic principle holds that if such phenomena as the gravitational constant, the exact electric charge on the proton, the mass of electrons and neutrons, and a number of other deep characteristics of the Universe differed at all, human life would be impossible. According to its proponents, the Universe is fine-tuned for human life. This raises more than a few questions. For one, who was the presumed cosmic dial-twiddler? (Obvious answer, for those so inclined: God.) Second, what's the basis for presuming that the key physical constants in such a Universe have been fine-tuned for us and not to ultimately give rise to the bacteria and viruses that outnumber us by many orders of magnitude? For a more general perspective, Douglas Adams developed what has become known as the ‘puddle theory’: Imagine a puddle waking up one morning and thinking, ‘This is an interesting world I find myself in – an interesting hole I find myself in – fits me rather neatly, doesn’t it? In fact it must have been made to have me in it!’ It appears that Adams favoured a puddle-thropic principle. Or at least, the puddle did. But perhaps I should be more serious about an idea that has engaged not just theologians and satirists but more than a few hard-headed physicists. The Australian astrophysicist Brandon Carter introduced the phrase ‘anthropic principle’ at a conference in Poland in 1973 celebrating the 500th anniversary of the birth of Copernicus. Copernicus helped evict the Earth – and thus, humanity – from its prior centrality, something that the anthropic principle threatens (or promises) to re-establish. For Carter, ‘our location in the Universe is necessarily privileged to the extent of being compatible with our existence as observers’. In other words, if the Universe were not structured in such a way as to permit us to exist and, thus, to observe its particular traits, then – it should be obvious – we wouldn’t be around to marvel at its suitability for our existence! In A Brief History of Time (1988), the late British physicist Stephen Hawking described a number of physical constants and astrophysical phenomena that seem at least consistent with the anthropic principle. Hawking noted that ‘if the rate of expansion one second after the Big Bang had been smaller by even one part in a hundred thousand million million, the Universe would have recollapsed before it ever reached its present size’. In short, a change so small it challenges the imagination, and the Big Bang would have turned into a kind of Big Crunch. Albert Einstein considered the 'cosmological constant', which he introduced in 1917, his 'biggest blunder'. Considering the emergence of the anthropic principle, however, it seems prescient. Einstein was troubled by the fact that gravity would cause the Universe to collapse onto itself (that Big Crunch), so he surmised a constant – essentially out of thin air – that pulled in the opposite direction, causing the cosmos to remain stable. The American physicist Steven Weinberg – not a religious believer – points out that if this now-confirmed constant were just a smidgeon larger, the Universe would be vaporously insubstantial. It would never have stopped expanding at a rate that precludes the formation of galaxies, never mind planets or mammals such as ourselves. In 1961, providing even more fodder for the anthropic principle, the American physicist Robert Dicke suggested that, at an estimated 14.5 billion years of age, our Universe stands at a 'golden interval', neither too young nor too old, but just right. Any younger – ie, if the Big Bang had occurred in the more recent past – and it would not have allowed enough time for nucleosynthesis to stock the Universe with elements heavier than hydrogen and helium. There would be no medium-size, rocky planets and thus, no us. By the same token, if the Universe were substantially older than it is, most stars would have matured into white and red dwarfs. They would unable to support stable planetary systems. The four fundamental interactions connecting mass and energy – gravitation, electromagnetic attraction and repulsion, and the 'strong' and 'weak' nuclear forces – also appear balanced precisely as needed to produce matter and, ultimately, life. Put it all together and there appears to be a significant case for the anthropic principle. Not everyone, however, agrees that the necessary conditions for a life-supporting Universe are so delicate. 'The parameters of our Universe,' writes the astrophysicist Fred Adams at the University of Michigan, 'could have varied by large factors and still allowed for working stars and potentially habitable planets.' What to believe?

It's important to note that the anthropic principle exists in two primary forms, 'strong' and 'weak'. Over-simplifying, the weak principle is teleological. It holds that, as Carter had pointed out, whatever conditions are observed in the Universe must allow the observer to exist. In short, if these constants weren't as they are, we wouldn't be around to worry about them. To this, Hawking added that even slight alterations in the life-enabling constants of fundamental physics in this hypothesised multiverse could 'give rise to universes that, although they might be very beautiful, would contain no one able to wonder at that beauty'. The weak version of the anthropic principle thus poses a logical conundrum. The strong version is very different; it is in essence a religious expression, maintaining that some divine being created the Universe for human life. An even stronger version has been called the final anthropic principle, namely that 'intelligent information-processing must come into existence in the Universe, and, once it comes into existence, will never die out'. Martin Gardner, a former maths and science writer for Scientific American, dubbed it the 'completely ridiculous anthropic principle' (CRAP). The anthropic assertion, whether in its weak, strong or final version, has generated some more serious, and interesting, responses. One is contained within Einstein's remark: 'What really interests me is whether God had any choice in the creation of the world.' Posing whether 'God had any choice' was Einstein's way of asking if the manifold characteristics of the physical Universe, such as the speed of light, the charge of the electron and the proton, etc, are fixed or susceptible to alternatives. If fixed, they might appear to have been organised with carbon-based life in mind, but were actually not 'free parameters' in the first place. Note that Einstein was asking if the deep laws of physics might have in fact fixed the various physical constants of the Universe as the only values that they could possibly have, given the nature of reality, rather than having been ordained for some ultimate end – notably, us. At present, we simply don't know whether the way the world works is the only way it could; in short, whether currently identified laws and physical constants are somehow bound together, according to physical law, irrespective of whether human beings – or anything else – eventuated. The Universe is a big place and despite our understandable fascination with the anthropic principle, the stark truth is that nearly all of it is incompatible with life – at least our carbon-based, water-dependent version of it. Given the abundance of other possible locations, if humans existed simply as a result of chance alone, we'd find ourselves (very briefly) somewhere in the very cold empty void of outer space, and would be dead almost instantly. Might this, in turn, contribute to the conclusion that our very existence is evidence of a beneficent designer? But we're not the outcome of a strictly random process: we find ourselves occupying the third planet from the Sun, which has sufficient oxygen, liquid water, moderate temperatures, and so forth. It isn't a coincidence that we occupy a planet that is suitable for life, if only because we couldn't survive where it isn't. There are many ways and contexts in which to interpret what might be called the unexpectedness of our existence, none of which necessarily supports the conclusion of divine planning. Physics has many possible explanations for what masquerades as cosmic fine-tuning. Of these, one of the more intriguing (albeit difficult to grasp) is the possibility of 'multiverses', which revisits the question of probabilities before versus after an event, albeit in a somewhat different guise. Shanks suggests that the multiverse hypothesis 'does to the anthropic Universe what Copernicus's heliocentric hypothesis did to the cosmological vision of the Earth as a fixed centre of the Universe'. Post-Copernicus, the Earth is known to be just one planet among many, in one galaxy among many. Perhaps we're just the occupants of one universe among many. Interestingly, even as he demoted the Earth, Copernicus himself placed the Sun in the centre of the Universe, just as he assumed that planetary orbits were perfect circles. This was an assumption common in early astronomy, based on the notion that the 'heavenly bodies' are perfect, just as, in their geometry, circles are perfect. Galileo, too, presumed circular planetary orbits. It was the German mathematician and astronomer Johannes Kepler, who showed the world that they are elliptical. For the possibility of extraterrestrial life, it seems likely (although by no means certain) that it would have to reside on one or more exoplanets, asteroids or perhaps a comet, rather than within a star or freely floating in open space. Such exoplanets would have to be associated with stars that, for example, don't emit massive amounts of X-rays or other forms of radiation. This all presumes 'life as we know it'.

Quantum mechanics offers another potential solution to the anthropic conundrum; one that seems, if anything, weirder than the multiverse hypothesis. According to theory, matter, at its most fundamental level, is made up of probabilistic wave functions, which only transition to 'reality' when a conscious observer intervenes to measure or perceive it. In the famous 'double-slit experiment', light is revealed to be either a particle or a wave only after it is measured as one or the other. The American theoretical physicist John Wheeler, one of the pioneers of quantum mechanics suggested a participatory anthropic principle, whereby, believe it or not, the Universe had to include conscious beings in order for it – not necessarily us – to exist. I don't believe it. At the same time, the fact that one of the world's most renowned physicists floated this as a genuine possibility gives at least some credence to the notion that perhaps this or some other inverted version of the weak anthropic principle shouldn't be rejected out of hand. There are, of course, people who reject evolution out of hand but who might nonetheless be intrigued by the following argument: maybe it's not surprising that we live in a Universe suitable for life, not because that Universe has been fine-tuned for us (the strong anthropic principle) or has somehow been 'made real' by us (Wheeler's inverted weak anthropic principle), but because we are fine-attuned to it as a result of natural selection. Just as the physical qualities of air have selected for the structure of bird wings, and the anatomy of fish speaks eloquently about the nature of water, maybe the nature of the physical Universe has in the most general sense, selected for life, and thus, for us. There is also a more bizarre way of incorporating natural selection into the anthropic quest. What if natural selection occurs at the level of galaxies, or even universes, such that those offering the potential for life are more likely to replicate themselves? If so, then compared with life-denying galaxies, life-friendly ones might conceivably have produced more copies of themselves, providing greater opportunities for life forms such as ourselves. Aside from the unlikelihood of this 'explanation', it remains unclear how or why such pro-life galaxies would be favoured over their more barren alternatives. Nonetheless, the American theoretical physicist Lee Smolin has pursued the notion of 'cosmological natural selection', whereby perhaps not just galaxies but entire universes replicate themselves, courtesy of black holes. If so, then what sort of universes would be favoured – 'selected for', as biologists put it? Easy: those that employ physical laws and constants that are more fit, ie, that lend themselves to being reproduced. This conveniently explains (if explanation is the correct word) why our Universe contains black holes: it's how they replicate. It also leads to the supposition that perhaps intelligent beings can contribute to the selective advantage of their particular universe, via the production of black holes, and who-knows-what-else. The American astronomer Carl Sagan broached another no less weird version of the anthropic principle in his novel Contact (1985). In it, an extraterrestrial intelligence advises the heroine to study transcendental numbers – numbers that are not algebraic – of which the best-known example is pi. She computes one such number out to 1020 places, at which point she detects a message embedded in it. Since such numerology is fundamental to mathematics itself and is thus, in a sense, a property of the basic fabric of the Universe, the implication is that the cosmos itself is somehow a product of intelligence. The message is clearly an artificial one and not the result of random noise. Or maybe the Universe itself is alive, and the various physical and mathematical constants are part of its metabolism. Such speculation is great fun, but it's science fiction, not science. It should be clear at this point that the anthropic argument readily devolves – or dissolves – into speculative philosophy and even theology. Indeed, it is reminiscent of the 'God of the gaps' perspective, in which God is posited whenever science hasn't (yet) provided an answer. Calling upon God whenever there is a gap in our scientific understanding may be tempting, but it is not even popular among theologians, because as science grows, the gaps – and thus, God – shrinks. It remains to be seen whether the anthropic principle, in whatever form, succeeds in expanding our sense of ourselves beyond that illuminated by science. I wouldn't bet on it. Yet, despite what has been called 'Copernican mediocrity', the deflating recognition that we aren't the centre of the Universe, all this debunking of human specialness isn't necessarily cause for despair or for a spasm of species self-denigration. Just because the anthropic principle is shaky at best, this need not, and should not, give rise to an alternative 'misanthropic principle'. Regardless of how special we are (or aren't), aren't we well-advised to treat everyone – including the other life forms with which we share this planet – as the precious beings we like to imagine us all to be?

Adapted from Aeon

<u>Exercise III</u>.

Fill in the gaps.

1) I ____________ they don't have a particularly good understanding of cause and effect.

2) She goes over to a little ______________, touches it with her toes, watches the ripples.

3) Expansion may continue more slowly, or the universe may even ________________.

4) Growth looks softer than expected and inflation is a ________________ more energetic.

5) At the same time, funding from local authorities has often been ____________________.

6) He assumes the accuracy of her _______________, and jumps to sweeping generalizations.

7) But what happens if that high rate of development and growth does not _________________?

8) You may realize that you haven't given yourself or your talent enough__________________.

9) Individuals have a responsibility to consume wisely, stimulating _____________ demand.

10) Eventually the massive centrifugal forces on the rear tyre caused it to __________________.

<u>Exercise IV</u>.

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

to presume, to evict, to recollapse, to surmise, to eventuate, stark, void, to intervene, to broach

<u>Exercise V</u>.

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

preclude	belief in or acceptance of something as true
delicate	prescribe; determine (something)
manifold	let air or gas out of (a tire, balloon, or similar object)
transcendental	tending to remind one of something
to dissolve	many and various
to lend	of or relating to a spiritual or nonphysical realm
reminiscent	become incorporated into a liquid so as to form a solution
to deflate	prevent from happening; make impossible
to ordain	very fine in texture or structure; of intricate workmanship or quality
credence	grant to (someone) the use of (something) on the understanding that it shall be returned

Exercise VI.

Identify the part of speech the words belong to.

blunder, prescient, vaporously, insubstantial, teleological, conundrum, assertion, susceptible, beneficent, mediocrity

Exercise VII.

Match the words to make word combinations:

intelligent	arrogance
religious	theory
golden	direction
electric	concept
gravitational	phenomena
opposite	interval
astrophysical	believer
puddle	constant
philosophical	charge
anthropic	design

<u>Exercise VIII</u>.

Summarize the article "Anthropic arrogance".

3. Going nowhere fast

Exercise I.

Say what Russian words help to guess the meaning of the following words: standard, model, experiments, crisis, data, decades, quantum, copies, mysteries, elegant

Exercise II.

Make sure you know the following words and word combinations.
bedrock, fleeting, alight, hull, to stall, to annihilate, to squeeze, tethered, steer, bleak

Going nowhere fast

After the success of the Standard Model, experiments have stopped answering to grand theories. Is particle physics in crisis?

In recent years, physicists have been watching the data coming in from the Large Hadron Collider (LHC) with a growing sense of unease. We've spent decades devising elaborate accounts for the behaviour of the quantum zoo of subatomic particles, the most basic building blocks of the known universe. The Standard Model is the high-water mark of our achievements to date, with some of its theoretical predictions verified to within a one-in-ten-billion chance of error – a simply astounding degree of accuracy. But it leaves many questions unanswered. For one, where does gravity come from? Why do matter particles always possess three, ever-heavier copies, with peculiar patterns in their masses? What is dark matter, and why does the universe contain more matter than antimatter? In the hope of solving some of these mysteries, physicists have been grafting on elegant and exciting new mathematical structures to the Standard Model. The programme follows an arc traced by fundamental physics since the time of Isaac Newton: the pursuit of unification, in which science strives to explain seemingly disparate ‘surface’ phenomena by identifying, theorising and ultimately proving their shared ‘bedrock’ origin. This top-down style of thinking has yielded many notable discoveries. Newton perceived that both an apple falling to the ground, and the planets orbiting around the sun, could be explained away by gravity. The physicist Paul Dirac came up with antimatter in 1928 by marrying quantum mechanics and Einstein’s special theory of relativity. And since the late 20th century, string theorists have been trying to reconcile gravity and quantum physics by conceiving of particles as tiny vibrating loops of string that exist in somewhere between 10 and 26 dimensions. So when the European Organization for Nuclear Research (CERN) cranked up the LHC just outside Geneva for a second time, hopes for empirical validation were running high. The fruits of physicists’ most adventurous top-down thinking would finally be put to the test. In its first three-year run, the LHC had already notched up one astounding success: CERN announced that the Higgs boson had been found, produced in high-energy, head-on collisions between protons. The new particle existed for just a fleeting fraction of a second before decaying into a pair of tell-tale photons. What set the scientific world alight was not the excitement of a new particle per se, but the fact it was a smoking gun for a theory about how matter gets its mass. Until the British physicist Peter Higgs and others came up with their hypothetical boson in 1964, the emerging mathematical model had predicted – against the evidence – that particles should have no mass at all. Eventually, half a century after the 'fix' was first proposed, the boson officially entered the subatomic bestiary, the last bit of the Standard Model to be experimentally verified. This time, though, none of the more exotic particles and interactions that theorists hoped to see has been forthcoming. The null results are now encrusting the hull of the Standard Model. It looks like the centuries-long quest for top-down unification has stalled, and particle physics might have a full-blown crisis on its hands. Behind the question of mass, an even bigger and uglier problem was lurking in the background of the Standard Model: why is the Higgs boson so light? In experiments it weighed in at 125 times the mass of a proton. But calculations using the theory implied that it should be much bigger – roughly ten million billion times bigger, in fact.

This super-massive Higgs boson is meant to be the result of quantum fluctuations: an ultra-heavy particle-antiparticle pair, produced for a fleeting instant and then subsequently annihilated. Quantum fluctuations of ultra-heavy particle pairs should have a profound effect on the Higgs boson, whose mass is very sensitive to them. The other particles in the Standard Model are shielded from such quantum effects by certain mathematical symmetries – that is, things don't change under transformation, like a square turned through 90 degrees – but the Higgs boson feels the influence very keenly. Except that it doesn't, because the mass of the Higgs appears to be so small. One logical option is that nature has chosen the initial value of the Higgs boson mass to precisely offset these quantum fluctuations, to an accuracy of one in 1016. However, that possibility seems remote at best, because the initial value and the quantum fluctuation have nothing to do with each other. It would be akin to dropping a sharp pencil onto a table and having it land exactly upright, balanced on its point. In physics terms, the configuration of the pencil is unnatural or fine-tuned. Just as the movement of air or tiny vibrations should make the pencil fall over, the mass of the Higgs shouldn't be so perfectly calibrated that it has the ability to cancel out quantum fluctuations. However the problem with the Higgs boson could be explained away by a new, more foundational theory: supersymmetry. To grasp supersymmetry, we need to look a bit more closely at particles. Particles behave a bit like tiny spinning tops, although the amount of their spin is restricted. For example, all electrons in the universe have the same amount of spin; all photons have double this amount, and all Higgs bosons have no spin at all. The fundamental unit of spin is the spin of the electron. Other particles may only have spins equal to some whole number multiplied by the electron's spin. Supersymmetry is an idea that connects particles of different spins: it says they are different aspects of the same underlying object. Importantly, the large quantum fluctuations of particle-antiparticle pairs that affect the Higgs boson make the Higgs lighter if the spin of the antiparticle is an odd number multiple of an electron's spin, or heavier if the spin of the antiparticle is an even number multiple of an electron's spin. What this means is that supersymmetry can balance the quantum effects on the mass of the Higgs boson like a see-saw. On one side sit all of the odd-number spin particles, exactly balanced against the other side with the even-number spin particles. The overall effect is that the see-saw doesn't move, and the Higgs boson experiences no huge quantum influences on its mass.

A major consequence of supersymmetry is that every particle we know about should have a copy (a 'superpartner') with exactly the same properties – except for two things. One, its spin should differ by one unit. And two, the superpartner should be heavier. The mass of the superpartner is not fixed, but the heavier one makes them, the less exact the cancellation between the particle and its superpartner, and the more you have to rely on the mass of the particle itself being fine-tuned. One can make superpartners have a mass of around 1,000 times that of a proton, and they still function reasonably well. But increase the mass by a factor of 10 and the theory goes back to looking quite unnatural. By smashing protons together, the LHC should be able to produce these superpartners, provided they weigh around 1,000 times the mass of a proton. To do this, you change the energy of the proton beams into the mass of the predicted superpartners, via Einstein's equation of special relativity: $E=mc2$ (energy equals the square of the mass). Each collision is a quantum process, however, which means it's inherently random and you can't predict exactly what will happen. But using the correct theory, you can calculate the relative probabilities of various outcomes. By measuring billions upon billions of collisions, you can then check the theory's predictions against the relative frequencies of particles that are created. As you can already tell, finding out what happens at the point of the protons colliding involves a lot of detective work. In this case, you try to check how often supersymmetric particles are produced by watching them decay into more ordinary particles. The positions of these byproducts are measured by huge detectors that act like enormous three-dimensional cameras. The signature of supersymmetric particles was meant to be the production of a heavy invisible particle, which could sneak through the detector like a thief, leaving no trace. These very weakly interacting particles are candidates for the origin of dark matter in the universe; the strange, invisible stuff that we know from cosmological measurement should be about four times more prevalent than ordinary matter. The red flag for their presence was meant to be theft of momentum from a collision, meaning that the momentum before and after the collision doesn't balance. My colleagues and I watched the LHC closely for such tell-tale signs of superpartners. None have been found. We started to ask whether we might have missed them somehow. Perhaps some of the particles being produced were too low in energy for the collisions to be observed. Or perhaps we were wrong about dark matter particles – maybe there was some other, unstable type of particle.

Another possibility was that the superpartners were a bit heavier than expected; so perhaps the mass of the Higgs boson did have somecancellation in it (one part in a few hundred, say). But as the data rolled in and the beam energy of the LHC was ramped up, supersymmetry became more and more squeezed as a solution to the Higgs boson naturalness problem. The trouble is that it's not clear when to give up on supersymmetry. True, as more data arrives from the LHC with no sign of superpartners, the heavier they would have to be if they existed, and the less they solve the problem. But there's no obvious point at which one says 'ah well, that's it – now supersymmetry is dead'. Everyone has their own biased point in time at which they stop believing, at least enough to stop working on it. The LHC is still going and there's still plenty of effort going into the search for superpartners, but many of my colleagues have moved on to new research topics. For the first 20 years of my scientific career, I cut my teeth on figuring out ways to detect the presence of superpartners in LHC data. It could be that we got the wrong end of the stick with how we frame the puzzle of the Higgs boson. Perhaps we're missing something from the mathematical framework with which we calculate its mass. Researchers have worked along these lines and so far come up with nothing, but that doesn't mean there's no solution. Another suspicion relates to the fact that the hypothesis of heavy particles relies on arguments based on a quantum theory of gravity – and such a theory has not yet been verified, although there are mathematically consistent constructions. Perhaps the bleakest sign of a flaw in present approaches to particle physics is that the naturalness problem isn't confined to the Higgs boson. Calculations tell us that the energy of empty space (inferred from cosmological measurements to be tiny) should be huge. This would make the outer reaches of the universe decelerate away from us, when in fact observations of certain distant supernovae suggest that the outer reaches of our universe are accelerating. Supersymmetry doesn't fix this conflict. Many of us began to suspect that whatever solved this more difficult issue with the universe's vacuum energy would solve the other one concerning the mass of the Higgs. All these challenges arise because of physics' adherence to reductive unification. But none of our top-down efforts seem to be yielding fruit. One of the difficulties of trying to get at underlying principles is that it requires us to make a lot of theoretical presuppositions, any one of which could end up being wrong. We were hoping by this stage to have measured the mass of some superpartners, which would have given us some data on which to pin our assumptions. But we haven't found anything to measure. Instead, many of us have switched from the old top-down style of working to a more humble, bottom-up approach. Instead of trying to drill down to the bedrock by coming up with a grand theory and testing it, now we're just looking for any hints in the experimental data, and working bit by bit from there. If some measurement disagrees with the Standard Model's predictions, we add an interacting particle with the right properties to explain it. Then we look at whether it's consistent with all the other data. Finally, we ask how the particle and its interactions can be observed in the future, and how experiments should sieve the data in order to be able to test it. The bottom-up method is much less ambitious than the top-down kind, but it has two advantages: it makes fewer assumptions about theory, and it's tightly tethered to data. This doesn't mean we need to give up on the old unification paradigm, it just suggests that we shouldn't be so arrogant as to think we can unify physics right now, in a single step. It means we should use empirical data to check and steer us at each instance, rather than making grand claims that come crashing down when they're finally confronted with experiment.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) A visit to Cambodia will inspire and ______________ even the most seasoned travellers.

2) They are two practices serving the same purpose that come from _______________ worlds.

3) It's a piece of the _________________ upon which the future of spaceflight is being built.

4) How do we ________________ God's deliberate use of natural evil to accomplish his will?

5) Surely he can't preside over every quantum ________________ or interaction of quarks?

6) There, they are likely to hit other trapped dark matter particles and ________________.

7) We have reached the limit of what our experiment can do with this _______________.

8) Rushing breakfast, naturally, also is much more ________________ among people who work.

9) The distant ________________ were brighter because they were younger, the study found.

10) With the _________________ to each distinct component, comes the repulsion of the other.

Exercise IV.

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

to devise	shock or greatly surprise
to encrust	a part of the circumference of a circle or other curve
to reconcile	reduce speed; slow down
offset	plan or invent (a complex procedure, system, or

	mechanism) by careful thought
graft	cover (something) with a hard surface layer
upright	restore friendly relations between
to infer	counteract (something) by having an opposing force or effect
arc	a piece of living tissue that is transplanted surgically
to decelerate	deduce or conclude (information) from evidence and reasoning rather than from explicit statements
to astound	vertical

Exercise VI.

Identify the part of speech the words belong to.

disparate, fluctuation, configuration, cancellation, prevalent, adherence, humble, supernovae, sieve

Exercise VII.

Match the words to make word combinations:

empirical	structures
mathematical	validation
top-down	zoo

particle	particles
dark	blocks
theoretical	chance
building	style
subatomic	matter
quantum	predictions
one-in-ten-billion	physics

Exercise VIII.

Summarize the article “Going nowhere fast”

4. Through two doors

Exercise I.

Say what Russian words help to guess the meaning of the following words: experiment, microscopic, mechanics, phase, form, individual, photons, electrons, barrier, intuition

Exercise II.

Make sure you know the following words and word combinations.
Profound, opaque, startling, contingent, adherent, ascribed, to traverse, to shun

Through two doors

How a sunbeam split in two became physics' most elegant experiment, shedding light on the underlying nature of reality

Microscopic particles, governed by the laws of quantum mechanics, throw up some of the biggest questions about the nature of our underlying reality. Do we live in a universe that is deterministic – or given to chance and the rolls of dice? Does reality at the smallest scales of nature exist independent of observers or observations – or is reality created upon observation? And are there 'spooky actions at a distance', Albert Einstein's phase for how one particle can influence another particle instantaneously, even if the two particles are miles apart. As profound as these questions are, they can be asked and understood by looking at modern variations of a simple experiment that began as a study of the nature of light more than 200 years ago. It's called the double-slit experiment, and its findings course through the veins of experimental quantum physics. In its simplest form, the experiment involves sending individual particles such as photons or electrons, one at a time, through two openings or slits cut into an otherwise opaque barrier. The particle lands on an observation screen on the other side of the barrier. If you look to see which slit the particle goes through (our intuition, honed by living in the world we do, says it must go through one or the other), the particle behaves like, well, a particle, and takes one of the two possible paths. But if one merely monitors the particle landing on the screen after its journey through the slits, the photon or electron seems to behave like a wave, ostensibly going through both slits at once. When microscopic entities have the option of doing many things at once, they seem to indulge in all possibilities. Such behaviour is impossible to visualise. Common sense fails us when dealing with the world of the quantum. To explain the outcome of something as simple as a particle encountering two slits, quantum physics falls back on mathematical equations. But unlike in classical physics, where the equations let us calculate, say, the precise trajectory of a ball, the equations of quantum physics allow us to make only probabilistic statements about what will happen to the photon or electron. Crucially, these equations paint no clear picture about what is actually happening to the particles between the source and the screen. It's no wonder then that different interpretations of the double-slit experiment offer alternative perspectives on reality. The history of the double-slit experiment goes back to the early 1800s, when physicists were debating the nature of light. Does light behave like a wave or is it made of particles? The latter view had been advocated in the 17th century by no less a physicist than Isaac Newton. Light, Newton said, is constituted of particles. The Dutch scientist Christiaan Huygens argued otherwise. Light, he said, is a wave – the name given to the vibrations of the medium in which the wave is travelling. In the first years of the 19th century, Thomas Young seemingly settled the debate. He was the first to perform an experiment with a ray of sunlight, a sunbeam, through two narrow slits. On a screen on the other side, he observed not two strips of light – as you'd expect if light is made of particles going through one slit or the other – but a pattern of alternating bright and dark fringes, characteristic of two sets of waves interacting with each other. This view of light as a wave gained strong mathematical support when the Scottish physicist James Clerk Maxwell developed his theory of electromagnetism in the 1860s, showing that light, too, is an electromagnetic wave.

That would have been the end of story – if not for the birth of quantum physics, which began with the German physicist Max Planck's argument in 1900 that energy comes in quanta, or tiny, indivisible units. Then, in 1905, Einstein studied the photoelectric effect, in which light falling on certain metals dislodges electrons; the effect can be explained only if light is also made of quanta, with each quantum of light analogous to a particle. These quanta of light came to be called photons. Now, the double-slit experiment gets maddeningly counterintuitive. Imagine beaming light at two slits one quantum, or particle, at a time. Our classical sensibilities tell us that the photon has to go through one slit or the other. And on the screen on the other side, each photon creates a spot, and we expect these spots to pile up behind the two slits and form two bright strips. But it's the quantum world, so of course that's not what happens. As the photons land on the photographic plate, over time an interference pattern emerges. But our source is emitting light one photon at a time. The photographic plate is recording its arrival as an individual particle. And – this is crucial – the photons are going through the apparatus one at a time. There's no interaction between one photon and the next, or the first photon and the 10th, and so on. So, what's interfering with what? This is where the mathematics comes in. In the mid-1920s, a few fabulously talented physicists, among them Heisenberg, Pascual Jordan, Max Born and Paul Dirac in one group, and Erwin Schrödinger on his own, developed two ways of mathematically depicting the behaviour of the quantum underworld. These two ways turned out to be equivalent. It boils down to this: the state of any quantum system is represented by a mathematical abstraction called a wavefunction. There is a single equation – called the Schrödinger equation – which tells us how this wavefunction, and hence the state of the quantum system, changes with time. This is what allows physicists to predict the probabilities of experiment outcomes. In the context of the double-slit experiment, think of the wavefunction as an undulating surface that encodes information about the location of the photon. When the photon emerges from its source, the wavefunction is peaked at one location, and nearly zero everywhere else, suggesting that the photon is localised near the source. But now mathematics kicks in. The progress of the photon can be captured by the Schrödinger equation, which reveals how the wavefunction evolves with time. The wavefunction starts to spread, as a wave would, with different values at different places. These values are related to the probabilities of finding the particle in those locations, should you choose to look. As this wavefunction spreads, it encounters the two slits. The wavefunction (which, don't forget, is a mathematical abstraction) splits: one component goes through the left slit and the other through the right slit. Two wavefunctions emerge from the other side, and each spreads and evolves, still according to the Schrödinger equation. By the time the individual wavefunctions reach the photographic plate, they have spread out enough to start interfering with each other like the waves in the ocean. The photon's state is now given by a wavefunction that is a combination of the two components' interfering wavefunctions: the photon itself is now said to be in a 'superposition' of having gone through both slits. At the photographic plate, upon detection, this combined wavefunction again peaks in one location and goes to more or less zero everywhere else. The photon is registered at that location. It all seems to make sense – sort of – until you start digging into the mathematical equations. What's a wavefunction and what does it mean for a wavefunction to go through two slits? Is the wavefunction something real? And how does one figure out where the wavefunction will peak when it encounters the photographic plate? Why does it peak there and not elsewhere? In the equations of quantum mechanics, the wavefunction is, well, a mathematical function. For any quantum system with more than two particles, the wavefunction does not live in the three familiar spatial dimensions of our world. Rather, it exists in something called a configuration space (an abstract mathematical space, the number of dimensions of which mushrooms with increasing number of particles, but we can ignore that for now).

All this seems understandable, but upon closer examination more questions appear. Did the photon go through both slits at once? Does the photon have a trajectory, as it leaves the source and is eventually detected at the photographic plate? And given that the mathematics says that there are many regions where the photon can be found with a non-zero probability, why does it end up in one of those regions and not others? Finally, if the photon didn't go through both slits, but rather the wavefunction did, is the wavefunction real? Trying to answer such questions takes us into the heart of what's confounding about quantum mechanics, and brings us in contact with profound philosophical issues about the nature of reality. Take the question of determinism. When you throw a baseball in the classical world, physics will tell you where it will land. Not so in the quantum realm. The wavefunction cannot predict the exact location at which the photon will land – only its probability of landing at any one of a number of spots. For any given photon, you can never predict with certainty where it will be found: all you can say is that it will be found in region A with probability X, or in region B with probability Y, and so on. These probabilities are born out when you do the experiment numerous times with identical photons, but the precise destiny of an individual photon is not for us to know. Nature at its most fundamental seems random. The double-slit experiment also allows us to explore notions of realism, the idea that an objective reality exists independent of observers or observation. Common sense tells us that the photon must have a clear path from the source to the photographic plate, but the mathematical formalism of standard quantum mechanics does not have a variable that captures the position of a particle as it moves – only a starting point and an end point that is contingent upon observation. And so, the photon does not have a trajectory. In fact, in one way of interpreting the formalism – named the Copenhagen interpretation after the place where it took shape – the photon has no objective reality until it lands on the photographic plate. At its extreme, the Copenhagen interpretation is often said to be antirealist. More generally, antirealism takes the position that reality does not exist independent of an observer (an observer does not necessarily mean a conscious human, it could be a photographic plate; opinions vary on this). Einstein was a realist. He was adamant that standard quantum mechanics is incomplete, in that it lacks the necessary variables to capture trajectory – the position and momentum of a particle as it moves. Einstein was also an adherent of the principle of locality: the notion that something happening in one place cannot influence something happening elsewhere any faster than the speed of light. Taken together, this philosophical position is called local realism.

The opposite of locality – nonlocality – gets highlighted by something as simple as the double-slit experiment. When the photon's wavefunction nears the photographic plate, the photon is in a quantum superposition of being in many places at once (this is not to say that the photon actually is in these places simultaneously, it's just a way of talking about the mathematics; the photon itself is not yet ascribed reality in the standard way of thinking about it). Upon observation, the wavefunction is said to collapse, in that its value peaks at one location and goes to near-zero elsewhere. The photon is localised – and thus found to be at one of its many possible locations. If the wavefunction is something real, then its collapse is a nonlocal event. A measurement caused the wavefunction to peak in one location and simultaneously go to zero elsewhere. In principle, the wavefunction could be spread across kilometres, and this scenario would still hold. Regions of spacetime far separated from each other would be instantly influenced by the measurement-induced collapse in one location. There is another way to think about the wavefunction that avoids this difficultly. Many followers of standard quantum mechanics would say that the wavefunction is epistemic– it merely captures our knowledge about the reality. If so, the collapse is merely a sharpening of our knowledge about reality, and so it's not a physical event and hence does not imply nonlocality. But if the wavefunction is not real – then what goes through the two slits? Surely a photon, which cannot be divided any further into smaller parts, cannot go through both slits at once? Something must traverse both slits simultaneously to generate the interference pattern. If not the photon or its wavefunction, what else could it be? The questions about the wavefunction remain. Besides the status of the wavefunction, perhaps the most well-known issue accentuated by the double-slit experiment is how something in the quantum realm can sometimes act like a wave and sometimes like a particle, a phenomenon called wave-particle duality. If we don't care about knowing which slit a photon goes through, the photon behaves like a wave, and lands on a certain part of the photographic plate. Crucially, the photons almost never go to regions that will remain dark. But our classical minds rebel. We cannot disregard the conviction that the photon has to go through one slit or the other. So we put detectors next to the slits (let's assume that our detectors work without destroying the photons). Something weird happens. The photons will now go through one or the other slit. Curiously, this time they act like particles and they will go to those regions on the photographic plate that they shunned when acting like a wave.

It was clear that whether a photon behaves like a wave or a particle depends on the choice of the experimental setup. Based on this finding, in 1978 the American physicist John Wheeler dreamed up perhaps the most famous version of the double-slit experiment, which he called 'delayed choice'. Wheeler's bright idea was to ask: what if we delayed the choice of the type of experiment to perform until after the photon had entered the apparatus? Say it enters an apparatus that is configured to look for the photon's wave nature. So, the photon should – according to the standard way of thinking – go into a superposition of taking two paths. If the two paths are recombined, they interfere, and we get fringes. Now, said Wheeler, let's perform a sleight of hand. Just before the photon is detected, let's reconfigure the apparatus so that it's now looking for the photon's particle nature. As it happens, you cannot fool the photon no matter how hard you try. Experimentalists have performed Wheeler's thought experiment with increasing precision and sophistication – and the quantum world rules. When they remove, at the very last instant, the device that recombines the two photon paths, the photon acts like a particle, suggesting that it took one path or the other, even though at the start it should have entered a superposition of taking both paths at once. Based on such results, Wheeler argued that the photon has no intrinsic nature –

either wave or particle – before it's detected. Otherwise, if it entered the apparatus like a particle and you chose to look at its wave nature, it would have to go back in time and re-enter the apparatus as a wave. To avoid the common sense-defying conceptual problems of standard quantum mechanics, there have been myriad attempts to reinterpret the results and pose new theories. One of these efforts is the so-called de Broglie-Bohm theory, which holds that reality is both a wave and a particle. In this theory, a particle is real and has a definite position at all times, and hence a trajectory; but the particle is guided by a pilot wave that evolves according to the Schrödinger equation. In the context of a double-slit experiment, the particle always goes through one slit or the other, but the pilot wave, or the wavefunction, goes through both and interferes with itself on the other side of the slits, and this interference pattern guides the particle to the photographic plate. It's hard to overstate the importance of the double-slit experiment to the entire enterprise of quantum mechanics, despite its astonishing simplicity and elegance. But physics has yet to successfully explain the double-slit experiment. The case remains unsolved.

Adapted from Aeon

Exercise III.

Fill in the gaps.

1) This is becoming quite an amazingly ________________ effect, at least in the short term.

2) Keeping coffee in an _________________, airtight container on the kitchen counter is ideal.

3) The review shows ___________________ differences in states'contribution to climate change.

4) Women now ______________ almost 42 percent, more than tripling their previous share.

5) There have always been background, _________________ conversations about how it might work

6) Hydrological changes, such as the pumping of groundwater for use by humans, cause the ground beneath us to ____________.

7) Once, access to food, sanitation and heated accommodation were income ______________.

8) Nevertheless, meteorologists are ________________ that our world is still getting warmer.

9) Color theory has ________________ perceptual and psychological effects to this contrast.

10) he time they take to ______________ the chamber depends on their charge and their mass.

Exercise IV.

Make up sentences of your own with the following word combinations: within a one-in-ten-billion chance of error, to come up with antimatter, to crank up, to be put to the test, to notch up, against the evidence, at the very last instant, to peak in one location, go to zero, to be spread across kilometres

Exercise V.

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

profound	move with a smooth wavelike motion

to indulge	remove from an established or fixed position
to constitute	refusing to be persuaded or to change one's mind
undulate	allow oneself to enjoy the pleasure of
fringe	a formal declaration that someone is guilty of a criminal offense, made by the verdict of a jury or the decision of a judge in a court of law
sensibility	be (a part) of a whole
to dislodge	the ability to appreciate and respond to complex emotional or aesthetic influences; sensitivity
conviction	very great or intense
adamant	the outer, marginal, or extreme part of an area, group, or sphere of activity

Exercise VI.

Identify the part of speech the words belong to: standard, experiment, particle, physics, crisis, subatomic, basic, predictions, accuracy, gravity

Exercise VII.

Match the words to make word combinations:

photon	sense
photographic	barrier

electromagnetic	picture
clear	plate
probabilistic	experiment
precise	paths
common	wave
opaque	statements
microscopic	trajectory
double-slit	particles

Exercise VIII .

Summarize the article "Through two doors"

SUPPLEMENTARY READING

Quantum Theory Rebuilt From Simple Physical Principles
Physicists are trying to rewrite the axioms of quantum theory from scratch in an effort to understand what it all means. The problem? They've been almost too successful.

Scientists have been using quantum theory for almost a century now, but embarrassingly they still don't know what it means. An informal poll taken at a 2011 conference on Quantum Physics and the Nature of Reality showed that there's still no consensus on what quantum theory says about reality — the participants remained deeply divided about how the theory should be interpreted.

Some physicists just shrug and say we have to live with the fact that quantum mechanics is weird. So particles can be in two places at once, or communicate instantaneously over vast distances? Get over it. After all, the theory works fine. If you want to calculate what experiments will reveal about subatomic particles, atoms, molecules and light, then quantum mechanics succeeds brilliantly.

But some researchers want to dig deeper. They want to know why quantum mechanics has the form it does, and they are engaged in an ambitious program to find out. It is called quantum reconstruction, and it amounts to trying to rebuild the theory from scratch based on a few simple principles.

If these efforts succeed, it's possible that all the apparent oddness and confusion of quantum mechanics will melt away, and we will finally grasp what the theory has been trying to tell us. "For me, the ultimate goal is to prove that quantum theory is the only theory where our imperfect experiences allow us to build an ideal picture of the world," said Giulio Chiribella, a theoretical physicist at the University of Hong Kong.

There's no guarantee of success — no assurance that quantum mechanics really does have something plain and simple at its heart, rather than the abstruse collection of mathematical concepts used today. But even if quantum reconstruction efforts don't pan out, they might point the way to an equally tantalizing goal: getting beyond quantum mechanics itself to a still deeper theory. "I think it might help us move towards a theory of quantum gravity," said Lucien Hardy, a theoretical physicist at the Perimeter Institute for Theoretical Physics in Waterloo, Canada.

The basic premise of the quantum reconstruction game is summed up by the joke about the driver who, lost in rural Ireland, asks a passer-by how to get to Dublin. "I wouldn't start from here," comes the reply. Where, in quantum mechanics, is "here"? The theory arose out of attempts to understand how atoms and molecules interact with light and other radiation, phenomena that classical physics couldn't explain. Quantum theory was empirically motivated, and its rules were simply ones that seemed to fit what was observed. It uses mathematical formulas that, while tried and trusted, were essentially pulled out of a hat by the pioneers of the theory in the early 20th century. Take Erwin Schrödinger's equation for calculating the probabilistic properties of quantum particles. The particle is described by a "wave function” that encodes all we can know about it. It’s basically a wavelike mathematical expression, reflecting the well-known fact that quantum particles can sometimes seem to behave like waves. Want to know the probability that the particle will be observed in a particular place? Just calculate the square of the wave function (or, to be exact, a slightly more complicated mathematical term), and from that you can deduce how likely you are to detect the particle there. The probability of measuring some of its other observable properties can be found by, crudely speaking, applying a mathematical function called an operator to the wave function.

But this so-called rule for calculating probabilities was really just an intuitive guess by the German physicist Max Born. So was Schrödinger’s equation itself. Neither was supported by rigorous derivation. Quantum mechanics seems largely built of arbitrary rules like this, some of them — such as the mathematical properties of operators that correspond to observable properties of the system — rather arcane. It’s a complex framework, but it’s also an ad hoc patchwork, lacking any obvious physical interpretation or justification.

Compare this with the ground rules, or axioms, of Einstein’s theory of special relativity, which was as revolutionary in its way as quantum mechanics. (Einstein launched them both, rather miraculously, in 1905.) Before Einstein, there was an untidy collection of equations to describe how light behaves from the point of view of a moving observer. Einstein dispelled the mathematical fog with two simple and intuitive principles: that the speed of light is constant, and that the laws of physics are the same for two observers moving at constant speed relative to one another. Grant these basic principles, and the rest of the theory follows. Not only are the axioms simple, but we can see at once what they mean in physical terms. What are the analogous statements for quantum mechanics? The eminent physicist John Wheeler once asserted that if we really understood the central point of quantum theory, we would be able to state it in one simple sentence that anyone could understand. If such a statement exists, some quantum reconstructionists suspect that we’ll find it only by rebuilding quantum theory from scratch: by tearing up the work of Bohr, Heisenberg and Schrödinger and starting again. One of the first efforts at quantum reconstruction was made in 2001 by Hardy, then at the University of Oxford. He ignored everything that we typically associate with quantum mechanics, such as quantum jumps, wave-particle duality and uncertainty. Instead, Hardy focused on probability: specifically, the probabilities that relate the possible states of a system with the chance of observing each state in a measurement. Hardy found that these bare bones were enough to get all that familiar quantum stuff back again. Hardy assumed that any system can be described by some list of properties and their possible values. For example, in the case of a tossed coin, the salient values might be whether it comes up heads or tails. Then he considered the possibilities for measuring those values definitively in a single observation. You might think any distinct state of any system can always be reliably distinguished (at least in principle) by a measurement or observation. And that’s true for objects in classical physics.

In quantum mechanics, however, a particle can exist not just in distinct states, like the heads and tails of a coin, but in a so-called superposition — roughly speaking, a combination of those states. In other words, a quantum bit, or qubit, can be not just in the binary state of 0 or 1, but in a superposition of the two.

But if you make a measurement of that qubit, you'll only ever get a result of 1 or 0. That is the mystery of quantum mechanics, often referred to as the collapse of the wave function: Measurements elicit only one of the possible outcomes. To put it another way, a quantum object commonly has more options for measurements encoded in the wave function than can be seen in practice. Hardy's rules governing possible states and their relationship to measurement outcomes acknowledged this property of quantum bits. In essence the rules were (probabilistic) ones about how systems can carry information and how they can be combined and interconverted. Hardy then showed that the simplest possible theory to describe such systems is quantum mechanics, with all its characteristic phenomena such as wavelike interference and entanglement, in which the properties of different objects become interdependent. "Hardy's 2001 paper was the 'Yes, we can!' moment of the reconstruction program," Chiribella said. "It told us that in some way or another we can get to a reconstruction of quantum theory." More specifically, it implied that the core trait of quantum theory is that it is inherently probabilistic. "Quantum theory can be seen as a generalized probability theory, an abstract thing that can be studied detached from its application to physics," Chiribella said. This approach doesn't address any underlying physics at all, but just considers how outputs are related to inputs: what we can measure given how a state is prepared (a so-called operational perspective). "What the physical system is is not specified and plays no role in the results," Chiribella said. These generalized probability theories are "pure syntax," he added — they relate states and measurements, just as linguistic syntax relates categories of words, without regard to what the words mean. In other words, Chiribella explained, generalized probability theories "are the syntax of physical theories, once we strip them of the semantics." The general idea for all approaches in quantum reconstruction, then, is to start by listing the probabilities that a user of the theory assigns to each of the possible outcomes of all the measurements the user can perform on a system. That list is the "state of the system." The only other ingredients are the ways in which states can be transformed into one another, and the probability of the outputs given certain inputs. This operational approach to reconstruction "doesn't assume space-time or causality or anything, only a distinction between these two types of data," said Alexei Grinbaum, a philosopher of physics at the CEA Saclay in France. To distinguish quantum theory from a generalized probability theory, you need specific kinds of constraints on the probabilities and possible outcomes of measurement. But those constraints aren't unique. So lots of possible theories of probability look quantum-like. How then do you pick out the right one? "We can look for probabilistic theories that are similar to quantum theory but differ in specific aspects," said Matthias Kleinmann, a theoretical physicist at the University of the Basque Country in Bilbao, Spain. If you can then find postulates that select quantum mechanics specifically, he explained, you can “drop or weaken some of them and work out mathematically what other theories appear as solutions.” Such exploration of what lies beyond quantum mechanics is not just academic doodling, for it’s possible — indeed, likely — that quantum mechanics is itself just an approximation of a deeper theory. That theory might emerge, as quantum theory did from classical physics, from violations in quantum theory that appear if we push it hard enough. Some researchers suspect that ultimately the axioms of a quantum reconstruction will be about information: what can and can’t be done with it. One such derivation of quantum theory based on axioms about information was proposed in 2010 by Chiribella, then working at the Perimeter Institute, and his collaborators Giacomo Mauro D’Ariano and Paolo Perinotti of the University of Pavia in Italy. “Loosely speaking,” explained Jacques Pienaar, a theoretical physicist at the University of Vienna, “their principles state that information should be localized in space and time, that systems should be able to encode information about each other, and that every process should in principle be reversible, so that information is conserved.” (In irreversible processes, by contrast, information is typically lost — just as it is when you erase a file on your hard drive.)

What’s more, said Pienaar, these axioms can all be explained using ordinary language. “They all pertain directly to the elements of human experience, namely, what real experimenters ought to be able to do with the systems in their laboratories,” he said. “And they all seem quite reasonable, so that it is easy to accept their truth.” Chiribella and his colleagues showed that a system governed by these rules shows all the familiar quantum behaviors, such as superposition and entanglement.

One challenge is to decide what should be designated an axiom and what physicists should try to derive from the axioms. Take the quantum no-cloning rule, which is another of the principles that naturally arises from Chiribella’s reconstruction. One of the deep findings of modern quantum theory, this principle states that it is impossible to make a duplicate of an arbitrary, unknown quantum state. It sounds like a technicality (albeit a highly inconvenient one for scientists and mathematicians seeking to design quantum computers). But in an effort in 2002 to derive quantum mechanicsfrom rules about what is permitted with quantum information, Jeffrey Bub of the University of Maryland and his colleagues Rob Clifton of the University of Pittsburgh and Hans Halvorson of Princeton University made no-cloning one of three fundamental axioms. One of the others was a straightforward consequence of special relativity: You can’t transmit information between two objects more quickly than the speed of light by making a measurement on one of the objects. The third axiom was harder to state, but it also crops up as a constraint on quantum information technology. In essence, it limits how securely a bit of information can be exchanged without being tampered with: The rule is a prohibition on what is called “unconditionally secure bit commitment.” These axioms seem to relate to the practicalities of managing quantum information. But if we consider them instead to be fundamental, and if we additionally assume that the algebra of quantum theory has a property called non-commutation, meaning that the order in which you do calculations matters (in contrast to the multiplication of two numbers, which can be done in any order), Clifton, Bub and Halvorson have shown that these rules too give rise to superposition, entanglement, uncertainty, nonlocality and so on: the core phenomena of quantum theory. Another information-focused reconstruction was suggested in 2009by Borivoje Dakić and Časlav Brukner, physicists at the University of Vienna. They proposed three "reasonable axioms" having to do with information capacity: that the most elementary component of all systems can carry no more than one bit of information, that the state of a composite system made up of subsystems is completely determined by measurements on its subsystems, and that you can convert any "pure" state to another and back again (like flipping a coin between heads and tails). Dakić and Brukner showed that these assumptions lead inevitably to classical and quantum-style probability, and to no other kinds. What's more, if you modify axiom three to say that states get converted continuously — little by little, rather than in one big jump — you get only quantum theory, not classical. (Yes, it really is that way round, contrary to what the "quantum jump" idea would have you expect — you can interconvert states of quantum spins by rotating their orientation smoothly, but you can't gradually convert a classical heads to a tails.) "If we don't have continuity, then we don't have quantum theory," Grinbaum said. A further approach in the spirit of quantum reconstruction is calledquantum Bayesianism, or QBism. Devised by Carlton Caves, Christopher Fuchs and Rüdiger Schack in the early 2000s, it takes the provocative position that the mathematical machinery of quantum mechanics has nothing to do with the way the world really is; rather, it is just the appropriate framework that lets us develop expectations and beliefs about the outcomes of our interventions. It takes its cue from the Bayesian approach to classical probability developed in the 18th century, in which probabilities stem from personal beliefs rather than observed frequencies. In QBism, quantum probabilities calculated by the Born rule don't tell us what we'll measure, but only what we should rationally expect to measure. In this view, the world isn't bound by rules — or at least, not by quantum rules. Indeed, there may be no fundamental laws governing the way particles interact; instead, laws emerge at the scale of our observations. This possibility was considered by John Wheeler, who dubbed the scenario Law Without Law. It would mean that "quantum theory is merely a tool to make comprehensible a lawless slicing-up of nature," said Adán Cabello, a physicist at the University of Seville. Can we derive quantum theory from these premises alone? "At first sight, it seems impossible," Cabello admitted — the ingredients seem far too thin, not to mention arbitrary and alien to the usual assumptions of science. "But what if we manage to do it?" he asked. "Shouldn't this shock anyone who thinks of quantum theory as an expression of properties of nature?"

In Hardy's view, quantum reconstructions have been almost too successful, in one sense: Various sets of axioms all give rise to the basic structure of quantum mechanics. "We have these different sets of axioms, but when you look at them, you can see the connections between them," he said. "They all seem reasonably good and are in a formal sense equivalent because they all give you quantum theory." And that's not quite what he'd hoped for. "When I started on this, what I wanted to see was two or so obvious, compelling axioms that would give you quantum theory and which no one would argue with."

So how do we choose between the options available? "My suspicion now is that there is still a deeper level to go to in understanding quantum theory," Hardy said. And he hopes that this deeper level will point beyond quantum theory, to the elusive goal of a quantum theory of gravity. "That's the next step," he said. Several researchers working on reconstructions now hope that its axiomatic approach will help us see how to pose quantum theory in a way that forges a connection with the modern theory of gravitation — Einstein's general relativity. Look at the Schrödinger equation and you will find no clues about how to take that step. But quantum reconstructions with an "informational" flavor speak about how information-carrying systems can affect one another, a framework of causation that hints at a link to the space-time picture of general relativity. Causation imposes chronological ordering: An effect can't precede its cause. But Hardy suspects that the axioms we need to build quantum theory will be ones that embrace a lack of definite causal structure — no unique time-ordering of events — which he says is what we should expect when quantum theory is combined with general relativity. "I'd like to see axioms that are as causally neutral as possible, because they'd be better candidates as axioms that come from quantum gravity," he said. Hardy first suggested that quantum-gravitational systems might show indefinite causal structure in 2007. And in fact only quantum mechanics can display that. While working on quantum reconstructions, Chiribella was inspired to propose an experiment to create causal superpositions of quantum systems, in which there is no definite series of cause-and-effect events. This experiment has now been carried out by Philip Walther's lab at the University of Vienna — and it might incidentally point to a way of making quantum computing more efficient. "I find this a striking illustration of the usefulness of the reconstruction approach," Chiribella said. "Capturing quantum theory with axioms is not just an intellectual exercise. We want the axioms to do something useful for us — to help us reason about quantum theory, invent new communication protocols and new algorithms for quantum computers, and to be a guide for the formulation of new physics." But can quantum reconstructions also help us understand the "meaning" of quantum mechanics? Hardy doubts that these efforts can resolve arguments about interpretation — whether we need many worlds or just one, for example. After all, precisely because the reconstructionist program is inherently "operational," meaning that it focuses on the "user experience" — probabilities about what we measure — it may never speak about the "underlying reality" that creates those probabilities. "When I went into this approach, I hoped it would help to resolve these interpretational problems," Hardy admitted. "But I would say it hasn't." Cabello agrees. "One can argue that previous reconstructions failed to make quantum theory less puzzling or to explain where quantum theory comes from," he said. "All of them seem to miss the mark for an ultimate understanding of the theory." But he remains optimistic: "I still think that the right approach will dissolve the problems and we will understand the theory." Maybe, Hardy said, these challenges stem from the fact that the more fundamental description of reality is rooted in that still undiscovered theory of quantum gravity. "Perhaps when we finally get our hands on quantum gravity, the interpretation will suggest itself," he said. "Or it might be worse!" Right now, quantum reconstruction has few adherents — which pleases Hardy, as it means that it's still a relatively tranquil field. But if it makes serious inroads into quantum gravity, that will surely change. In the 2011 poll, about a quarter of the respondents felt that quantum reconstructions will lead to a new, deeper theory. A one-in-four chance certainly seems worth a shot. Grinbaum thinks that the task of building the whole of quantum theory from scratch with a handful of axioms may ultimately be unsuccessful. "I'm now very pessimistic about complete reconstructions," he said. But, he suggested, why not try to do it piece by piece instead — to just reconstruct particular aspects, such as nonlocality or causality? "Why would one try to reconstruct the entire edifice of quantum theory if we know that it's made of different bricks?" he asked. "Reconstruct the bricks first. Maybe remove some and look at what kind of new theory may emerge." "I think quantum theory as we know it will not stand," Grinbaum said. "Which of its feet of clay will break first is what reconstructions are trying to explore." He thinks that, as this daunting task proceeds, some of the most vexing and vague issues in standard quantum theory — such as the process of measurement and the role of the observer — will disappear, and we'll see that the real challenges are elsewhere. "What is needed is new mathematics that will render these notions scientific," he said. Then, perhaps, we'll understand what we've been arguing about for so long.

Adapted from The Wired

When a Harvard Professor Talks About Aliens

News about extraterrestrial life sounds better coming from an expert at a high-prestige institution.

Astrophysicists usually don't get chased by reporters, but that's what happened to Avi Loeb last November. They bombarded Loeb's phone lines. They showed up at his office with television crews. One of them even followed him home and confronted him at the front door, demanding Loeb answer a question.

"Do you believe that extraterrestrial intelligence exists?"

Days earlier, Loeb had published a new research paper in an astrophysics journal. Scientists publish thousands of research papers every year in journals big and small, prestigious and obscure. Usually, aside from some basic coverage by science journalists, these papers attract little public attention. But Loeb's latest work covered a topic that is historically very attention-getting: aliens.

The subject of the paper was a mysterious space rock known as 'Oumuamua. When it was discovered in October 2017, the rock was the talk of the astronomy community. 'Oumuamua is the first interstellar object astronomers have seen in our solar system; it did not originate here, but likely traveled for billions and billions of years, past countless other stars, before reaching our own. Telescopes caught it just after it sped past the sun. They can't see it anymore, but 'Oumuamua is still going. Eventually, it will cross the edge of our solar system and into interstellar space, again. The leading hypothesis among astronomers is that 'Oumuamua is an odd-looking comet, a remnant of another solar system that was kicked out by natural forces and sent barreling through the cosmos.

Loeb offered a different explanation: 'Oumuamua could be a probe that was deliberately sent to the solar system by an alien civilization.

It's no surprise that news of Loeb's theory took off. The detection of extraterrestrial beings, whether they're the wrinkly ET kind or the teenymicrobial type, would be among the most significant scientific discoveries in human history. The thought of finding sapient life beyond Earth, of learning that we are not alone, is exhilarating and disorienting. The suggestion that it might actually have happened is doubly so.

But there's another reason the paper was so widely covered: Loeb is a tenured Harvard professor.

"If this was some random astronomer that you had never heard of from, say, Equatorial Guinea, you probably wouldn't write a story on it," says Bryan Gaensler, the director of the University of Toronto's Dunlap Institute for Astronomy and Astrophysics, and a former colleague of Loeb's at Harvard. "There's a lot of astronomers that have outlandish ideas, and most of them aren't taken seriously by the community, and most of the time the media don't really give attention to them."
Loeb has two decades' worth of experience and is well regarded in the field. But that background doesn't come up in news stories. Harvard does.

Loeb even looks the part of someone you'd believe about, well, an extraterrestrial spaceship zooming past Earth. Bespectacled, with a neat haircut, Loeb is the antithesis of the History Channel's disheveled, wild-haired man-turned-meme, who mentioned aliens one too many times. If both men approached you on the street and told you aliens existed, which one would you believe?

Several astronomers I spoke with echoed Gaensler's sentiments. So did Loeb himself. He recognizes that his name-brand employer likely attracted the news organizations—and probably primed their readers to trust him.

"It's not just affiliation; it's the fact that I'm chair of the astronomy department [at Harvard]," Loeb said. He rattled off a series of other legitimizing titles: director of the Institute for Theory and Computation; founding director of the Black Hole Initiative; chair of the Board on Physics and Astronomy of the National Academies; chair of the scientific committee for the Breakthrough Starshot Initiative.
Coming from an expert at a high-prestige institution, with credentials in the relevant field, news of an encounter with extraterrestrial life would be more believable to most people, says Michael Varnum, a psychology professor at Arizona State University. Varnum studies a very niche and very relevant topic: how the public might react to the news of an alien discovery.

The prestige effect is magnified, too, “if the evidence or arguments are technical enough that it is not easy for laypeople to understand or evaluate them,” he says. The journalists who cover Loeb make him seem even more trustworthy. “Part of what reinforces that credibility is coverage in news outlets with reputations for serious journalism,” Varnum says.

Loeb, pleasantly surprised by the media reaction, has leaned into the press interest. He has given dozens of interviews to a variety of news organizations since his paper was published in November, from The Verge to The New Yorker.

Some astronomers, however, wish he’d stop.

“‘Oumuamua was exciting, but I’m getting a little frustrated,” says Karen Meech, an astronomer at the University of Hawaii Institute for Astronomy, and one of the people who discovered the interstellar object. “Now it just won’t die.”

Meech, you might have guessed, doesn’t buy Loeb’s theory.

‘Oumuamua is unlike anything else astronomers have seen in the solar system. It doesn’t orbit the sun, like everything else around here. It has an extremely elongated shape. It’s moving very fast, and even seemed to accelerate as it sped through our part of the solar system.

But many astronomers, including those who discovered ‘Oumuamua, say that these features can be attributed to natural phenomena. That acceleration, for instance, could have been caused by icy particles of comet melting in the sun’s warmth.

Astronomers also checked ‘Oumuamua for signs that it came from a technologically advanced alien civilization. (I use “checked” loosely here, because the best way to truly determine where ‘Oumuamua came from is to chase after it with a spacecraft, which modern technology can’t do.) In December 2017, the Green Bank Telescope in West Virginia, one of the world’s most powerful radio observatories, tuned toward ‘Oumuamua and listened for faint radio transmissions. The idea to do it came from Loeb himself. The telescope didn’t detect anything.

“That doesn’t necessarily prove anything, of course,” says Seth Shostak, an astronomer at the seti Institute. “The fact that we didn’t pick up transmissions doesn’t rule out the possibility that [‘Oumuamua] could be something directed here.”

It’s not the suggestion of alien origins that bugs Meech and other astronomers. When faced with puzzling cosmic phenomena, astronomers must explore myriad possibilities, including extraterrestrial ones. The alien option is the least likely explanation, as history has shown, but it’s always on the table.

What bothers them is how Loeb has presented this potential explanation to the press. Unlike in his paper, which hedges with many a “may” and “might,” the astrophysicist sounds certain in news stories. In The Verge: “I cannot think of another explanation for the peculiar acceleration of ‘Oumuamua.” In The New Yorker: “It is much more likely that it is being made by artificial means, by a technological civilization.” To me, in a recent interview: “In my mind, it’s not speculative at all.”

“It doesn’t look identical to things we would see in our solar system, but why should you expect that if it’s coming from elsewhere?” Meech says. “We would all love to have discoveries of aliens, but if you're going to go down that route, you have to have ironclad evidence."

Loeb says that the peculiarities of 'Oumuamua are evidence. In his view, the acceleration could be a result of 'Oumuamua, an artificial probe, taking advantage of free solar energy for an extra push.

Loeb and his colleagues at Breakthrough Starshot, a million-dollar project, are trying to develop such technology, known as lightsails, to send to the star nearest our own. He resists the suggestion that his work is unscientific speculation, and says public discussion of potential explanations—all of them—gives laypeople a real-time look at the scientific process.

"Very often scientists say, Let's not communicate to the public; let's talk among ourselves," he said. "They build this ivory tower, don't explain what they're doing, and then they come out with a statement once they know the answer."

Some astronomers are grateful for Loeb's approach, even if they're wary of his certainty. "He is using tenure and his stature the way we all imagine it's supposed to be used: As a shield so that he can explore potentially unpopular research avenues without fear of retribution or ostracism," Jason Wright, an astronomer at Pennsylvania State University, wrote in a recent blog post. "We all imagine that's what we would do in his position (I hope!) but too often it ends up just being a club to get junior scientists to conform to one's vision for what 'proper' science looks like and what 'good' problems are."

Wright proposed a controversial theory of his own in 2015, when telescopesdetected a strange clump of matter orbiting a nearby star. He and his fellow scientists suggested that the material could be megastructures built by an advanced civilization. A few years later, the same scientists concluded that the megastructures were likely just cosmic dust.

"History is on the side of skepticism when it comes to this stuff," Shostak says. Scientists who do think we could be closer to discovering extraterrestrial life worry that breathless news coverage of weird cosmic phenomena could negatively affect the reception of the real deal—whenever that comes along.

"If and when we do find extraterrestrials—and I think there's a real chance that we might detect some sort of life, intelligent or not, in the next decade or two—we're going to have a 'boy who cried wolf' problem," says Gaensler, the University of Toronto astronomer. "The people who find real evidence of this are probably not going to get the credit they deserve, because we've heard this all before."

In popular culture, Earth's first encounters with extraterrestrial life are unequivocal. One moment, we're alone; the next, we can't deny the existence of aliens. But in reality, the first evidence of alien life—like the early evidence in many scientific breakthroughs—could look much less certain. If there's one lesson from this story, it's that the public's willingness to get excited about it might depend on where the people who first discover aliens work. An Ivy League affiliation wouldn't hurt.

Adapted from The Atlantic

The Case Against Dark Matter

A proposed theory of gravity does away with dark matter, even as new astrophysical findings challenge the need for galaxies full of the invisible mystery particles.

For 80 years, scientists have puzzled over the way galaxies and other cosmic structures appear to gravitate toward something they cannot see. This hypothetical "dark matter" seems to outweigh all visible matter by a startling ratio of five to one, suggesting that we barely know our own universe. Thousands of physicists are doggedly searching for these invisible particles. But the dark matter hypothesis assumes scientists know how matter in the sky ought to move in the first place. This month, a series of developments has revived a long-disfavored argument that dark matter doesn't exist after all. In this view, no missing matter is needed to explain the errant motions of the heavenly bodies; rather, on cosmic scales, gravity itself works in a different way than either Isaac Newton or Albert Einstein predicted. The latest attempt to explain away dark matter is a much-discussed proposal by Erik Verlinde, a theoretical physicist at the University of Amsterdam who is known for bold and prescient, if sometimes imperfect, ideas. In a dense 51-page paper posted online on Nov. 7, Verlinde casts gravity as a byproduct of quantum interactions and suggests that the extra gravity attributed to dark matter is an effect of "dark energy" — the background energy woven into the space-time fabric of the universe. Instead of hordes of invisible particles, "dark matter is an interplay between ordinary matter and dark energy," Verlinde said. To make his case, Verlinde has adopted a radical perspective on the origin of gravity that is currently in vogue among leading theoretical physicists. Einstein defined gravity as the effect of curves in space-time created by the presence of matter. According to the new approach, gravity is an emergent phenomenon. Space-time and the matter within it are treated as a hologram that arises from an underlying network of quantum bits (called "qubits"), much as the three-dimensional environment of a computer game is encoded in classical bits on a silicon chip. Working within this framework, Verlinde traces dark energy to a property of these underlying qubits that supposedly encode the universe. On large scales in the hologram, he argues, dark energy interacts with matter in just the right way to create the illusion of dark matter.

In his calculations, Verlinde rediscovered the equations of "modified Newtonian dynamics," or MOND. This 30-year-old theory makes an ad hoc tweak to the famous "inverse-square" law of gravity in Newton's and Einstein's theories in order to explain some of the phenomena attributed to dark matter. That this ugly fix works at all has long puzzled physicists. "I have a way of understanding the MOND success from a more fundamental perspective," Verlinde said.

Many experts have called Verlinde's paper compelling but hard to follow. While it remains to be seen whether his arguments will hold up to scrutiny, the timing is fortuitous. In a new analysis of galaxiespublished on Nov. 9 in Physical Review Letters, three astrophysicists led by Stacy McGaugh of Case Western Reserve University in Cleveland, Ohio, have strengthened MOND's case against dark matter. The researchers analyzed a diverse set of 153 galaxies, and for each one they compared the rotation speed of visible matter at any given distance from the galaxy's center with the amount of visible matter contained within that galactic radius. Remarkably, these two variables were tightly linked in all the galaxies by a universal law, dubbed the "radial acceleration relation." This makes perfect sense in the MOND paradigm, since visible matter is the exclusive source of the gravity driving the galaxy's rotation (even if that gravity does not take the form prescribed by Newton or Einstein). With such a tight relationship between gravity felt by visible matter and gravity given by visible matter, there would seem to be no room, or need, for dark matter.

Even as dark matter proponents rise to its defense, a third challenge has materialized. In new research that has been presented at seminars and is under review by the Monthly Notices of the Royal Astronomical Society, a team of Dutch astronomers have conducted what they call the first test of Verlinde's theory: In comparing his formulas to data from more than 30,000 galaxies, Margot Brouwer of Leiden University in the Netherlands and her colleagues found that Verlinde correctly predicts the gravitational distortion or "lensing" of light from the galaxies — another phenomenon that is normally attributed to dark matter. This is somewhat to be expected, as MOND's original developer, the Israeli astrophysicist Mordehai Milgrom, showed years ago that MOND accounts for gravitational lensing data. Verlinde's theory will need to succeed at reproducing dark matter phenomena in cases where the old MOND failed.

Kathryn Zurek, a dark matter theorist at Lawrence Berkeley National Laboratory, said Verlinde's proposal at least demonstrates how something like MOND might be right after all. "One of the challenges with modified gravity is that there was no sensible theory that gives rise to this behavior," she said. "If [Verlinde's] paper ends up giving that framework, then that by itself could be enough to breathe more life into looking at [MOND] more seriously."

In Newton's and Einstein's theories, the gravitational attraction of a massive object drops in proportion to the square of the distance away from it. This means stars orbiting around a galaxy should feel less gravitational pull — and orbit more slowly — the farther they are from the galactic center. Stars' velocities do drop as predicted by the inverse-square law in the inner galaxy, but instead of continuing to drop as they get farther away, their velocities level off beyond a certain point. The "flattening" of galaxy rotation speeds, discovered by the astronomer Vera Rubin in the 1970s, is widely considered to be Exhibit A in the case for dark matter — explained, in that paradigm, by dark matter clouds or "halos" that surround galaxies and give an extra gravitational acceleration to their outlying stars. Searches for dark matter particles have proliferated — with hypothetical "weakly interacting massive particles" (WIMPs) andlighter-weight "axions" serving as prime candidates — but so far, experiments have found nothing.

Meanwhile, in the 1970s and 1980s, some researchers, including Milgrom, took a different tack. Many early attempts at tweaking gravity were easy to rule out, but Milgrom found a winning formula: When the gravitational acceleration felt by a star drops below a certain level — precisely 0.00000000012 meters per second per second, or 100 billion times weaker than we feel on the surface of the Earth — he postulated that gravity somehow switches from an inverse-square law to something close to an inverse-distance law. “There’s this magic scale,” McGaugh said. “Above this scale, everything is normal and Newtonian. Below this scale is where things get strange. But the theory does not really specify how you get from one regime to the other.”

Physicists do not like magic; when other cosmological observations seemed far easier to explain with dark matter than with MOND, they left the approach for dead. Verlinde’s theory revitalizes MOND by attempting to reveal the method behind the magic.

Verlinde, ruddy and fluffy-haired at 54 and lauded for highly technical string theory calculations, first jotted down a back-of-the-envelope version of his idea in 2010. It built on a famous paper he had written months earlier, in which he boldly declared that gravity does not really exist. By weaving together numerous concepts and conjectures at the vanguard of physics, he had concluded that gravity is an emergent thermodynamic effect, related to increasing entropy (or disorder). Then, as now, experts were uncertain what to make of the paper, though it inspired fruitful discussions.

The particular brand of emergent gravity in Verlinde’s paper turned out not to be quite right, but he was tapping into the same intuition that led other theorists to develop the modern holographic description of emergent gravity and space-time — an approach that Verlinde has now absorbed into his new work.

In this framework, bendy, curvy space-time and everything in it is a geometric representation of pure quantum information — that is, data stored in qubits. Unlike classical bits, qubits can exist simultaneously in two states (0 and 1) with varying degrees of probability, and they become “entangled” with each other, such that the state of one qubit determines the state of the other, and vice versa, no matter how far apart they are. Physicists have begun to work out the rules by which the entanglement structure of qubits mathematically translates into an associated space-time geometry. An array of qubits entangled with their nearest neighbors might encode flat space, for instance, while more complicated patterns of entanglement give rise to matter particles such as quarks and electrons, whose mass causes the space-time to be curved, producing gravity. “The best way we understand quantum gravity currently is this holographic approach,” said Mark Van Raamsdonk, a physicist at the University of British Columbia in Vancouver who has done influential work on the subject. The mathematical translations are rapidly being worked out for holographic universes with an Escher-esque space-time geometry known as anti-de Sitter (AdS) space, but universes like ours, which have de Sitter geometries, have proved far more difficult. In his new paper, Verlinde speculates that it’s exactly the de Sitter property of our native space-time that leads to the dark matter illusion. De Sitter space-times like ours stretch as you look far into the distance. For this to happen, space-time must be infused with a tiny amount of background energy — often called dark energy —

which drives space-time apart from itself. Verlinde models dark energy as a thermal energy, as if our universe has been heated to an excited state. (AdS space, by contrast, is like a system in its ground state.) Verlinde associates this thermal energy with long-range entanglement between the underlying qubits, as if they have been shaken up, driving entangled pairs far apart. He argues that this long-range entanglement is disrupted by the presence of matter, which essentially removes dark energy from the region of space-time that it occupied. The dark energy then tries to move back into this space, exerting a kind of elastic response on the matter that is equivalent to a gravitational attraction. Because of the long-range nature of the entanglement, the elastic response becomes increasingly important in larger volumes of space-time. Verlinde calculates that it will cause galaxy rotation curves to start deviating from Newton's inverse-square law at exactly the magic acceleration scale pinpointed by Milgrom in his original MOND theory.

Van Raamsdonk calls Verlinde's idea "definitely an important direction." But he says it's too soon to tell whether everything in the paper — which draws from quantum information theory, thermodynamics, condensed matter physics, holography and astrophysics — hangs together. Either way, Van Raamsdonk said, "I do find the premise interesting, and feel like the effort to understand whether something like that could be right could be enlightening." One problem, said Brian Swingle of Harvard and Brandeis universities, who also works in holography, is that Verlinde lacks a concrete model universe like the ones researchers can construct in AdS space, giving him more wiggle room for making unproven speculations. "To be fair, we've gotten further by working in a more limited context, one which is less relevant for our own gravitational universe," Swingle said, referring to work in AdS space. "We do need to address universes more like our own, so I hold out some hope that his new paper will provide some additional clues or ideas going forward." Verlinde could be capturing the zeitgeist the way his 2010 entropic-gravity paper did. Or he could be flat-out wrong. The question is whether his new and improved MOND can reproduce phenomena that foiled the old MOND and bolstered belief in dark matter. One such phenomenon is the Bullet cluster, a galaxy cluster in the process of colliding with another. The visible matter in the two clusters crashes together, but gravitational lensing suggests that a large amount of dark matter, which does not interact with visible matter, has passed right through the crash site. Some physicists consider this indisputable proof of dark matter. However, Verlinde thinks his theory will be able to handle the Bullet cluster observations just fine. He says dark energy's gravitational effect is embedded in space-time and is less deformable than matter itself, which would have allowed the two to separate during the cluster collision. But the crowning achievement for Verlinde's theory would be to account for the suspected imprints of dark matter in the cosmic microwave background (CMB), ancient light that offers a snapshot of the infant universe. The snapshot reveals the way matter at the time repeatedly contracted due to its gravitational attraction and then expanded due to self-collisions, producing a series of peaks and troughs in the CMB data. Because dark matter does not interact, it would only have contracted without ever expanding, and this would modulate the amplitudes of the CMB peaks in exactly the way that scientists observe. One of the biggest strikes against the old MOND was its failure to predict this modulation and match the peaks' amplitudes. Verlinde expects that his version will work — once again, because matter and the gravitational effect of dark energy can separate from each other and exhibit different behaviors. "Having said this," he said, "I have not calculated this all through." While Verlinde confronts these and a handful of other challenges, proponents of the dark matter hypothesis have some explaining of their own to do when it comes to McGaugh and his colleagues' recent findings about the universal relationship between galaxy rotation speeds and their visible matter content. In October, responding to a preprint of the paper by McGaugh and his colleagues, two teams of astrophysicists independently argued that the dark matter hypothesis can account for the observations. They say the amount of dark matter in a galaxy's halo would have precisely determined the amount of visible matter the galaxy ended up with when it formed. In that case, galaxies' rotation speeds, even though they're set by dark matter and visible matter combined, will exactly correlate with either their dark matter content or their visible matter content (since the two are not independent). However, computer simulations of galaxy formation do not currently indicate that galaxies' dark and visible matter contents will always track each other. Experts are busy tweaking the simulations, but Arthur Kosowsky of the University of Pittsburgh, one of the researchers working on them, says it's too early to tell if the simulations will be able to match all 153 examples of the universal law in McGaugh and his colleagues' galaxy data set. If not, then the standard dark matter paradigm is in big trouble. "Obviously this is something that the community needs to look at more carefully," Zurek said. Even if the simulations can be made to match the data, McGaugh, for one, considers it an implausible coincidence that dark matter and visible matter would conspire to exactly mimic the predictions of MOND at every location in every galaxy. "If somebody were to come to you and say, 'The solar system doesn't work on an inverse-square law, really it's an inverse-cube law, but there's dark matter that's arranged just so that it always looks inverse-square,' you would say that person is insane," he said. "But that's basically what we're asking to be the case with dark matter here."

Given the considerable indirect evidence and near consensus among physicists that dark matter exists, it still probably does, Zurek said. "That said, you should always check that you're not on a bandwagon," she added. "Even though this paradigm explains everything, you should always check that there isn't something else going on."

Adapted from The Atlantic

To Solve the Biggest Mystery in Physics, Join Two Kinds of Law

Reductionism breaks the world into elementary building blocks. Emergence finds the simple laws that arise out of complexity. These two complementary ways of viewing the universe come together in modern theories of quantum gravity.

Suppose aliens land on our planet and want to learn our current scientific knowledge. I would start with the 40-year-old documentary Powers of Ten. Granted, it's a bit out of date, but this short film, written and directed by the famous designer couple Charles and Ray Eames, captures in less than 10 minutes a comprehensive view of the cosmos.

The script is simple and elegant. When the film begins, we see a couple picnicking in a Chicago park. Then the camera zooms out. Every 10 seconds the field of vision gains a power of 10 — from 10 meters across, to 100, to 1,000 and onward. Slowly the big picture reveals itself to us. We see the city, the continent, Earth, the solar system, neighboring stars, the Milky Way, all the way to the largest structures of the universe. Then in the second half of the film, the camera zooms in and delves into the smallest structures, uncovering more and more microscopic details. We travel into a human hand and discover cells, the double helix of the DNA molecule, atoms, nuclei and finally the elementary quarks vibrating inside a proton.

The movie captures the astonishing beauty of the macrocosm and microcosm, and it provides the perfect cliffhanger endings for conveying the challenges of fundamental science. As our then-8-year-old son asked when he first saw it, "How does it continue?" Exactly! Comprehending the next sequence is the aim of scientists who are pushing the frontiers of our understanding of the largest and smallest structures of the universe. Finally, I could explain what Daddy does at work!

Powers of Ten also teaches us that, while we traverse the various scales of length, time and energy, we also travel through different realms of knowledge. Psychology studies human behavior, evolutionary biology examines ecosystems, astrophysics investigates planets and stars, and cosmology concentrates on the universe as a whole. Similarly, moving inward, we navigate the subjects of biology, biochemistry, and atomic, nuclear and particle physics. It is as if the scientific disciplines are formed in strata, like the geological layers on display in the Grand Canyon.

Moving from one layer to another, we see examples of emergence and reductionism, these two overarching organizing principles of modern science. Zooming out, we see new patterns "emerge" from the complex behavior of individual building blocks. Biochemical reactions give rise to sentient beings. Individual organisms gather into ecosystems. Hundreds of billions of stars come together to make majestic swirls of galaxies.

As we reverse and take a microscopic view, we see reductionism at work. Complicated patterns dissolve into underlying simple bits. Life reduces to the reactions among DNA, RNA, proteins and other organic molecules. The complexity of chemistry flattens into the elegant beauty of the quantum mechanical atom. And, finally, the Standard Model of particle physics captures all known components of matter and radiation in just four forces and 17 elementary particles.

Which of these two scientific principles, reductionism or emergence, is more powerful? Traditional particle physicists would argue for reductionism; condensed-matter physicists, who study complex materials, for emergence. As articulated by the

Nobel laureate (and particle physicist) David Gross: Where in nature do you find beauty, and where do you find garbage?

Take a look at the complexity of reality around us. Traditionally, particle physicists explain nature using a handful of particles and their interactions. But condensed matter physicists ask: What about an everyday glass of water? Describing its surface ripples in terms of the motions of the roughly 1024 individual water molecules — let alone their elementary particles — would be foolish. Instead of the impenetrable complexities at small scales (the "garbage") faced by traditional particle physicists, condensed matter physicists use the emergent laws, the "beauty" of hydrodynamics and thermodynamics. In fact, when we take the number of molecules to infinity (the equivalent of maximal garbage from a reductionist point of view), these laws of nature become crisp mathematical statements.

While many scientists praise the phenomenally successful reductionist approach of the past centuries, John Wheeler, the influential Princeton University physicist whose work touched on topics from nuclear physics to black holes, expressed an interesting alternative. "Every law of physics, pushed to the extreme, will be found to be statistical and approximate, not mathematically perfect and precise," he said. Wheeler pointed out an important feature of emergent laws: Their approximate nature allows for a certain flexibility that can accommodate future evolution.

In many ways, thermodynamics is the gold standard of an emergent law, describing the collective behavior of a large number of particles, irrespective of many microscopic details. It captures an astonishingly wide class of phenomena in succinct mathematical formulas. The laws hold in great universality — indeed, they were discovered before the atomic basis of matter was even established. And there are no loopholes. For example, the second law of thermodynamics states that a system's entropy — a measure of the amount of hidden microscopic information — will always grow in time.

Modern physics provides a precise language to capture the way things scale: the so-called renormalization group. This mathematical formalism allows us to go systematically from the small to the large. The essential step is taking averages. For example, instead of looking at the behavior of individual atoms that make up matter, we can take little cubes, say 10 atoms wide on each side, and take these cubes as our new building blocks. One can then repeat this averaging procedure. It is as if for each physical system one makes an individualPowers of Ten movie.

Renormalization theory describes in detail how the properties of a physical system change if one increases the length scale on which the observations are made. A famous example is the electric charge of particles that can increase or decrease depending on quantum interactions. A sociological example is understanding the behavior of groups of various sizes starting from individual behavior. Is there wisdom in crowds, or do the masses behave less responsibly?

Most interesting are the two endpoints of the renormalization process: the infinite large and infinite small. Here things will typically simplify because either all details are washed away, or the environment disappears. We see something like this with the two cliffhanger endings in Powers of Ten. Both the largest and the smallest structures of the universe are astonishingly simple. It is here that we find the two "standard models," of particle physics and cosmology.

Remarkably, modern insights about the most formidable challenge in theoretical physics — the push to develop a quantum theory of gravity — employ both the reductionist and emergent perspectives. Traditional approaches to quantum gravity, such as perturbative string theory, try to find a fully consistent microscopic description of all particles and forces. Such a "final theory" necessarily includes a theory of gravitons, the elementary particles of the gravitational field. For example, in string theory, the graviton is formed from a string that vibrates in a particular way. One of the early successes of string theory was a scheme to compute the behavior of such gravitons.

However, this is only a partial answer. Einstein taught us that gravity has a much wider scope: It addresses the structure of space and time. In a quantum-mechanical description, space and time would lose their meaning at ultrashort distances and time scales, raising the question of what replaces those fundamental concepts.

A complementary approach to combining gravity and quantum theory started with the groundbreaking ideas of Jacob Bekenstein and Stephen Hawking on the information content of black holes in the 1970s, and came into being with the seminal work of Juan Maldacenain the late 1990s. In this formulation, quantum space-time, including all the particles and forces in it, emerges from a completely different "holographic" description. The holographic system is quantum mechanical, but doesn't have any explicit form of gravity in it. Furthermore, it typically has fewer spatial dimensions. The system is, however, governed by a number that measures how large the system is. If one increases that number, the approximation to a classical gravitational system becomes more precise. In the end, space and time, together with Einstein's equations of general relativity, emerge out of the holographic system. The process is akin to the way that the laws of thermodynamics emerge out of the motions of individual molecules.

In some sense, this exercise is exactly the opposite of what Einstein tried to achieve. His aim was to build all of the laws of nature out of the dynamics of space and time, reducing physics to pure geometry. For him, space-time was the natural "ground level" in the infinite hierarchy of scientific objects — the bottom of the Grand Canyon. The present point of view thinks of space-time not as a starting point, but as an end point, as a natural structure that emerges out of the complexity of quantum information, much like the thermodynamics that rules our glass of water. Perhaps, in retrospect, it was not an accident that the two physical laws that Einstein liked best, thermodynamics and general relativity, have a common origin as emergent phenomena.

In some ways, this surprising marriage of emergence and reductionism allows one to enjoy the best of both worlds. For physicists, beauty is found at both ends of the spectrum.

Adapted from Quanta Magazine

A Theory of Reality as More Than the Sum of Its Parts

New math shows how, contrary to conventional scientific wisdom, conscious beings and other macroscopic entities might have greater influence over the future than does the sum of their microscopic components.

In his 1890 opus, The Principles of Psychology, William James invoked Romeo and Juliet to illustrate what makes conscious beings so different from the particles that make them up.

"Romeo wants Juliet as the filings want the magnet; and if no obstacles intervene he moves towards her by as straight a line as they," James wrote. "But Romeo and Juliet, if a wall be built between them, do not remain idiotically pressing their faces against its opposite sides like the magnet and the filings. … Romeo soon finds a circuitous way, by scaling the wall or otherwise, of touching Juliet's lips directly."

Erik Hoel, a 29-year-old theoretical neuroscientist and writer, quoted the passage in a recent essay in which he laid out his new mathematical explanation of how consciousness and agency arise. The existence of agents — beings with intentions and goal-oriented behavior — has long seemed profoundly at odds with the reductionist assumption that all behavior arises from mechanistic interactions between particles. Agency doesn't exist among the atoms, and so reductionism suggests agents don't exist at all: that Romeo's desires and psychological states are not the real causes of his actions, but merely approximate the unknowably complicated causes and effects between the atoms in his brain and surroundings.

Hoel's theory, called "causal emergence," roundly rejects this reductionist assumption.

"Causal emergence is a way of claiming that your agent description is really real," said Hoel, a postdoctoral researcher at Columbia University who first proposed the idea with Larissa Albantakis andGiulio Tononi of the University of Wisconsin, Madison. "If you just say something like, 'Oh, my atoms made me do it' — well, that might not be true. And it might be provably not true."

Using the mathematical language of information theory, Hoel and his collaborators claim to show that new causes — things that produce effects — can emerge at macroscopic scales. They say coarse-grained macroscopic states of a physical system (such as the psychological state of a brain) can have more causal power over the system's future than a more detailed, fine-grained description of the system possibly could. Macroscopic states, such as desires or beliefs, "are not just shorthand for the real causes," explained Simon DeDeo, an information theorist and cognitive scientist at Carnegie Mellon University and the Santa Fe Institute who is not involved in the work, “but it’s actually a description of the real causes, and a more fine-grained description would actually miss those causes.”

“To me, that seems like the right way to talk about it,” DeDeo said, “because we do want to attribute causal properties to higher-order events [and] things like mental states.”

Hoel and collaborators have been developing the mathematics behind their idea since 2013. In a May paper in the journal Entropy, Hoel placed causal emergence on a firmer theoretical footing by showing that macro scales gain causal power in exactly the same way, mathematically, that error-correcting codes increase the amount of information that can be sent over information channels. Just as codes reduce noise (and thus uncertainty) in transmitted data — Claude Shannon’s 1948 insight that formed the bedrock of information theory — Hoel claims that macro states also reduce noise and uncertainty in a system’s causal structure, strengthening causal relationships and making the system’s behavior more deterministic.

“I think it’s very significant,” George Ellis, a South African cosmologist who has also written about top-down causation in nature, said of Hoel’s new paper. Ellis thinks causal emergence could account for many emergent phenomena such as superconductivityand topological phases of matter. Collective systems like bird flocks and superorganisms — and even simple structures like crystals and waves — might also exhibit causal emergence, researchers said.

The work on causal emergence is not yet widely known among physicists, who for centuries have taken a reductionist view of nature and largely avoided further philosophical thinking on the matter. But at the interfaces between physics, biology, information theory and philosophy, where puzzles crop up, the new ideas have generated excitement. Their ultimate usefulness in explaining the world and its mysteries — including consciousness, other kinds of emergence, and the relationships between the micro and macro levels of reality — will come down to whether Hoel has nailed the notoriously tricky notion of causation: Namely, what’s a cause? “If you brought 20 practicing scientists into a room and asked what causation was, they would all disagree,” DeDeo said. “We get mixed up about it.”

In a fatal drunk driving accident, what’s the cause of death? Doctors name a ruptured organ, while a psychologist blames impaired decision-making abilities and a sociologist points to permissive attitudes toward alcohol. Biologists, chemists and physicists, in turn, see ever more elemental causes. “Famously, Aristotle had a half-dozen notions of causes,” DeDeo said. “We as scientists have rejected all of them except things being in literal contact, touching and pushing.”

The true causes, to a physicist, are the fundamental forces acting between particles; all effects ripple out from there. Indeed, these forces, when they can be isolated, appear perfectly deterministic and reliable — physicists can predict with high precision the outcomes of particle collisions at the Large Hadron Collider, for instance. In this view, causes and effects become hard to predict from first principles only when there are too many variables to track. Furthermore, philosophers have argued that causal power existing at two scales at once would be twice what the world needs; to avoid double-counting, the "exclusion argument" says all causal power must originate at the micro level. But it's almost always easier to discuss causes and effects in terms of macroscopic entities. When we look for the cause of a fatal car crash, or Romeo's decision to start climbing, "it doesn't seem right to go all the way down to microscopic scales of neurons firing," DeDeo said. "That's where Erik [Hoel] is jumping in. It's a bit of a bold thing to do to talk about the mathematics of causation." Friendly and large-limbed, Hoel grew up reading books at Jabberwocky, his family's bookstore in Newburyport, Massachusetts. He studied creative writing as an undergraduate and planned to become a writer. (He still writes fiction and has started a novel.) But he was also drawn to the question of consciousness — what it is, and why and how we have it — because he saw it as an immature scientific subject that allowed for creativity. For graduate school, he went to Madison, Wisconsin, to work with Tononi — the only person at the time, in Hoel's view, who had a truly scientific theory of consciousness.

Tononi conceives of consciousness as information: bits that are encoded not in the states of individual neurons, but in the complex networking of neurons, which link together in the brain into larger and larger ensembles. Tononi argues that this special "integrated information" corresponds to the unified, integrated state that we experience as subjective awareness. Integrated information theory has gained prominence in the last few years, even as debates have ensued about whether it is an accurate and sufficient proxy for consciousness. But when Hoel first got to Madison in 2010, only the two of them were working on it there. Tononi tasked Hoel with exploring the general mathematical relationship between scales and information. The scientists later focused on how the amount of integrated information in a neural network changes as you move up the hierarchy of spatiotemporal scales, looking at links between larger and larger groups of neurons. They hoped to figure out which ensemble size might be associated with maximum integrated information — and thus, possibly, with conscious thoughts and decisions. Hoel taught himself information theory and plunged into the philosophical debates around consciousness, reductionism and causation.

Hoel soon saw that understanding how consciousness emerges at macro scales would require a way of quantifying the causal power of brain states. He realized, he said, that "the best measure of causation is in bits." He also read the works of the computer scientist and philosopher Judea Pearl, who developed a logical language for studying causal relationships in the 1990s called causal calculus. With Albantakis and Tononi, Hoel formalized a measure of causal power called "effective information," which indicates how effectively a particular state influences the future state of a system. (Effective information can be used to help calculate integrated information, but it is simpler and more general and, as a measure of causal power, does not rely on Tononi's other ideas about consciousness.)

The researchers showed that in simple models of neural networks, the amount of effective information increases as you coarse-grain over the neurons in the network — that is, treat groups of them as single units. The possible states of these interlinked units form a causal structure, where transitions between states can be mathematically modeled using so-called Markov chains. At a certain macroscopic scale, effective information peaks: This is the scale at which states of the system have the most causal power, predicting future states in the most reliable, effective manner. Coarse-grain further, and you start to lose important details about the system's causal structure. Tononi and colleagues hypothesize that the scale of peak causation should correspond, in the brain, to the scale of conscious decisions; based on brain imaging studies, Albantakis guesses that this might happen at the scale of neuronal microcolumns, which consist of around 100 neurons.

Causal emergence is possible, Hoel explained, because of the randomness and redundancy that plagues the base scale of neurons. As a simple example, he said to imagine a network consisting of two groups of 10 neurons each. Each neuron in group A is linked to several neurons in group B, and when a neuron in group A fires, it usually causes one of the B neurons to fire as well. Exactly which linked neuron fires is unpredictable. If, say, the state of group A is {1,0,0,1,1,1,0,1,1,0}, where 1s and 0s represent neurons that do and don't fire, respectively, the resulting state of group B can have myriad possible combinations of 1s and 0s. On average, six neurons in group B will fire, but which six is nearly random; the micro state is hopelessly indeterministic. Now, imagine that we coarse-grain over the system, so that this time, we group all the A neurons together and simply count the total number that fire. The state of group A is {6}. This state is highly likely to lead to the state of group B also being {6}. The macro state is more reliable and effective; calculations show it has more effective information. A real-world example cements the point. "Our life is very noisy," Hoel said. "If you just give me your atomic state, it may be totally impossible to guess where your future [atomic] state will be in 12 hours. Try running that forward; there's going to be so much noise, you'd have no idea. Now give a psychological description, or a physiological one: Where are you going to be in 12 hours?" he said (it was mid-day). "You're going to be asleep — easy. So these higher-level relationships are the things that seem reliable. That would be a super simple example of causal emergence." For any given system, effective information peaks at the scale with the largest and most reliable causal structure. In addition to conscious agents, Hoel says this might pick out the natural scales of rocks, tsunamis, planets and all other objects that we normally notice in the world. "And the reason why we're tuned into them evolutionarily [might be] because they are reliable and effective, but that also means they are causally emergent," Hoel said. Brain-imaging experiments are being planned in Madison and New York, where Hoel has joined the lab of the Columbia neuroscientistRafael Yuste. Both groups will examine the brains of model organisms to try to home in on the spatiotemporal scales that have the most causal control over the future. Brain activity at these scales should most reliably predict future activity. As Hoel put it, "Where does the causal structure of the brain pop out?" If the data support their hypothesis, they'll see the results as evidence of a more general fact of nature. "Agency or consciousness is where this idea becomes most obvious," said William Marshall, a postdoctoral researcher in the Wisconsin group. "But if we do find that causal emergence is happening, the reductionist assumption would have to be re-evaluated, and that would have to be applied broadly."

Sara Walker, a physicist and astrobiologist at Arizona State University who studies the origins of life, hopes measures like effective information and integrated information will help define what she sees as the gray scale leading between nonlife and life (with viruses and cell cycles somewhere in the gray area). Walker has been collaborating with Tononi's team on studies of real and artificial cell cycles, with preliminary indications that integrated information might correlate with being alive. In other recent work, the Madison group has developed a way of measuring causal emergence called "black-boxing" that they say works well for something like a single neuron. A neuron isn't simply the average of its component atoms and so isn't amenable to coarse-graining. Black-boxing is like putting a box around a neuron and measuring the box's overall inputs and outputs, instead of assuming anything about its inner workings. "Black-boxing is the truly general form of causal emergence and is especially important for biological and engineering systems," Tononi said in an email. Walker is also a fan of Hoel's new work tracing effective information and causal emergence to the foundations of information theory and Shannon's noisy-channel theorem. "We're in such deep conceptual territory it's not really clear which direction to go," she said, "so I think any bifurcations in this general area are good and constructive." Robert Bishop, a philosopher and physicist at Wheaton College, said, "My take on EI" —effective information — "is that it can be a useful measure of emergence but likely isn't the only one." Hoel's measure has the charm of being simple, reflecting only reliability and the number of causal relationships, but according to Bishop, it could be one of several proxies for causation that apply in different situations.

Hoel's ideas do not impress Scott Aaronson, a theoretical computer scientist at the University of Texas, Austin. He says causal emergence isn't radical in its basic premise. After reading Hoel's recent essay for the Foundational Questions Institute, "Agent Above, Atom Below" (the one that featured Romeo and Juliet), Aaronson said, "It was hard for me to find anything in the essay that the world's most orthodox reductionist would disagree with. Yes, of course you want to pass to higher abstraction layers in order to make predictions, and to tell causal stories that are predictively useful — and the essay explains some of the reasons why."It didn't seem so obvious to others, given how the exclusion argument has stymied efforts to get a handle on higher-level causation. Hoel says his arguments go further than Aaronson acknowledges in showing that "higher scales have provably more information and causal influence than their underlying ones. It's the 'provably' part that's hard and is directly opposite to most reductionist thinking."Moreover, causal emergence isn't merely a claim about our descriptions or "causal stories" about the world, as Aaronson suggests. Hoel and his collaborators aim to show that higher-level causes — as well as agents and other macroscopic things — ontologically exist. The distinction relates to one that the philosopher David Chalmers makes about consciousness: There's the "easy problem" of how neural circuitry gives rise to complex behaviors, and the "hard problem," which asks, essentially, what distinguishes conscious beings from lifeless automatons. "Is EI measuring causal power of the kind that we feel that we have in action, the kind that we want our conscious experiences or selves to have?" said Hedda Hassel Mørch, a philosopher at New York University and a protégé of Chalmers'. She says it's possible that effective information could "track real ontological emergence, but this requires some new philosophical thinking about the nature of laws, powers and how they relate." The criticism that hits Hoel and Albantakis the hardest is one physicists sometimes make upon hearing the idea: They assert that noise, the driving force behind causal emergence, doesn't really exist; noise is just what physicists call all the stuff that their models leave out. "It's a typical physics point of view," Albantakis said, that if you knew the exact microscopic state of the entire universe, "then I can predict what happens until the end of time, and there is no reason to talk about something like cause-effect power." One rejoinder is that perfect knowledge of the universe isn't possible, even in principle. But even if the universe could be thought of as a single unit evolving autonomously, this picture wouldn't be informative. "What is left out there is to identify entities — things that exist," Albantakis said. Causation "is really the measure or quantity that is necessary to identify where in this whole state of the universe do I have groups of elements that make up entities? … Causation is what you need to give structure to the universe." Treating causes as real is a necessary tool for making sense of the world. Maybe we sort of knew all along, as Aaronson contends, that higher scales wrest the controls from lower scales. But if these scientists are right, then causal emergence might be how that works, mathematically. "It's like we cracked the door open," Hoel said. "And actually proving that that door is a little bit open is very important. Because anyone can hand-wave and say, yeah, probably, maybe, and so on. But now you can say, 'Here's a system [that has these higher-level causal events]; prove me wrong on it.'"

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